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Digitalization and Energy Efficiency in the Building Sector in Brazil

National and International Context

cooperação alemã DEUTSCHE ZUSAMMENARBEIT

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Glossary

ABNT	Brazilian Association of Technical Standards
AC	Alternating current
ANATEL	National Telecommunications Agency
ANEEL	National Agency of Electric Energy
BIM	Building Information Modeling
BEM	Building Energy Modeling
BMS	Building Management Systems
BMWK	German Federal Ministry for Economic Affairs and Climate Action
BMZ	German Federal Ministry for Economic Cooperation and Development
BNDES	National Bank for Economic and Social Development
BRL	Brazilian currency (Reais)
CAR	Conformity Assessment Requirements
CB3E	Brazilian Center for Energy Efficiency in Buildings
CBCS	Brazilian Council for Sustainable Construction
CDE	Common Data Environment
CDW	Construction and Demolition Waste
CFD	Computational Fluid Dynamics
CGIEE	Energy Efficiency Indicators and Levels Management Committee
CICE	Internal Energy Conservation Commission
CIM	City Information Modeling
CO_2	Carbon Dioxide
CONPET	National Program for the Rationalization of the Use of Oil and Natural Gas Derivatives
COP21	Conference of the Parties 2021
DALI	Digital Addressable Lighting Interface
DC	Direct Current
DER	Distributed Energy Resources
EaaS	Energy-as-a-Service
ECS	Electricity Compensation System
EESUD	Energy Efficiency for Sustainable Urban Development
EPE	Energy Research Office
EV	Electric Vehicle
GHG	Greenhouse Gases
GIZ	*Deutsche Gesellschaft für Internationale Zusammenarbeit* (German Cooperation for Sustainable Development)
GPR	General Property Registry
HU	Housing Unit
HVAC	Heating, Ventilation and Air Conditioning
IaaS	Infrastructure as a Service
IAF	International Accreditation Forum
IBGE	Brazilian Institute of Geography and Statistics
IEA	International Energy Agency
INI-C	Inmetro Normative Instruction for the Energy Efficiency Classification of Commercial, Service and Public Buildings
INI-R	Inmetro Normative Instruction for the Energy Efficiency Classification of Residential Buildings
Inmetro	National Institute of Metrology, Quality and Technology
IoT	Internet of Things
ISO	International Organization for Standardization
kWh	kilowatt-hour
LCA	Life Cycle Assessment
LGPD	General Personal Data Protection Law
m^2	Square meter

M&V	Measurement and Verification
MCID	Ministry of Cities
MCTI	Ministry of Science, Technology and Innovations
MDR	Ministry of Regional Development
MME	Ministry of Mines and Energy
MP	Ministry of Planning, Budget and Management
NDC	Nationaly Determined Contribution
NEB	National Energy Balance
NECL	National Energy Conservation Label
NOR	Net Operating Revenue
NR	Normative Resolution
PaaS	Platform as a Service
PBE	Brazilian Labeling Program
PDE	Decennial Energy Expansion Plan
PDEf	Ten-Year Energy Efficiency Plan
PEE	Energy Efficiency Program
PEEB	Program for Energy Efficiency in Buildings
PERS	Social Renewable Energy Program
PLC	Power Line Communication
PNCI	National Smart Cities Policy
PNIC	National Plan for Internet of Things
PNE	National Energy Plan
PNMC	National Policy on Climate Change
PPH	Possessions and Habits Research
PPT	Public Telecommunications Policies
PROCEL	National Electric Energy Conservation Program
R&D	Research and Development
RBC	Rule Based Control
RFID	Radio Frequency Identifiers
RI	Registration of Incorporation
S&T	Science and Technology
SIH	Social Interest Housing
TQR-C	Technical Quality Requirements for the Energy Efficiency Level of Commercial, Service and Public Buildings
TQR-R	Technical Quality Requirement for the Energy Efficiency Level of Residential Buildings
UBEM	Urban Energy Modeling
US$	Dollar
VPN	Virtual Private Network
WG	Working Group

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Executive summary

The building sector is one of the main energy consumers in the world energy matrix. In the European Union countries, for example, this sector represents around 40% of final energy consumption and 36% of CO_2 emissions. In Brazil, it is the third largest consumer of total energy and the first of electrical energy. Residential, commercial and public buildings account for about 15% of total energy consumption and 51% of electricity consumption.

Digital transformation in the buildings sector, as in all others, is becoming increasingly present in everyday life and making it possible to collect, store, structure, organize and process data in an unprecedented way. The set of available data is analyzed and related to specific contexts, generating useful information for the systematization of processes in an increasingly optimized way. Energy efficiency is among the functions to which digitalization can contribute.

The aspects addressed in this study present intrinsic complexity as the building sector is comprised of different realities and agents, such as developers, construction companies, design offices, building administrators, users, suppliers and manufacturers of materials and service providers. Each category of actor brings its own diversity in terms of size, specific objectives, financial conditions, specific challenges, which influence their adoption of technologies in everyday life. This complexity increases because it is still inserted in a very heterogeneous regulatory environment, a high level of informality and the late adoption of new technologies by the construction sector.

In the evaluation of digital technologies by phase of the building's life cycle (design, construction, operation, renovation and demolition) and by typology (commercial, public, single-family residence, multifamily residence and social interest housing) twenty were selected and are described and analyzed for each mentioned phase and typology.

The selection of digital solutions covered:

i. Management and automation technologies such as smart sensors, actuators and switches, Digital Addressable Lighting Interface (DALI), smart facades and other systems, virtual assistants, apps and smart controls, smart sockets and electric vehicle chargers, grid-connected smart electrical and electronic equipment, building management systems (BMS) and demand response, awareness and gamification apps, which are predominantly applied in the operating phase where 80% of the buildings' energy consumption takes place;

ii. Computer simulation and evaluation programs such as Building Energy Modeling (BEM), Computational Fluid Dynamics (CFD), Simulation of natural and artificial lighting, Management Systems of Energy Portfolio; Software for Life Cycle Assessment (LCA), which are widely applied in the design phase and enable more energy efficient and sustainable buildings;

iii. Data management and security technologies such as Blockchain and Cloud Computing;

iv. Technologies that increase productivity such as 3D printing, Agile Management Software and Augmented Reality; and the Building Information Modeling (BIM) technology, which works as a collaborative three-dimensional virtual model of the building with specific information associated with each element inserted in the constructive and material aspects.

The description and application of these technologies by phase of their life cycle and typology are presented in items 2.1.1 to 2.1.5.

For the selected digital solutions, a *status quo* assessment is carried out, based on the commercial availability of associated products and services, in Brazil and other countries, consolidated in relational matrices (in items 2.2.1 to 2.2.5) based on academic references and commercial (related to the summary table presented in Appendix 3).

This assessment shows that, in the design phase, there is commercial availability of products and services related to Building Information Modeling, different simulation categories, in addition to specific software for Life Cycle Assessment, agile management and augmented reality systems.

In the construction phase, the simulation technologies are excluded, the others presented are kept and, internationally, 3D Printing and Blockchain technologies are available (in Brazil still under development). For the operation phase, the commercial availability of solutions capable of promoting the control and automation of processes and services, such as sensors and actuators, DALI, virtual assistants, apps and smart controls, smart sockets, electric vehicle chargers, smart switches and smart electrical and grid-connected electronic equipment. The renovation phase reproduces the *status quo* of the design phase, adding 3D Printing solutions, available internationally and under development in the national context. In the demolition phase products and services for BIM, LCA, Agile Management and Augmented Reality were offered in the national context with the addition of Blockchain in the international context.

The regulatory policies and instruments implemented or under development in Brazil associated with energy efficiency and digitalization in the building sector cover three main areas: Energy Efficiency policies that may impact the building sector; regulatory instruments related to Smart Grids that can expand Digitalization in this sector; and policies directly linked to Digitalization in Buildings, as presented in item 2.3.

The legal framework related to energy efficiency began in the 1980s and has been improving over time. It is thoroughly described in this study. In the area of energy efficiency in buildings, PROCEL Edifica and PBE Edifica stand out. They are subprograms respectively of the National Electric Energy Conservation Program and the Brazilian Labeling Program. The cross-cutting nature of energy efficiency leads several government agencies to have energy efficiency initiatives that are more related to their sectors of activity, such as those of the Ministry of Economy and Ministry of Regional Development.

Regulatory instruments implemented and under development in Smart electricity grids, smart meters, distributed generation, demand response tariff mechanisms, opening up the electricity market, flexibility and digitalization of the electricity sector in terms of hourly pricing, internet of things; smart cities and dissemination of Building Information Modeling (BIM) are definitely elements that, together with the technologies described here, will boost the digitalization of the construction sector. All these aspects are the object of this study.

In spite of the strong framework built and under development, the transversal feature and complexity of digitalization implementations in buildings require more robustness and strengthening of coordination to become effective and synergistic. Recommendations for public policy actions will be the object of the next report.

Demand management for home appliances and lighting and air conditioning systems can aim to reduce energy consumption or reduce costs related to demand on the light bill. Both depend on the regulatory environment to which the associated buildings are subject. For energy savings, three technology families stand out: energy metering; energy management; and the technology intrinsic to the equipment (if they are efficient and manageable). Within the scope of the first two families, technologies such as BMS, sensors, smart actuators and switches, virtual assistants, smart apps and controls, smart sockets and DALI stand out. Such digital technologies work both to reduce energy consumption and in changing users' habits. Smart apps and controls give visibility to consumption information and guide users to save energy. Smart controls, virtual assistants and smart switches make it easy to control these devices. The management of more complex buildings, such as commercial and public, uses BMS and DALI technologies.

Regarding equipment and systems, the emerging digital technology of smart electrical and electronic equipment connected to the grid associates communication and remote control solutions with home appliances, which facilitates their integration with the management technologies already mentioned. Smart sockets and switches make it possible for appliances and systems that are not produced with onboard intelligence to also be controlled.

The conclusion is that energy saving has its potential strongly driven by digital technologies, making it possible to overcome the challenges of changing user habits, automatic management of loads and online monitoring of consumption.

Demand management to minimize electricity costs depends heavily on the regulation of the electricity system in which the building is inserted. Currently in Brazil, tariff group B has a monomial tariff and, optionally, a white tariff. For consumers in tariff group A with a binomial tariff where there are large shopping malls and commercial and public buildings, the technologies that manage their loads are essential, especially those connected to the air conditioning systems that, in these buildings, generally correspond to more than 30% of consumption. The technologies of building management systems and sensors, actuators and smart switches are essential for this management.

When buildings are analyzed together as in districts, there is a new layer of possibilities for optimization and sharing with the adoption of specific technologies or the integration between them, as well as the possibility of shared management of assets. Specific integration projects, careful monitoring of renovations or new constructions in the complex are essential. Examples of systems that can have their economic viability reinforced are renewable energy generation systems, solar thermal heating, shared hot water supply systems, thermal accumulation tanks, systems for supplying cold water or refrigerant fluids (for air conditioning), systems for collecting rainwater or wastewater treatment and storage. To do so, technologies related to simulation are essential, such as BEM, Urban Energy Modeling (UBEM), CFD, daylight simulation, LCA and energy portfolio simulation and management programs. In the operational phase, information management, control and automation technologies such as cloud computing, BIM, energy portfolio management, Blockchain, its smart contracts, artificial intelligence and associated hardware (sensors, actuators and smart switches) stand out, user information and gamification tools, smart sockets and electric car chargers.

Smart metering plays an important role in accelerating digitalization in buildings. It is worth mentioning that smart metering technologies are not restricted to electricity meters. A smart metering infrastructure must be composed of equipment that measures energy quantities and systems and software that store, manage and analyze the measured data. The use of measurement technologies covers all typology of building and generally happens in the operational phase during which the highest energy consumption occurs. In social interest housing, electronic meters are restricted to serving some projects with a differentiated tariff regime. The international experiences of installing smart meters in the buildings studied in the USA, European Union, Germany and the United Kingdom show the success using this equipment in any building, regardless of typology. This enables better management and operation of energy resources in these countries. The smart meter market has huge growth potential in the country, thanks to the current regulatory framework, and it can also leverage the market for other smart metering technologies.

With regard to technology for building certification, the advancement of technologies for capturing and transmitting images and documents, Blockchain, data security, among others, enable the digitalization of various certification processes and the creation of digital platforms to support the main existing certifications such as the PBE Edifica Labeling, LEED (Leadership in Energy and Environmental Design), EDGE (Excellence In Design for More Efficiencies), WELL Building Standard, BREEAM (Building Research Establishment Environmental Assessment Method), DGNB (*Deutsche Gesellschaft für Nachhaltiges Bauen*), and the AQUA-HQE (High Environmental Quality - *Haute Qualité Environnementale*).

The remote audit activities recommended by the ABNT ISO 19011 Standard - Guidelines for auditing management systems, of December 2018, are carried out using interactive communication technologies integrated with data security in conducting interviews, in the remote observation of the work carried out, in the filling in checklists and questionnaires and conducting critical document analysis with the participation of the auditee. Energy audits use various apps and software to automate and streamline their processes, reducing time and cost.

Regarding building typologies, certification, its digital platforms and remote inspections can be used for all typologies. Adoption of a certification is generally driven by a mandatory regulatory framework. This is not the Brazilian case.

It is noteworthy that because digital technologies generate agility, reliability and reduction of human and financial resources, notably in remote inspections, can constitute a great booster of voluntary certifications in the country, which today are not massively adopted due to barriers or lack of knowledge, lack of time, high cost for small buildings, among others.

As a general conclusion of this study, it can be said that there is a great potential for the use of digital solutions in buildings. For each phase of the building life cycle and typology, there are different agents involved with different barriers and challenges. The twenty selected technologies are expected to boost the impact of digitalization in increasing energy efficiency in buildings, highlighting sensors, actuators, smart sockets and switches, BIM, BEM, Blockchain, virtual assistants, Agile management tools, and building management systems. The global trend of increasing use of digital technologies in various sectors of the economy, the reduction of consumption of energy inputs, the modernization of the electric sector, the reduction of the costs of services and equipment of digital solutions, the more attentive behavior of consumers in relation to energy efficiency facilitated by more access to information and better control are the great drivers of this growing national market soon.

In order to contribute to the debate on the possible evolutionary paths of digitalization constraints in the medium and long-term building sector and to support the formulation or review of public policies, in the prospective phase of this study, three scenarios will be created regarding the potential for energy efficiency resulting from digitalization in the building sector in Brazil, recommended according to three implementation rates – slow, moderate or fast.

1. Introduction

The building sector is one of the main energy consumers in the world. In European Union countries, for example, this sector represents about 40% of final energy consumption and 36% of CO_2 emissions [1]. In Brazil, it is the third largest consumer of total energy and the first of electric energy. Residential, commercial and public buildings account for about 15% of total energy consumption and 51% of electricity consumption.

The demand generated by demographic, urban, and economic growth results in the construction of new projects, often increasingly larger and more complex buildings, which will contribute to an increase in greenhouse gas (GHG) emissions and electricity consumption by inhabitant. This trend shows the urgency of increasing the energy efficiency of buildings in all phases of the life cycle, particularly in the design, construction and operation phases. The study entitled "Smart and Efficient - Digital Solutions for Energy Saving in Buildings", recently published by the Program for Energy Efficiency in Buildings (PEEB), pointed out that adoption of digital technologies in the building sector can avoid 8-10% of emissions expected for buildings by 2030 [2].

Energy efficiency is considered a vehicle for technical, economic, environmental and social development of the country, contributing to the rational use of natural resources and energy security. Particularly in the building sector, there is a lot of untapped potential for reducing energy consumption in buildings with the use of digital solutions.

Digital technologies can contribute to energy efficiency throughout the life cycle of a building which will be demonstrated in this study. In the design phase, parameters of the building are defined, and they will determine its energy performance for years. These parameters encompass envelope, lighting, air conditioning, among others. New systems such as Building Information Modeling (BIM) can define the strategy for improving the energy efficiency of commercial, public and residential buildings at various phases of the life cycle. In addition, digitalization in the construction phase can contribute to the standardization of components and construction processes from the perspective of energy efficiency gains, by applying digital solutions on a large scale at a more affordable cost, including for social interest housing.

With the digital transformation in the building sector, it is expected that the use of smart meters will intensify capable of providing a two-way flow of energy and information, which when used at scale and associated with appropriate charging and smart dispatch systems enable smart grids to improve grid reliability, safety and efficiency of the entire electrical system.

The study was carried out within the scope of the Brazil-Germany Energy Partnership and the Energy Efficiency for Sustainable Urban Development (EESUD) project, which aims to meet the demands created by the Technical Group for Energy Efficiency in Buildings (TG-Buildings), linked to the Energy Efficiency Indicators and Levels Management Committee (CGIEE) of the Ministry of Mines and Energy (MME), regarding the role and potential of digital technologies associated with energy efficiency in the building sector at the national level.

The study aims to identify and systematize digital solutions and applications for residential, commercial and public buildings, in relation to different market sectors and consider the entire life cycle of the building, in order to provide a basis for the formulation of public policies aimed at increasing the energy efficiency of the building sector, through digital transformation [3]. To achieve this general objective, a methodology was conceived in three phases – exploratory-descriptive, prospective and propositional. In Appendix 1 of this document, the general methodology of the study is described, emphasizing that the results presented in this report refer to the first phase of the study. The results of the prospective and propositional phases will be the object of the final report of this study.

1.1 Text Organization

This report is structured in four chapters, including this introduction. In Chapter 2, the digital solutions for energy efficiency in buildings in Brazil and the world are initially analyzed by life cycle phase and building typology. Next, the *status quo* of digitalization in the building sector in Brazil and the world is presented, considering three levels of technological aptitude and summarizing the digitalization policies in the building sector in Brazil. These policies include instruments already implemented or under development. At the end, it addresses how the "intelligence" of the operation of buildings has been adopted in Brazil and the world.

In Chapter 3, the technologies applied to the management of building demand and the surroundings are analyzed, focusing on the management of household appliances, lighting and air conditioning, the management of connected buildings, smart grids, and the use of smart metering technologies by life cycle phase and building typology. Although smart metering related to energy billing takes place in the operation phase, there is the possibility of using these technologies for energy saving in other phases, such as in construction sites in the construction phase. This is followed by an overview of the national smart meter market and international experiences in the implementation of smart metering systems.

This chapter ends with an analysis of the digital technologies that have been used in the building certification process, with special emphasis on the application of remote inspection technologies, according to guidelines established in the ABNT NBR ISO 19011:2018 - Guidelines for auditing management systems – Corrected version: 2019 [4].

Finally, Chapter 4 summarizes the conclusions of the analyses presented in Chapters 2 and 3.

Appendix 1 summarizes the general methodology of the study and describes each of the phases of its development. Appendices 2 and 3 refer, respectively, to the definition of the typologies and the summary table of the digital solutions analyzed in Chapter 2. References from suppliers that supported the stratification of the *status quo* of digital technologies in Brazil and in the world are found in Appendix 4.

2. Analysis of digital solutions for energy efficiency in buildings in Brazil and worldwide

Digital transformation has become increasingly present in everyday life and makes it possible to collect, store, structure, organize and process data in an unprecedented way. The set of available data is analyzed and related to specific contexts, generating useful information for the systematization of processes in an increasingly optimized way.

Structured and stable processes are susceptible to automation, reducing the need for human interaction, in repetitive activities or complex, risky or painful control, which frees up time for the development of intellectual activities and minimizes failures without losing productivity. When processes involve multiple instances or stakeholders, there are transactions that require proper registration and relationships dictated by contracts, rules, regulations, laws, etc., which translate into programmable rules in smart contracts, which need to offer traceability, reliability, security and auditability.

The building sector, like all others, has becoming the focus of development of numerous strategies, technologies and digital solutions which apply to all phases of its life cycle and, to a greater or lesser extent, to the different typologies in which can be classified. Energy efficiency is among the functions to which digitalization can contribute.

The typologies and phases of the life cycle to be addressed in this study were analyzed by the technical team and the proposed structure, that comprises five typologies and five phases, was validated by the coordination of this study. A total of 11 national and four international references were analyzed, and a lack of standardization in the classification of building typologies was found. Some analyzed references grouped the renovation phase with the demolition phase. It was decided to separate them by the distinct use of digital technologies and by the specificities of these phases. Regarding the typologies of the residential sector, a separate study was necessary, which resulted in the definition of three typologies: single-family, multifamily and social interest housing (SIH). Appendix 2 presents the results of the analysis of building classifications.

It is important to emphasize that digitalization is an additional layer for improving performance and energy efficiency in buildings, helping to optimize and providing useful and structured information to help professionals in the field to conceive, enable and implement better solutions, but it does not replace passive design approaches and techniques in the design and construction phases.

It is during the operational phase that buildings emit the most carbon and consume energy and other resources throughout their life cycle, followed by the construction phase, so it is common sense that any approach aimed at improving energy efficiency has focus on the operation, although it is desirable to think of constructive processes that mitigate the consumption of resources in the other phases.

This chapter brings together analyses of digital solutions for energy efficiency in buildings in Brazil and the world by life cycle phase and building typology. Next, it presents the *status quo* of digitalization in the building sector in Brazil and the world, considering three levels of technological aptitude and summarizes digitalization policies in the building sector in Brazil, including instruments already implemented or under development. In the end, it addresses how the “intelligence” of the operation of buildings has been adopted in Brazil and in the world.

2.1 Digital solutions for energy efficiency in buildings by life cycle phase

This section deals with the mapping of digital solutions applicable to five types of buildings adopted in this work, in each of the phases of their respective life cycles. Therefore, we opted for the use of the morphological analysis technique, whose fundamental premise is to decompose a complex problem into variables. The logic of problem decomposition is to deal with less complex issues than the original system, thus enabling a deeper analysis of the parts. Further details are presented in Appendix 1 - Methodological note.

The buildings were broken down into seven main domains, which impact the energy consumption of buildings throughout their life cycle, namely: envelope; HVAC; lighting; water heating, equipment and socket loads; building infrastructure; and energy supply, generation and storage. These domains were related to the five building typologies adopted for this study and generated a morphological matrix for each phase of the building life cycle: design; construction; operation; renovation and demolition. The correlation cells between domains and typologies were then filled with technologies and digital solutions obtained from the literature and from the experience of the professionals involved in the elaboration of the work. The twenty technologies and digital solutions surveyed are consolidated in Appendix 3 - Overview of digital solutions in the building sector and are briefly described below.

Building Information Modeling (BIM)

It is a broad and multidisciplinary process for registration and structured management of diverse information about a building. It works as a detailed three-dimensional virtual model (minimum levels of detail are internationally discussed and there are initiatives to build libraries, in order to facilitate standardization) and collaborative (mainly from interoperability protocols) of the building, with specific information associated with each element inserted both in the constructive aspect and in the materials.

Building Energy Modeling (BEM)

It aims to use specific tools for simulations related to energy, whether thermal or electrical. Its primary use in the building sector is the estimation of electrical energy consumption during the operation of a given building. To this end, the demands of all systems that demand electricity are calculated, such as lighting, socket loads and HVAC. Simulations can be performed with a simplified three-dimensional model, with no furniture or installations. However, attention must be paid to the precision in the dimensions of the rooms and their existing equipment, with load inserted from the average per square meter (m^2).

Computational Fluid Dynamics (CFD)

Computer numerical simulation for analyzing the behavior of fluids (such as air) in processes or environments, with heat transmission or mass transport, chemical reactions and other related phenomena. It is based on complex fluid mechanics equations (Navier-Stokes equations), solved at all points of a high-resolution mesh, in 2D or 3D, which represents the discretization of the simulated volume.

Simulation of natural and artificial lighting

Computer simulation to evaluate the luminous and energy performance of lighting systems in buildings that involve a combination of multiple variables, which can be changed simultaneously in order to reconcile individual well-being, architecture and economy. The improvement of the processors' capacity enables the development of realistic models with the inclusion of natural lighting and shading to simulate different scenarios and generate databases for the analysis of different energy efficiency alternatives when the building is in the design phase or after construction.

Energy portfolio management system

An integrated approach, through simulation and the use of advanced algorithms, aiming at the broad evaluation and optimization of projects related to distributed generation, renewable energy, energy efficiency and cogeneration. It allows decision makers and professionals to carry out a pre-analysis and quickly and easily verify the technical and financial feasibility of opportunities to combine projects, gathered in a single platform. It also monitors real-time information on energy performance of buildings after construction, by means of setting energy reduction (or production) targets and issuing continuous reports on the reduction of greenhouse gas emissions associated with clean energy technologies in order to ensure that investment performance is maintained in the long term.

Software for life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a tool to systematically investigate the environmental performance of products and processes throughout their entire life cycle, starting with raw material extraction to disposal or recycling. After this assessment, it is possible to consciously identify opportunities for improvement. The methodology is not recent. However, the development of software and databases has facilitated its use in the building sector. There are now several specific types of software on the market that help in this evaluation.

3D printing

It is a class of additive manufacturing technologies, which enables the construction of complex three-dimensional components or even monolithic structures in situ. This is done by using virtual models and specific software, with minimal or no waste, from the sequential deposition of regular layers of material. There are several types of 3D printers, each using different materials, such as plastics, metals, or mortars.

Augmented Reality

Augmented Reality is the overlay of virtual objects on real environments, so that both coexist in the user's perspective. Its visualization depends on electronic equipment, such as adapted glasses or a camera phone.

Blockchain

It is a distributed ledger technology platform, which aims to decentralize processes and secure better the information exchanged. It works as a ledger of records and information about a project (or market, or currency), highly encrypted, which aims to make any transaction (whether of values or information) become a direct process between the parties involved, according to their roles and excluding the need for an intermediary. Distributed information is necessarily consensual and the degree of transparency for stakeholders can be controlled so that only important information for each party is accessed. The platform is governed by smart contracts which are software built to automatically evaluate the business rules of each transaction and record their results. On the Blockchain platform, smart contracts run simultaneously on several machines (at the network nodes, the responsibility of multiple stakeholders) and transactions are only validated if there is consensus between the results. Transactions made on Blockchain cannot be undone, which makes them extremely reliable and auditable. One of the most prominent and transformative uses of Blockchain can be seen in the electricity market, more precisely in applications designed for communication and for storing and sending data in smart energy transmission and distribution grids, in the management of energy contracts, in the sales of certificates of origin, and in smart dispatch in smart grids.

Agile management software

Agile management in buildings is the application in this sector of the principles of Agile management initially developed for software development. It consists of a set of practices aimed at improving the effectiveness of professionals, teams and organizations. It is based on adaptive planning, evolutionary development, early delivery and continuous improvement, and encourages flexible responses to changes in requirements, availability of resources and understanding of the problems to be solved. There are several techniques and several commercial products on the market associated with them. Among the management techniques used in buildings, the following stand out: SCRUM for teamwork that encourages teams to learn from experiences and to organize themselves while solving a problem; Kanban for communication and work transparency, in this technique the work items gain visual representation by allowing team members to see the state of each part of the work at any time; and the Lean method, whose focus is to diagnose and reduce all waste within the company or a specific project. One its concepts is MVPs, or minimum viable products which works as a kind of test to validate that idea. This technology can be used in conjunction with others such as BIM.

Building Management Systems (BMS)

They are smart and autonomous systems that aim to increase the comfort and safety levels of buildings, while simultaneously reduce energy consumption and operating costs.

Smart sensors, actuators and switches

This area encompasses multiple technologies, different types of equipment and techniques and is the basis of the digitalization process in monitoring and managing the variables that promote energy efficiency. Sensors are responsible for measuring the quantities that you want to manage, control or simply know and can be analog or digital. Analog sensor measurements go through a digitalization process to be used in digital techniques. The actuators, within a pre-established control logic, transform generally electrical energy into mechanical energy to perform the function intended by automation. The smart switch is an evolution that uses the information coming from the sensor to perform a certain action. It also includes the sophistication of being able to use communication and data transmission technologies for control through the internet, voice command or other form of remote command. In addition to performing energy management actions such as decreasing the intensity of the lighting without turning it off.

Sensors were made popular by industrial automation in the 50s and are now an essential part of building automation and management. They are activated by the change of physical quantities of the environment, installations or systems such as temperature, humidity, luminosity, pressure, mass movement, fluid movements or even binary states of other quantities. They can be categorized into capacitive, inductive, fiber optic, laser, ultrasonic, etc. Actuators as well as sensors were popularized by industrial automation and are used in buildings, mainly commercial, public and multifamily, in fluid control/adjustment, doors, skylights, etc.

Smart switches are the ones with embedded intelligence that usually involve sensors, data transmission via wi-fi, internal processing to receive and give commands and through them control the loads of buildings and homes. The affordability of this technology has led to its rapid popularization and, consequently, to the increase in the sale of home appliances and smart sockets that make such automation possible. There are several types of smart switches for sale and their control capacity ranges from one piece of equipment to several systems. Control through cell phones enables several functions for managing these loads that enable concrete energy efficiency actions even remotely.

Digitally Addressable Lighting Interface (DALI)

Known as DALI Protocol (Digital Addressable Lighting Interface), it is a digital communication system between lighting control devices, enabling the creation of flexible lighting with applications for the most diverse types of environments due to the wide set of possible programming. And because it is an international standard, established by the IEC 62386 standard (open protocol), it is independent of the product manufacturers, which ensures operational compatibility and data exchange between different equipment.

Smart facades and other systems

They are elements installed in the envelope of buildings that aim to increase the thermal and lighting comfort for users, and the energy efficiency of the building. They can be programmed to adjust according to weather conditions (Rule Based Control - RBC) or have a fixed routine.

Virtual assistants

Its function is to help users to perform tasks, even beyond the building sector. The technologies found are activated and controlled exclusively by voice, allowing the control of smart electrical and electronic equipment connected to the grid and other smaller smart devices. For the Virtual Assistants to work, compatibility between them and the equipment to be controlled is necessary.

Smart apps and controls

They are devices for monitoring the performance of the building in real time, providing data on its performance through wireless connections with devices installed throughout the rooms, being directly related to the popularization of IoT. Although apps and smart controls have the same functions, they have a different structure: some include a large screen for data visualization; others are apps for phones which facilitates access to information; and also include devices that allow the control of the systems.

Smart sockets and electric vehicle chargers

This is the so-called smart plug technology. The electric vehicles charges were grouped in this item, as they have embedded intelligence to perform their function. Smart sockets are adapters that are plugged into existing electrical sockets, have built-in wireless technology that allows equipment connected to these smart sockets to be controlled by cell phones, tablets or computers app or by voice commands, without the need for the equipment to be smart. In this way, you can control lighting, air conditioning, and household appliances. They are considered as the gateway to home automation because they are more affordable and easier to install.

Electric vehicle chargers have on-board wireless technology, which allows charging information, such as the end of charging, added autonomy, energy consumed, start and end time of each recharge to be transmitted to apps. This technology tends to have a rapid adoption in buildings due to the rapid evolution that electric vehicles have been presenting in terms of autonomy and cost reduction. This rapid adoption and the possibility of generating energy for the grid has led regulatory agencies around the world to study or implement more flexibility in the energy sector. In Brazil, the current regulation only allows the energy to flow from the distribution grid to the vehicle called G2V, that is, the vehicle as an energy consumer.

Smart electrical and electronic equipment connected to the grid

They are smart electronics connected to the grid that have the capacity to generate data on their performance throughout the operation that support decision-making on energy efficiency measures. When they work autonomously, they can be operated by smart apps, smart switches, or virtual assistants. Furthermore, in some countries they are used in demand management programs.

Demand response, awareness and gamification apps

Demand response refers to mechanisms to manage customer consumption in response to supply conditions, such as reducing or shifting energy consumption at critical moments through payments or in response to market prices, which requires specific pricing schemes. The best way to operationalize this type of strategy is through the use of smart meters, as well as smart electrical and electronic equipment connected to the grid and smart sockets, which can provide the automation of demand flexibility based on the tariff variation, the improvement of information and feedback (awareness) and the interface with energy efficiency programs.

Cloud Computing

It is the delivery of computing services using a network of remote servers hosted on the Internet to store, manage and analyze data. They can be offered at 3 different levels: Infrastructure as a service (IaaS), which offers critical computing, storage and networking resources on demand and pay-as-you-go; Platform as a service (PaaS), which in addition to IaaS items, provide an on-demand environment for developing, testing, delivering and managing Software apps; and Software as a service (SaaS), which in addition to PaaS-related services, offers on-demand, typically subscription-based, delivery of Software apps over the Internet. The following items present the morphological matrices by phase of the life cycle of buildings, notes on each solution in relation to the phase and considerations about the applicability to the five typologies listed.

2.1.1 LIFE CYCLE PHASE: Design

The design phase has the property of impacting the entire life cycle of a building and the characteristic of having the greatest flexibility in relation to changes throughout its life cycle. In other words, carrying out an adaptation in the design phase impacts less on the cost of the building than in the construction phase and much less than in the operation phase. This means that investing more in the design phase ensures that subsequent phases will face fewer setbacks, seeing as more problems are anticipated before construction and operation begins. Furthermore, when energy efficiency is adopted as a premise from the start, buildings will certainly have better energy performance during operation.

The morphological matrix of the digital solutions for the design phase is presented below. Next, the technologies and their applicability to the typologies of buildings and domains covered in this study are described, explaining the different bibliographic references in each element of this matrix.

Table 1 – Morphological matrix of digital solutions for the design phase. **Source: Made by the authors.**

Design					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Envelope	• Building Information Modeling (BIM) [[5-10; 12] • Building Energy Modeling (BEM) [15;16] • Computational Fluid Dynamics [CFD] • Software for life cycle assessment (LCA) [2;13] • Simulation of natural and artificial lighting 14] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-12] • Building Energy Modeling (BEM) [15;16] • Computational Fluid Dynamics [CFD] • Software for life cycle assessment (LCA) [2;13] • Simulation of natural and artificial lighting [14] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [15;16] • Computational Fluid Dynamics [CFD] • Software for life cycle assessment (LCA) [2;13] • Simulation of natural and artificial lighting [14] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [15;16] • Computational Fluid Dynamics [CFD] • Software for life cycle assessment (LCA) [2;13] • Simulation of natural and artificial lighting [14] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-12] • Building Energy Modeling (BEM) [11; 12; 15-16] • Computational Fluid Dynamics [CFD] • Software for life cycle assessment (LCA) [2;13] • Simulation of natural and artificial lighting [14] • Blockchain
HVAC	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [15;16] • Energy portfolio management systems • Software for life cycle assessment (LCA) [2;13] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [15;16] • Energy portfolio management systems • Software for life cycle assessment (LCA) [2;13] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [15;16] • Software for life cycle assessment (LCA) [2;13] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [11; 16] • Energy portfolio management systems • Software for life cycle assessment (LCA) [2;13] • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) [16] • Software for life cycle assessment (LCA) [2;13] • Blockchain

Table 1 – Morphological matrix of digital solutions for the design phase. **(Following part of previous table)**

Design					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Lighting	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [14-16] • Simulation of natural and artificial lighting [14] • Software for life cycle assessment (LCA) [2;13] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) • Simulation of natural and artificial lighting • Software for life cycle assessment (LCA) [2;13] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) • Simulation of natural and artificial lighting • Software for life cycle assessment (LCA) [2;13] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) • Simulation of natural and artificial lighting • Software for life cycle assessment (LCA) [2;13] • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 13] • Building Energy Modeling (BEM) • Simulation of natural and artificial lighting • Software for life cycle assessment (LCA) [2;13] • Blockchain
Equipment, socket loads	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) • Software for life cycle assessment (LCA) [13] •	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [12] • Software for life cycle assessment (LCA) [2;13] •	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [12] • Software for life cycle assessment (LCA) [2;13] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [12] • Software for life cycle assessment (LCA) [2;13] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) [12] • Software for life cycle assessment (LCA) [2;13] • Blockchain
Building infrastructure	• Building Information Modeling (BIM) [5-10; 17-19] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for life cycle assessment (LCA) [2; 13]	• Building Information Modeling (BIM) [5-10; 17-19] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for life cycle assessment (LCA) [2; 13]	• Building Information Modeling (BIM) [5-10; 17-19] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for life cycle assessment (LCA) [2;13]	• Building Information Modeling (BIM) [5-10; 17-19] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for life cycle assessment (LCA) [2;13]	• Building Information Modeling (BIM) [17-19] • Building Energy Modeling (BEM) • Software for life cycle assessment (LCA) [2;13]
Energy supply, generation and storage	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) [20] • Energy Portfolio Management System [21;22] • Software for life cycle assessment (LCA) [2; 13] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) • Energy portfolio management system [21] • Software for life cycle assessment (LCA) [2; 13] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Energy portfolio management systems [21;22] • Building Energy Modeling (BEM) [15] • Software for life cycle assessment (LCA) [2; 13] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Energy portfolio management systems [21;22] • Building Energy Modeling (BEM) [16] • Software for life cycle assessment (LCA) [2; 13] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Energy portfolio management systems [21; 22] • Building Energy Modeling (BEM) [16] • Software for life cycle assessment (LCA) [2; 13] • Blockchain

Building Information Modeling (BIM) [5-10; 17-19]

BIM technology has the potential to influence the digitalization and energy efficiency of all domains surveyed (both those that involve specific projects, such as envelope, HVAC and Lighting, as well as those that are installed in buildings, such as equipment, meters, etc.). It intends to function as a repository of technical information (and, therefore, of the specifications of materials, systems and equipment, as well as construction processes, units of measurement, type of associated labor, resources necessary for the construction or installation, etc.) on a building, linked to detailed three-dimensional graphic representations of its elements, regardless of the subsystems of which they are part. In addition, the software that uses the technology is equipped with views and packages of functionalities aimed at different specialties of designers and professionals related to civil construction.

This allows the design activities of each specialty to be performed collaboratively on a common platform that facilitates their compatibility, insofar as it not only enables the availability of base files among professionals but can also demonstrate (three-dimensionally and in technical visualizations such as plans, sections, elevations and details) interferences between specific projects, resulting in a “live” digital document. This document is more accurate, with less possibility of failure and obtained with less rework, which in conventional projects, structured in silos with specific knowledge and technologies and endowed with low interoperability would not be possible. However, it allows the gradual evolution of the details according to the maturity of the project, allowing its evolution from performance simulations (structural, thermal energetic, etc.) and the gradual extraction of consolidated data that feedback the design decisions and aim at meeting both specific premises and legal, regulatory and certification-related parameters. It is important to emphasize that the technology can be applied to any typology of buildings, but it is more viable for those with more complexity/size. Moreover, for the good functioning of collaborative work, there is generally wide use of cloud storage, in what is called Common Data Environment - CDE, which allows information about the project to be accessed by all teams.

The information associated with the elements makes it possible to save time and reduce errors and increase precision in budgeting processes, as the quantifications are automatically obtained based on the virtual model and can be associated with databases of unit price benchmarks (materials, labor, equipment, etc.) and other external indicators. The temporality dimension can also be included in the model, facilitating the elaboration of schedules and the planning of the construction phases, foreseeing interferences and restrictions related to machinery and other equipment necessary for the work and balancing of resources.

Better projects with more layers of planning and information tend to have a lower rate of errors, waste and rework, enabling the delivery of a better-quality building at a lower cost.

Fewer errors, less rework, automation of information processing, more predictability of operation and continuous feedback to improve the quality of the project, as well as the possibility of acting as a hub for centralized information from other systems and technologies, enable not only to save resources during the design phase but also subsidizes energy efficiency throughout the building's life cycle, as long as the model is kept up to date.

Considerations about the applicability to different typologies of the sector

BIM technology in the design phase is already at a very mature phase and tends to have a relationship of importance and applicability directly proportional to the complexity of the project, as it offers significant improvement and facilitates the compatibility of projects prepared by different professionals, as well as facilitates budgeting and organizes information. In this way, it applies more directly to larger buildings, commercial and service, public, multifamily residences, and even social interest housing, when multifamily or modular units are considered together. In the case of single-family buildings, except for high-end ones, the projects are generally carried out by a single professional, so that the perception of gain related to collaboration and compatibility tends to be reduced, as well as budgeting, given that the number of items to sized is considerably smaller. The perception of benefits is also reduced for smaller buildings of the other typologies.

Building Energy Modeling (BEM) [23; 24; 25]

BEM technology has the ability to act in most areas because it is related to electrical and thermal energy. These are the cases of HVAC systems, lighting, water heating, socket loads and equipment, as well as energy-consuming building infrastructure items, which can be evaluated together or individually. Thus, it is possible to diagnose the domain with the highest energy consumption, and consequently with more potential for improvement, and it is also possible the creation of alternatives to achieve a lower demand for electricity. It is important to note that the simulations take into account information about the local climate, such as temperatures, air humidity, insolation, etc. In larger buildings, an opportunity to use BEM is to estimate the heating of water by the HVAC system and consider its reuse in the building itself or to mitigate the unwanted heating of environments adjacent to the engine rooms. Another domain in which BEM is applied is the envelope, where the tool can be used to study the impact of different materials or even building guidelines on the building's electrical energy consumption or on the thermal comfort of users.

Building Energy Modeling has often been used in conjunction with Machine Learning in order to have optimal results for the simulations it can perform. Such a combination has been considerably beneficial for the performance of buildings, especially in scenarios where a certain performance benchmark must be reached, such as in European buildings NZEB – Net Zero Energy Buildings.

Considerations about the applicability to different typologies of the sector

The thermoenergetic simulation technology of buildings applied to the design phase helps the design of envelopes with the potential to provide greater thermal and lighting comfort to users and, at the same time, less dependent on energy-consuming systems. It also helps to optimize energy systems by seeking, for example, to take advantage of residual thermal loads. However, in Brazil, there is still a great lack of trained professionals working in the area, which increases the cost of simulations and restricts them to enthusiasts or those with explicit demands related to sustainability or energy efficiency certifications. The cost tends to be smaller for larger or high standard projects, especially those that can be replicated (reference floor plans and/or modular units), in this context they are directly applicable to Commercial and Service Buildings, whose interest is reflected in the better fixed operating cost. It tends to reduce vacancy rates and increase commercial value, as well as multifamily residences, whose model tends to be simpler in Brazil since they do not have central air conditioning systems. For multifamily buildings, however, there is an extra difficulty because users have little awareness of energy efficiency, so it is not a priority for much of the consumer market. Public buildings would have the enormous potential to make use of this technology, since the reduction of fixed infrastructure and operating costs is always well-received by society, freeing up resources for better uses. Similarly, Social Interest Housing, as they are generally highly replicated and, in some cases, vertical, for a similar reason could make use of technology in order to reduce operating costs, given that in general they tend to be subsidized rates. Feasibility is greatly reduced when the object is a single-family building or small commercial/services, given that the cost is not reduced, so that it is only feasible in high-end projects or those that are the subject of academic studies.

Computational Fluid Dynamics (CFD) [26-38]

CFD becomes an integral part of project design due to its ability to predict the effect of natural ventilation on buildings before they are built and to reduce the energy consumption of air conditioning equipment, analyzing the different strategies until a satisfactory and optimized result is obtained.

It is mainly used in studies of thermal comfort, dispersion of pollutants and aerodynamics of structures, allowing the creation of conditions very close to reality and reducing processing time compared to physical prototypes. Wind tunnels and other forms of physical testing often use empirical correction factors. In contrast, CFD can simulate airflow using a full-size digital model with no scale limitations, yielding all the quantitative and qualitative results you would expect from physical tests (e.g. drag and pressure loss), plus provide deeper insight into the fluid volume for 3D viewing.

The CFD methodology has three phases: pre-processing (definition of parameters and creation of the computational model), simulation (solving equations) and post- processing (extraction of relevant data, graphs and tables).

For the HVAC sector (heating, ventilation and air conditioning) there are specific modules in the CFD software that help simulate the diffusion of fluid substances in controlled environments (such as operating rooms and clean rooms), evaluate the conditioning of special rooms (such as datacenters) and heating inside specific equipment (microelectronics, motors), among others. This allows for a more efficient HVAC system, with the combined interaction between mechanical equipment, building and airflows.

Considerations about the applicability to different typologies of the sector

The CFD simulation technology has an even more restricted market than the thermoenergetic simulation, in Brazil, regarding its use to assess the potential for thermal comfort due to heat exchanges, mainly by convection, as a replacement or complement to heating systems. air conditioning. It follows the same logic previously presented for BEM, given that the market is incipient and there is a lack of specific professionals, in addition to the low value perceived by the standard user. Its applicability is greater for the design of complex hybrid conditioning systems or for specific locations where the wind regime has great potential (such as the State of Alagoas, for example). However, as in the case of BEM, the benefits arising from a well-conceived project in terms of passive natural ventilation solutions will be enjoyed throughout the life of the building, which can also be very favorable for public buildings and housing of social interest.

Simulation of natural and artificial lighting [39-56]

Through computer simulation it is possible to develop lighting projects with superior quality, from complex calculations to presentation renderings, and to scale more quickly and accurately the different types of systems for the most varied needs of uses and activities developed in the environments, but specially to obtain high levels of energy efficiency and light comfort.

Lighting calculation programs and software are notably important for the prediction and correct use of natural light (throughout the day and year), enabling a better understanding of the phenomenon by allowing the modeling of the physical performance of light rays and their effects according to the spectral properties of materials for any geometric complexity. Studies reviewed in the literature show that the availability and variations of daylight (temporal and spatial) under different conditions external to the building (view of the sky, clear or cloudy) have significant impacts on lighting environments and for improvement of user productivity, provided they are properly designed and used.

One of the fundamental variables to be considered in the simulated alternatives which aim at reducing energy consumption, is the interaction of the lighting system with other equipment and systems, such as air conditioning and facade shading devices.

Another factor considered in the design phase and that the simulations have helped is the integration of systems (artificial and natural lighting) and the efficient management of lighting and its activations, as well as the control of illuminance levels based on the use and occupation profiles. These require specific data processing, allowing the achievement of significant energy optimizations, so they have become a key strategy in terms of energy reduction and residual heat emission from lighting.

Among the more than 200 simulation tools currently listed in the Building Energy Simulation Tools Web Directory (BEST-D), a website maintained by the International Building Performance Simulation Association (IBPSA-USA), there are several programs for the development of lighting projects. From the graphical results and numerical reports generated by the programs, it is possible to estimate the energy to be specifically consumed by lighting, its cost and the environmental impact caused by the project alternatives even before its execution.

Considerations about the applicability to different typologies of the sector

The simulations of natural and artificial lighting are useful tools for adequate lighting projects in buildings of different uses and sizes. By using specific software for this function, it is possible to ensure adequate levels of lighting for users (lux) according to their activities, including taking into account natural light. This increases not only the lighting comfort but also the energy efficiency of the building, since it is possible to reduce the use of lamps and prioritize natural lighting. Some software even allow the sectioning of lighting systems, such as, for example, lamps close to windows and further away. In this way, it is possible that not all lamps are switched on at the same time, also contributing to the reduction of energy consumption. In Brazil, most of the software used is international, but because they use local climate data, they generate data with accuracy and allow their implementation in the national territory. However, a barrier is the lack of availability of professionals with mastery of the tools, either due to the lack of full knowledge of their use or the need for multidisciplinary knowledge in architecture and electrics.

Its major application is in large-scale projects or projects related to labeling/certifications, mainly in commercial and service buildings, as well as academic research. Replicability is a key element for the popularization of artificial lighting simulation in more projects (type reference floor plans and/or modular units). However, this factor is not applicable to simulating natural light, as it is directly influenced by local factors such as latitude, surroundings, shading, etc. In large projects, this cost has little impact on the final budget, but is generally not financially viable for single-family residences other than high-end ones. Social interest housing projects replicated in the same region and with the same orientation can benefit from the use of this technology, since the good use of natural lighting tends to reduce electricity consumption throughout the operation.

Energy Portfolio Management Systems [21; 22; 57-60]

Project analysis software and platforms contain specific modules for financial analysis, cash flow calculations, sensitivity and risk analysis, and can support all types of technologies for energy generation and use, both traditional and non-traditional sources. traditional clean energy sources such as conventional energy sources and technologies, helping to better understand and compare solutions and to determine the technical and financial feasibility of proposals even in the early phases of project development.

Sample models available for simulation may include: energy efficiency (from large industrial facilities to single-family residences), heating and cooling (e.g. biomass, heat pumps, solar air/water heating), energy (including renewables such as solar, wind, wave, hydroelectric, geothermal, etc., but also conventional ones such as gas/steam turbines and reciprocating engines), and the combination of energy and heat (or cogeneration), among other arrangements.

Most tools also have specific modules for analyzing different types of projects and can be applied to all types and sizes of buildings. They are also used to support the development of calculations for NZEB buildings.

Considerations about the applicability to different typologies of the sector

With the gradual reduction in the costs of implementing photovoltaic solar generation systems, the regulation of the sector and the frequent increase in electricity bills, motivated by the irregularity of the levels of the reservoirs and the additional dispatch of thermal plants in recent years, the adoption of distributed generation is growing in the country. Other inputs, such as natural gas and liquefied petroleum gas, have also suffered successive increases, so that the search for solar thermal collectors for water heating has also been increasing. Such tools are the best way to properly size these and other systems that use renewable energy. They are more used for less verticalized buildings, that is, those whose coverage area is relatively large in relation to the number of units, which encompass on commercial buildings such as shopping malls, large retailers, supermarkets, public, commercial and non-vertical buildings, single-family buildings and social interest housing.

This software also helps in the dimensioning of qualified cogeneration systems, geothermal energy, use of residual thermal energy from different processes, and HVAC systems, being used mainly in large commercial buildings as well as verticalized public buildings.

Software for life cycle assessment (LCA) [2; 13; 61; 62]

The life cycle assessment emphasizes the materials to be used in a given building, thus having the potential for use in all domains of the building. However, there is more influence on the envelope, especially in residential buildings, being used to define the materials of the construction sealing materials. In non-residential buildings, there is more investigation of the domains of lighting, building infrastructure and HVAC. Although elements that consume electricity are often addressed - such as light bulbs - what really matter is LCA and its environmental impact throughout its life cycle. One of the biggest challenges for life cycle assessment is the use of international software. In this way, the databases of these programs may not necessarily represent the local reality where the analysis is being carried out. This is due to the differences in the processes throughout the entire life cycle. It is therefore necessary to emphasize the importance of using up-to-date data, according to a spatial-temporal and technological approach.

Considerations about the applicability to different typologies of the sector

Due to its application of analysis of the environmental impacts of materials throughout their life cycle, the life cycle assessment has the potential to be used in all typologies of the sector. However, it is noteworthy that its current high cost of execution limits its applications to larger projects, such as commercial and services, as well as high-end residential projects. Although they are large emitters of greenhouse gases, they also represent a small fraction of the Brazilian construction market, and their dissemination on a larger scale is ideal for achieving national climate goals. Its replicability is complex, since many elements of an LCA are related to the construction site, even involving the distance from the material production site to the construction site. Therefore, even in low-cost but modular projects that are built in several locations, it is not feasible to carry out just one life cycle assessment. The development of a national database could contribute to the reduction of the time to perform an LCA - and consequently its cost. Currently, data collection for a life cycle assessment is carried out based on international databases and information gathered by the team itself which is labor intensive. Such action would also help in the accuracy of the evaluations carried out.

Augmented Reality [17; 63]

Using this technology, it is possible to create prototypes and/or virtual models for better visualization of the project by the team responsible for its conception. Therefore, it is not only possible to better understand the experiences and sensations transmitted to the user, but also to visualize the assembly of complex elements and check their feasibility. It is the only phase of the building's life cycle in which the use of cell phones with cameras/tablets is prioritized instead of glasses adapted for viewing, especially due to the lower cost and more practicality.

Considerations about the applicability of augmented reality to different typologies of the sector

The use of Augmented Reality in different typologies depends directly on a digital model of the building to be built to allow its visualization. Since most projects currently use some platform of this type, from the most complex ones such as BIM to the simplest just for rendering, this factor is not a barrier to its implementation and allows its use in all typologies of the building sector. However, there is a greater interest in its use in residential typologies, and it can currently even be seen in sales stands of some multifamily developments. The dominance of this typology is due to the tradition of visits to “decorated apartments” before the purchase of units, which can be replaced by Augmented Reality at a considerably lower cost for construction companies. Single Family Homes also take advantage of this technology, but on a smaller scale and with the aim of reminding the emotional bond with the place before construction and making changes to the project. This technology is not used in social interest housing projects as there is no interaction between customers and builders during the project.

Blockchain [64]

At the design phase, several applications can help the sector, such as the ones that obtain funds for the feasibility of projects, without the need for middlemen, but the biggest contribution to energy efficiency from Blockchain technology refers to its use related to certifications. In this case, it is possible to add a Blockchain layer to the potential energy efficiency certifications (such as the PBE Edifica Labels and the Procel Edificação Seal), providing: more agility in the concession, since the verification of attributes could be carried out with smart contracts which would reduce wait times; providing increased trust, as automated processes that are recognized among stakeholders in each transaction reduce the chance of human error and misunderstandings between the parties; increased flow of information and controlled transparency, allowing each stakeholder to access only the data that concern them; full auditability, since transactions cannot be undone and, finally, the possibility of adding tangible value to efficiency through the issuance, linked to certifications, of fungible tokens (backed by assets, whose type, quantity, quality and value are comparable) of potential energy efficiency. In Brazil, there is a constant pioneering initiative in the third Procel Resource Investment Plan, called Smart Selo Procel Project– Applications on Blockchain Platform for Energy Efficiency Certification, which intends to add a Blockchain layer to the Procel Seal and may be made available for Buildings. Therefore, it applies to all types of buildings in their subsystems considered in the assessment for the Seal (therefore, envelope, HVAC, lighting and water heating), as well as for equipment covered by the Seal.

Considerations on blockchain applicability to different typologies of the sector

Blockchain technology, once incorporated into the Procel Seal, should influence Commercial, Service and Public buildings in the envelope, HVAC and lighting domains, as well as equipment and outlet loads, besides building infrastructure (such as pumps) and photovoltaic solar generation systems. As for residential typologies, across their entire spectrum, the envelope, the water heating and, on the equipment side, the socket loads, air conditioning and lighting and photovoltaic solar generation systems should influence.

Agile Management Software

At this phase of buildings, computer programs based on agile frameworks, such as SCRUM, Kanban and Prince2, become important tools that support the construction of the digital twin of the building, which provides a detailed structure, but with friendly interaction to manage complex projects that gather a lot of information. The need for a realistic 3D visualization, both external and internal, has proved to be paramount.

Considerations on the applicability of agile management software to different types of the sector

The technologies associated with Agile Management can be scaled to be used in projects of all types, however they tend to be more used in larger projects that normally focus on multifamily, commercial, and public residences. The standardization of social interest housing projects has not motivated the use of more robust design tools that would allow a rapid change of the project in response to customer demands.

Cloud Computing

In the design phase, cloud storage is an enabling technology for sharing and collaborative editing of files, such as what occurs in the Common Data Environment (CDE) related to BIM technology. The processing power in the cloud allows you to reduce the simulation time, making it possible to test more solutions in a reduced time in order to obtain greater efficiency. In addition, it avoids the purchase and maintenance of hardware, and minimizes the need for local IT infrastructure teams.

Considerations about the applicability of cloud computing to different typologies of the sector

The use of cloud computing has become more accessible, especially with the popularization of servers, platforms and software that allow the service to be offered in retail. Despite this, its benefits are more used in projects that demand multiple users working at the same time or in which there is a need to send documents for complementary projects (air conditioning, lighting, etc.), or even those with high complexity and that demand high processing power to perform specific analyses (such as results of complex simulations) or generate final products (such as renderings). When only one person is responsible for the project, the use of cloud computing loses part of its collaborative platform function, functioning as a backup and allowing information to be shared with the client and, eventually, some third-party service providers. Therefore, it is generally used in multifamily, commercial, public or service housing projects, due to its size and complexity of execution.

2.1.2 LIFE CYCLE PHASE: Construction

In the construction phase lies the responsibility to realize the projects as faithfully as possible while preserving the specified quality and properties. It is very common that, given the high rejection to changes in the civil construction sector in Brazil and the low maturity and specialization of the workforce in general, the final product differs greatly from the projected one, which can considerably impact the simulated performances during the entire operating phase. Furthermore, although the absolute impact on resource consumption is not as high as that of the operation phase, in relative terms, considering the comparatively short timeframe, it is the largest concentrated impact.

That said, it is important to think about how digitalization can make the constructed building more faithful to the project (or better), as well as helping to reduce resource consumption and emissions during the construction phase.

The morphological matrix of the digital solutions for the construction phase is presented below. Next, the technologies and their applicability to the typologies of buildings and domains covered in this study are described. The same technologies can be used in different typologies and are repeated here because the bibliographic references that supported the study are different.

Table 2 – Morphological matrix of digital solutions for the construction phase. **Source: Made by the authors.**

Construction					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Envelope	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • 3D printing [12;17; 65] • Augmented Reality [66] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • 3D printing [12;65] • Augmented Reality [12; 66] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality [66] • 3D printing [12;17; 65] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • 3D printing [12; 17; 65] • Augmented Reality [66] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • 3D printing [12; 17; 65] • Augmented Reality [66] • Blockchain
HVAC	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain
Lighting	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10;12] • Software for life cycle assessment (LCA) [2; 13] • Blockchain

Table 2 – Morphological matrix of digital solutions for the construction phase. **(Following part of previous table)**

Construction					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Water heating	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10;12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10;12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10;12] • Software for life cycle assessment (LCA) [2; 13] • Augmented Reality • Blockchain
Equipment, socket loads	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10; 12] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain
Building infrastructure	• Building Information Modeling (BIM) [5-10; 19] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain	• Building Information Modeling (BIM) [5-10;18] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain	• Building Information Modeling (BIM) [5-10;18; 9] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain	• Building Information Modeling (BIM) [5-10;18; 9] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain
Energy supply, generation and storage	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Energy Portfolio Management Systems • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) • Blockchain

Building Information Modeling (BIM) [5-10; 12; 18; 19]

At this phase of the building's life cycle, the BIM model plays the role of guidance for the construction, both through the set of drawings and technical information, and through the facilitation of management and logistics through the planning, timing and ordering of the construction phases. This enables the visualization and editing of each of its “layers” at its own time, as well as the boundary conditions necessary for its execution and acceptance parameters. The costs associated with these steps also allow the monitoring of disbursements, as well as the comparison with the forecast, allowing more control and mitigation possibilities.

On the other hand, the BIM model demands a constant increase in detailing and the updating of parameters in a way that is compatible with the way in which each element was actually built, installed or implemented. Here, for example, information on execution status, acquisition and installation dates and warranty periods for equipment and elements, changes in geometry, materials, etc., in relation to the executive project, execution times and resource allocation for each element, phase or component system of the building, so that, at the end of the construction phase, we have the “as-built” project, which will greatly facilitate the operation. This is so because the record represents precisely what is built, and contains additional information about warranties, expiry dates, suppliers, instructions for use and maintenance of materials and equipment, estimated deadlines for preventive maintenance, automation schedule and rules and setup of operating hours for each component, etc.

Considerations about the applicability to different typologies of the sector

In the construction phase, BIM technology has great potential for use in the building sector and in Brazil there are already specific policies to encourage its adoption. Following the example of the European Union (Directive 2014/24/EU), Brazil is establishing a legal framework for the adoption of BIM, within the scope of the BIM BR Strategy, established by Decree No. 10,306 on April 2, 2020, which establishes the use of BIM in the direct or indirect execution of engineering works and services carried out by agencies and bodies of the federal public administration, gradually expanding the adoption in staggered phases until 2028. The market reserve that is built from a structured initiative like this increases the availability of qualified professionals in the market, which direct their performance to other typologies, initially the most complex, such as commercial and service buildings, all the way to multifamily residences and housing projects of social interest, until they are definitively popularized and adopted for single-family buildings in general, which is essential to update the project that the construction phase encompasses. At this phase, dynamic budgeting and the ordering of the phases of the work tend to increase the quality and predictability of delivery in the sector and facilitate the management of the warehouse, purchases and control of the progress of the work, issues that can be perceived as a benefit in any typology.

Software for Life Cycle Assessment (LCA) [61; 62; 67]

The life cycle assessment is an important tool for reducing the environmental impacts of the construction site. It makes it possible to quantify the impacts caused by the production, transport and use of the equipment used, as well as the consumption of energy and water, throughout the entire operation [67]. LCA has the potential to identify opportunities for materials that would initially be discarded and that could possibly be reused in the project itself. However, if the solution is in fact disposal, it is also within your scope to choose a suitable place for its destination, taking into account the end of life (reuse, recycling or others) and the environmental impact of its transport.

Considerations about the applicability of software for LCA to different typologies of the sector

Although the scope of the life cycle assessment is applicable to any typology of building, in practice, it is used primarily for commercial and service buildings, multifamily residences and high-end single-family residences, aimed at markets interested in environmental management and sustainability. It is observed that if this tool were used in public policy instruments for social interest housing, perhaps it would enable the adoption of energy efficiency solutions, whether passive or digital, in terms of financing because as the additional initial investments could be justified by the operating cost reduction over time.

Augmented Reality [12; 17; 66; 73]

The use of Augmented Reality during construction is related to overlaying the virtual model of the floor plan (or other technical drawings) as it was designed in the real environment. Thus, it is possible to check what was built and guide the assembly of complex elements. It not only contributes to the speed of processes, but also to the safety of employees and reduces the chance for error.

It is worth mentioning that Augmented Reality only allows the visualization of a virtual model in a real environment, that is, if there is no compatibility between the domains (example: overlap between lighting and water pipes), the technology cannot be used at the construction site. Therefore, to take full advantage of the potential of Augmented Reality, it is recommended to use it in conjunction with a virtual model with more precision and more information, such as Building Information Modeling (BIM).

Augmented reality can contribute to the training of employees in productive activities, reducing the need for preliminary study and replacing printed manuals and assembly instructions, which are not always clear enough. This is so especially when related to complex assemblies, such as mechanical systems and electrical systems, as it recognizes elements and instructs step by step the use of tools, connections and processes, with visible and linked information until the objectives are achieved.

Considerations about the applicability of augmented reality to different typologies of the sector

Due to the need to visualize multiple technical drawings at the construction site through Augmented Reality, its applicability is greater in large-scale projects or projects that use the BIM platform. Thus, it is used more often in commercial and service buildings, public, multifamily residences, and social interest housing (when they are multifamily or modular). In the case of single-family residences, despite Augmented Reality being useful in the design phase, due to the considerably lower complexity of the construction site and execution, it is not so common except in very high standard homes.

3D printing [12; 17; 65; 68-72]

With regard to construction industry, it fundamentally applies to the envelope, but the threshold of technology allows it to be used for the printing of complex parts of mechanical equipment, as long as there is a vectorized three-dimensional model, a printer of compatible material and suitable software, which allows the construction of specific mechanisms (as well as their maintenance using spare parts). As far as the envelope is concerned, there are fundamentally two types of broad categories of printers that can be used: those that make large monolithic prints *in situ*, generally using cement-based mortar (but which can be adapted to use other types of mortar with a smaller carbon footprint), structural or not; and those that print (in situ or remotely) parts/components for prefabrication or creation of molds for the manufacturing of modular prefabricated items. As it is additive manufacturing, it allows the construction of highly complex geometries, some of which would not even be possible by other methods, with minimal or no waste. This happens because it deposits, in a controlled way, successive layers of material until reaching the final three-dimensionally modeled shape, rather than processing a pre-existing block of base material. The benefits are reduced use of material and the very low generation of solid waste, the speed and the possibility of precise formal freedom and without execution errors, the logistical gains considering that less labor is used, the printing of components which generate light parts that are easy to handle and assemble. The printing of components eliminates the use of heavy machinery that consume fossil energy and reduce the impact of transport.

Considerations about the applicability to different typologies of the sector

The 3D Printing Machines for mortars (cement based or not) are used to print monolithic structures and closures in situ. Their differential is the possibility to generate complex shapes in a relatively short time for small units, generating complete opaque structures and closures in about one day, however they still have a high cost because of the structure needed to build three-dimensional coordinate axes of a larger size than the units you want to build. It has high applicability for condominiums or social interest housing, where there is great replicability of the units, diluting the implementation cost and reducing the final delivery time. Smaller printers generate individual parts, so the process must be repeated continuously until the desired number of elements is completed, since it is an automated and silent process, it can be carried out without interruptions. Another strategy for this typology of machine is to print molds for use on the construction site, allowing complex shapes to be obtained at a relatively low cost due to their replicability. In this way, it is possible to apply it in modular projects with a lower budget, such as, for example, multifamily, public buildings and even social interest housing which depends on the durability of the mold. Due to size and budget limitations, single-family residences tend not to explore the use of 3D printers, except in academic studies that aim to explore their potential in future scenarios, disregarding their cost and with an eye toward technical possibilities.

Blockchain

With regard to the construction phase, Blockchain technology has great potential to facilitate commercial and real estate transactions, with the acquisition of land, division into plots, and the issuance of the General Property Registry (RGI) of each unit sold. In addition, it can greatly assist in the logistics of inventory and warehouse control, especially if associated with the use of Radio Frequency Identifiers (RFID), allowing the monitoring of the transport of materials and their location in construction, which prevents corruption and theft, as well as it makes it possible to monitor the integrity of the work. It can also be associated with BIM technology and sensor networks to help in comparing the quantities of materials used with project estimates, or even in the graphic comparison between real-time images of the construction site and the phases of work reported in the BIM model project, linking billings to execution milestones governed by smart contracts. When used with building materials, Blockchain becomes an important tool for monitoring the life cycle of the building, and it can supply inventories and life cycle assessment Software. Returning to the field of smart contracts, Blockchain can assist in the management of third parties by adopting automatic parameters to allow invoicing.

Considerations about the applicability to different typologies of the sector

With the existing Blockchain technologies, it is possible to control the entire in and out of construction materials at the site in order to reduce loss of material and theft. However, it is necessary to evaluate the cost-benefit of adopting the required hardware and software infrastructure, considering that the implementation is more viable in larger commercial, service and public buildings, as well as multifamily residences and social interest housing, whose construction is generally managed by large contractors. Currently, the application to single-family residential buildings offers less perception of benefits, except for environmental certifications in which the construction site is part of the score, so the entire process must be monitored and validated. In these cases, regardless of size or typology, the use of Blockchain is an excellent alternative due to contract security and auditability.

Agile Management Software [74-79]

In this phase, the use of computer programs of the Agile method has been shown to be effective in controlling the progress of projects. A construction project usually involves long phases and different teams on each phase. Alignment problems between the professionals involved, lack of clarity in deadlines and obstacles in the transparency of the process can seriously compromise the quality in the execution of a work. The Agile methodology at this phase facilitates the prevention and control of irregularities in budgets and deadlines, the integration of people with the project, and reviews and changes in the schedules and by doing so shortens cycles and allows agility in the processes and improvement of the management of the activities.

Thus, agile methodologies propose new ways of implementing projects, bypassing these common problems. It puts the customer at the center in all decisions to be made. The purpose is not just to build something for the client, but together with the client, while participating as much as possible in the process. With this, we were able to identify errors much more easily in the processes, in addition to allowing more flexibility to change what is necessary during execution.

Considerations on the applicability of Agile management software to different typologies of the sector

The use of this technology should be strongly disseminated in construction companies that operate in the commercial sector due to the advantages that it achieves notably in large and complex project implementations where logistics are central. Commonly reported aspects include risk reduction, cost reduction, shorter deadlines, project customization, and increased team productivity. Therefore, they apply primarily to constructions carried out by construction companies or large contractors, regardless of typology.

Cloud Computing

During construction, cloud services remain essential as they provide easy communication between the office and the construction site, suppliers, third-party service providers and customers. The relative importance of the topic tends to grow as the services associated with the cloud become more diverse and comprehensive and the construction site becomes digital. Digital files can reduce paper usage, print costs, make it easier to get up-to-date files and reduce the possibility of mistakes and rework.

Considerations about the applicability of cloud computing to different typologies of the sector

The use of Cloud Computing is applicable in all typologies, considering that designers are not necessarily on site all the time, allowing for more fluid communication between the office and the construction site. It also makes it possible to provide new technical drawings and updated information in real time, should there be any necessary modifications. Cloud Computing is also seen as a support technology and works as a facilitator of others previously presented, such as Augmented Reality. It then becomes a key element in more complex projects requiring a reliable and fast internet infrastructure.

Smart sensors, actuators and switches [74; 80]

One of the challenges pointed out in the literature is the reduction of resource consumption during the construction phase. Energy management in this phase requires the use of energy, fuel and water consumption sensors. The data generated by these sensors could be used for the management and education of construction workers. Graphs with daily consumption and actions to encourage the economy of these inputs, through goals or competitions between teams, could be elaborated. The inclusion of the theme of environmental awareness in training, work safety, company standards and work instructions could have positive effects by taking advantage of the real data provided by the sensors. The application of smart switches could make this management partly be done remotely by both those responsible for the construction and the workers.

Smart sensors and switches could quantify common waste found on construction sites in Brazil, such as the use of equipment without maintenance and improper use leading to higher consumption, not taking into account the efficiency of equipment, machines and appliances for the temporary installations of the works, use of low-efficiency light bulbs in areas where construction works are located, use of low-quality faucets and sinks, and assistance in collecting rainwater for reuse on site.

Considerations about the applicability to different typologies of the sector

This technology could be applied to all typologies, however, the construction of single-family residences generally does not have enough sophistication for this type of monitoring to provide positive impacts. With regard to other typologies, the application grows in importance in the same proportion as the size of the construction site. It is interesting to note that although energy savings are transformed into profits for construction companies with the reduction of expenses, this action has received little attention in Brazil. In the construction of Social Interest housing, this technology is only feasible for large projects.

2.1.3 LIFE CYCLE PHASE: Operation

The largest share of resource consumption and emissions in the entire life cycle of buildings occurs during the operation phase. It is important to realize that at this phase, major changes imply high costs, so the boundary conditions for what must be managed are established and specific improvements need to wait for opportunity costs to become viable. It is worth mentioning the benefits of digitalization by automating repetitive activities or reactive to factors in constant change, in order to avoid excessive allocation of personnel (which implies costs) and human errors; by tracking and analyzing information to verify compliance operation, predict the need for maintenance and improve performance; by automatically managing transactions and dispatches of energy assets between the units that comprise it and external instances, among other benefits.

The morphological matrix of the digital solutions for the operation phase is presented below. Next, the technologies and their applicability to the typologies of buildings and domains covered in this study are described.

Table 3 – Morphological matrix of digital solutions for the operation phase. **Source: Made by the authors.**

Operation					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Envelope	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • 3D printing [65] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81] • Sensors and actuators [82] • Smart Facades and other systems [83; 84] • Cloud Computing	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • 3D printing [65] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81] • Sensors and actuators • Smart Facades and other systems [81;84] • Cloud Computing	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) [2; 13] • 3D printing [65] • Augmented Reality [66] • Blockchain • Sensors and actuators • Demand response, awareness and gamification apps [86] • Smart Facades and other systems [83]	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) [2; 13] • 3D printing [65] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) • Sensors and actuators [82] • Demand response, awareness and gamification apps [86] • Smart Facades and other systems [83; 84]	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) [2; 13] • 3D printing [65] • Augmented Reality [66] • Blockchain • Sensors and actuators [82] • Demand response, awareness and gamification apps [86] • Smart Facades and other systems [83]

Table 3 – Morphological matrix of digital solutions for the operation phase. **(Following part of previous table).**

Operation					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
HVAC	• Building Information Modeling (BIM) [5-10; 12; 85 • Building Energy Modeling (BEM) • Energy Portfolio Management Systems • Software for Life Cycle Assessment (LCA) [2;13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 84; 85; 87; 89-91; 93; 94] • Sensors and actuators [82; 84; 85; • 87; 90; 93; 94] • Virtual assistants • Smart Controls/Smart Displays /Smart Apps [90] • Smart sockets and electric vehicle chargers • Cloud Computing	• Building Information Modeling (BIM) [5-10;12] • Building Energy Modeling (BEM) • Energy Portfolio Management Systems • Software for Life Cycle Assessment (LCA) [2;13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 84; 87-90; 91; 93-95] • Sensors and actuators [84; 87; 90; 93 • -95] • Virtual assistants • Smart apps and controls [90] • Smart sockets and electric vehicle chargers • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12; 85] • Software for Life Cycle Assessment (LCA) [2;13] • Augmented Reality [66] • Blockchain • Sensors and actuators • Virtual assistants • Smart apps and controls [90] • Smart sockets and electric vehicle chargers • Demand response, awareness and gamification apps [86; 92] • Building Management Systems (BMS) [81; 84; 87; 91] • Sensors and actuators [87]	• Building Information Modeling (BIM) [5-10; 12; 85] • Software for Life Cycle Assessment (LCA) [2;13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 84; 87; 90; 91; 93; 94] • Sensors and actuators [82; 84; 87- • 90; 93; 94] • Virtual assistants • Smart Apps and Controls [84; 90; 93] • Smart sockets and electric vehicle chargers • Demand response, awareness and gamification apps [86; 92]	• Building Information Modeling (BIM) [5-10; 12; 85] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality • Blockchain • Sensors and actuators [82; 84; 87; • 90; 93; 94] • Virtual assistants • Smart apps and controls • smart sockets • Demand response, awareness and gamification apps [86; 92] • Building management systems (BMS)[81; 84; 87; 90; 91; 94]
Lighting	• Building Information Modeling (BIM) [5-10;12] • Building Energy Modeling (BEM) [14; 39; 96] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Building management systems (BMS) [14; 39; 84; 90; 91; 93; 94] • Sensors and actuators [14; 39; 82; • 85; 90; 93; 94; 97] • Digital Addressable Lighting Interface (DALI) [14] • Virtual assistants • Smart Apps and Controls [39; 84; 90; 93]	• Building Information Modeling (BIM) [5-10; 12] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Building management systems (BMS) [39; 84; 90; 91; 94; 95; 93] • Sensors and actuators [39; 90; 94; • 95; 93] • Digitally Addressable Lighting Interface (DALI) • Virtual assistants • Smart Apps and Controls [39; 84; 90; 93]	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Sensors and actuators • Virtual assistants • Smart apps and controls • Demand response, awareness and gamification apps [86; 92] • Building management systems (BMS) [91]	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [39; 84; 90; 91; 93; 94] • Sensors and actuators [82; 90; 94; • 93; 97] • Digitally Addressable Lighting Interface (DALI) • Virtual assistants • Smart Apps and Controls [39; 84; 90; 93] • Demand response, awareness and gamification apps [86; 92]	• Building Information Modeling (BIM) [5-10; 12] • Blockchain • Sensors and actuators [39; 82; 93; • 94] • Virtual assistants • Smart Apps and Controls [39; 93] • Demand response, awareness and gamification apps [86; 92] • Building Management Systems (BMS) [39; 91; 93; 94]

Table 3 – Morphological matrix of digital solutions for the operation phase. (Following part of previous table)

Operation					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Water heating	• Building Information Modeling (BIM) [5-10;12] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 94; 98] • Sensors and actuators [82; 94]	• Building Information Modeling (BIM) [5-10;12] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 94] • Sensors and actuators [94]	• Building Information Modeling (BIM) [5-10;12} • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 84; 98] • Sensors and actuators	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 84; 94; 98] • Sensors and actuators [82; 94]	• Building Information Modeling (BIM) [5-10; 12] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Sensors and actuators [82; 94] • Building Management Systems (BMS) [81; 84; 90; 94; 98]
Equipment, socket loads	• Building Information Modeling (BIM) [16; 5-10] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) • Blockchain • Building Management Systems (BMS) [81; 94] • Sensors and actuators [94; 82] • Virtual assistants • Smart sockets and electric vehicles chargers [84; 94] • Smart electrical and electronic equipment connected to the grid [96; 99; 100] • Cloud Computing	• Building Information Modeling (BIM) [5-10;12] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Building Management Systems (BMS) [81; 93-95] • Sensors and actuators [93-95] • Virtual assistants • Smart sockets and electric vehicles chargers [84; 94] • Smart electrical and electronic equipment connected to the grid [97] • Cloud Computing	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Building Management Systems (BMS) [84] • Sensors and actuators [84] • Virtual assistants • Smart sockets and electric vehicle chargers • Demand response, awareness and gamification apps [86] • Smart electrical and electronic equipment connected to the grid [97; 99; 100] • Cloud Computing	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Building Management Systems (BMS) [83; 93] • Sensors and actuators [81; 83; 93] • Virtual assistants • Smart sockets and electric vehicle chargers [93] • Demand response, awareness and gamification apps [85] • Smart electrical and electronic equipment connected to the grid [93; 98; 99] • Cloud Computing	• Building Information Modeling (BIM) [5-10; 12; 16] • Blockchain • Sensors and actuators [82; 94] • Virtual assistants • Smart sockets and electric vehicle chargers [94] • Demand response, awareness and gamification apps [18; 86] • Smart electrical and electronic equipment connected to the grid [18; 84; 97; 99; 100] • Cloud Computing

Table 3 – Morphological matrix of digital solutions for the operation phase. **(Following part of previous table)**

Operation					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Building infrastructure	• Building Information Modeling (BIM) [5-10; 12;18; 19] • Building Energy Modeling (BEM) • Energy portfolio management systems [94] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 84; 91; 94] • Sensors and actuators [82; 93; 94] • Cloud computing	• Building Information Modeling (BIM) [5-10;12] • Building Energy Modeling (BEM) • Energy Portfolio Management Systems • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Building Management Systems (BMS) [81; 84; 91; 93; 94] • Sensors and actuators [93; 94] • Cloud computing	• Building Information Modeling (BIM) [5-10;12] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Building Management Systems (BMS) [81; 91; 102] • Sensors and actuators [98; 102] • Virtual assistants • Smart sockets and electric vehicle chargers • Smart electrical and electronic equipment connected to the grid • Demand response, awareness and gamification apps [102]	• Building Information Modeling (BIM) [5-10; 19] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Building Management Systems (BMS) [81; 91; 94; 102] • Sensors and actuators [82; 94; 98; • 102] • Virtual assistants • Smart sockets and electric vehicle chargers [94] • Smart electrical and electronic equipment connected to the grid [96; 99] • Demand response, awareness and gamification apps [102]	• Building Information Modeling (BIM) [5-10; 19] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Sensors and actuators [82; 94; 98; • 101; 102] • Virtual assistants • Smart sockets and electric vehicle chargers [94] • Smart electrical and electronic equipment connected to the grid • Demand response, awareness and gamification apps [102] • Building Management Systems (BMS) [81; 91; 94; 102]
Energy supply, generation and storage	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems [21; 81; 84; 94] • Software for Life Cycle Assessment (LCA) • Blockchain • Sensors and actuators [82] • Smart sockets and electric vehicle chargers [81] • Cloud Computing	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems [21; 81; 84; 94] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Sensors and actuators [94] • Smart sockets and electric vehicle chargers [81] • Cloud Computing	• Building Information Modeling (BIM) [5-10] • Energy portfolio management systems [21; 81; 98; 104; 105] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Sensors and actuators • Smart sockets and electric vehicle chargers • Demand response, awareness and gamification apps [86] • Cloud Computing	• Building Information Modeling (BIM) [5-10] • Energy portfolio management systems [21; 81; 94; 98; 104; 105] • Software for Life Cycle Assessment (LCA) [2; 13] • Blockchain • Sensors and actuators [82; 94] • Smart sockets and electric vehicle chargers [94] • Demand response, awareness and gamification apps [86] • Cloud Computing	• Building Information Modeling (BIM) [5-10] • Software for Life Cycle Assessment (LCA) [2; 13] • Augmented Reality [66] • Blockchain • Virtual assistants • Smart sockets and electric vehicle chargers [94] • Demand response, awareness and gamification apps [86] • Energy portfolio management systems [21; 81; 84; 94; 98; 104; • 105] • Cloud Computing

Building Information Modeling (BIM) [5-10; 18; 19; 85]

The as-built project, in the BIM model and its associated databases, brings with it the entire repository of relevant information about the building and it allows the manager or a management service (which can even serve single-family residential buildings or sets of buildings) to access, adjust and alert the owner about best practices, maintenance periodicity, etc. In order to remain useful, it is important for the manager to keep the information up to date, attributing to the model the history of changes that the building undergoes over time, small renovations, equipment replacements, resource consumption values, etc.

The association of information from the as-built project, built in the BIM model, and data from different sensors (with different functions) distributed throughout the building allows the creation of a Digital Twin of the building. The physical world information coming from the sensors and associated with the virtualized objects of the model can be submitted to machine learning analysis, in order to adapt and automate user preferences or react to imposed restrictions (such as environmental comfort criteria and energy efficiency), adjust operational criteria for optimization, anticipate problems and test possibilities in a virtual environment (no need to purchase materials, real tests, risks, etc.), enable predictive maintenance criteria, etc.

Considerations on the applicability of BIM to different typologies of the sector

Regarding the as-built project, its relatively low cost makes it applicable to all typologies of housing: multifamily, single-family, social interest housing, commercial and service, and public housing. As they allow the user to have guidelines on the three-dimensional positioning of installations and/or structural elements, they can be especially useful in residential typologies where maintenance and small works supervised by the users themselves are more frequent. The application of the Digital Twin is limited to buildings of greater complexity and automation, being generally used in commercial and service typologies.

Building Energy Modeling (BEM) [23; 96; 103]

The use of BEM in the operation phase depends on obtaining real-time data about the building, such as room occupancy, and climatic variables, such as temperature. Such data are crucial for carrying out multiple simulations associated with Machine Learning in order to detect relationships and even give guidelines to users. Therefore, the building can perform simulations in real time considering the conditions and evaluate options that can improve the energy performance of the building. Some examples are recommending turning off lights or air conditioning in empty areas. In some cases, buildings can even predict the behavior of users in the short term. Through the sensors, it would be possible to identify whether it is a working day or not and create a more adequate energy profile, or even consider whether it is really beneficial for the thermal performance of the building to turn off the HVAC during lunch.

Considerations on the applicability of BEM and the different typologies of the sector

The use of the BEM requires real-time data from the building, that is, at least one sensor system that provides data for it to carry out the simulations in order to generate the alternatives. Therefore, due to the complexity not only of establishing the technology itself, but also of the entire network of sensors and a wireless connection for them to reach the computer where the simulations will be carried out, the use of BEM in the operation is limited to commercial and service buildings. Despite BEM technology being able to respond to the demands of Social, Public and Single-family Housing typologies, with the current availability in the national market there is no sustained adoption of these in the sector, except in very high standard single-family projects.

Energy Portfolio Management Systems [20; 21; 57-60; 81; 84; 85; 93; 94; 98; 100; 104-105-106]

The integrated management between energy consumption and energy generation from different sources, with or without energy storage (batteries), can be performed in an automatic, balanced and flexible manner through computational tools that assist in the arrangement of solutions in an optimized and economical way. A hybrid system with built-in intelligence can also prioritize the supply from renewable sources (self-production) instead of grid supply in order to meet sustainability goals and save energy costs.

Energy portfolio management software and programs allow those responsible for building operations to check in real time (hourly or sub-hourly, intervals with direct connection to databases such as SQL) the energy performance of their facilities, integrate data high resolution, constantly issue various typologies of reports and graphs (such as weekly and daily time series, load duration curve and heat map graphs), perform building energy balance calculations, as well as frequent consumption forecasts and comparisons (or production) with the established goals. In the building operation and maintenance phase, it is also sometimes necessary to compare facilities with other similar facilities (benchmark analysis), which has been helped by new digital technologies.

Considerations on the applicability of energy portfolio management systems to different typologies of the sector

In the operational phase, there is still a need for a paradigm shift regarding the need for competent professionals to operate buildings with a focus on energy performance. This issue greatly impacts the use of this typology of tool as a solution, given that it is not an autonomous technology, but a support technology for decision. Currently, its use is more frequent in commercial and service buildings managed by facilities companies committed to the theme and public buildings with Internal Energy Conservation Commissions (CICE) formed and active. The applicability, however, extends to other typologies of buildings and considering the recent variation in energy costs and the beginning of operation of distributed generation systems, a market share can be created for the outsourcing of the management of these assets which increases the use of this class of digital tools.

Software for Life Cycle Assessment (LCA) [2; 13; 61; 62]

The benefits of Life Cycle Assessment throughout the building operation are related to the reduction of its environmental impacts using renewable sources to generate clean energy on site. Although energy microgeneration through sources such as photovoltaic and wind energy itself does not have an environmental impact, it is also necessary to consider their transport, manufacturing process and disposal in order to choose the most appropriate option.

Considerations about the applicability of software for LCA to different typologies of the sector

Despite the use of renewable sources for energy generation being consolidated in all typologies, the realization of a Life Cycle Assessment associated with such implementation is rare. It usually occurs on large commercial and service projects aiming for an NZEB certification. However, with the popularization of the carbon credits market (and even with the proposal of credits for the reduction of energy consumption) it is believed that the adoption of LCA in the operation phase of all typologies will be consolidated.

3D printing [65]

For cases of complex envelopes and built from printed components (whether single or modular), it is not difficult to predict the availability of a printer that works during the building's operation to provide replacement parts, especially those subjected to greater forces or that make up dynamic systems (with more wear and tear). In this case, the logistic gain described for the construction phase is maintained. As printers use metals or thermosetting plastics, material from damaged parts is recyclable, even locally, either by additional equipment or by the printer itself.

Considerations on the applicability of 3D printing to different typologies of the sector

The applicability of 3D Printing in the operation, considering a scenario in which the machinery has already been acquired to carry out the work, is viable in any of the typologies. There is considerable progress in the evolution of 3D printing of thermosetting plastic materials, making it possible today to print small parts at a relatively low cost. Therefore, feasibility is related to the size of the part to be printed (and therefore to the capacity of the printer). Metal 3D printers are considerably more expensive and may only be viable for large projects of any typology, as a shared service between many units or by a large public or private institution.

Augmented Reality [17; 66; 73]

Augmented Reality, when used during operation, is a key tool for greater efficiency and safety in the maintenance and inspection of infrastructure and lighting, HVAC and water heating systems in buildings.

Considerations about the applicability to augmented reality to different typologies of the sector

For the maintenance of building infrastructure, Augmented Reality is a tool that can be used in any typology, as long as the necessary technical drawings are available for visualization and compatible with what is built. Therefore, there is a greater application in the commercial, service, public, social interest housing and multifamily housing sectors, where the use of the BIM platform allows the production of multiple technical drawings with precision.

Blockchain [100]

In the operational phase, Blockchain can help control assets (electricity, water, gas, heat, cold, etc.) consumed and generated, controlling dispatches automatically through smart contracts. This control and dispatch can take place between the units of the building or in consolidated transactions between the building and the utility companies or other buildings. The issue of certifications makes sense again at this phase, with emphasis on the certifications of origin of renewable energies which are acquired by buildings that intend to achieve a neutral energy balance, but do not have enough distributed generation sources to do so. Although it is not yet an established practice, there is also the possibility of tokenizing the energy efficiency in the operation, from the comparison of the effective consumption of the building with a benchmark calibrated with building parameters. Strictly speaking, it is possible to digitalize (via tokens) all tradable assets in the electricity sector, respecting their characteristics and parameters by different fungibilities, which would allow the formation of a specific trade ecosystem, especially with the current scenario of increased energy commercialization in the free market, with associated services and remuneration via tokens. Practices like these make it possible to create mechanisms to promote energy efficiency with a very high degree of reliability and added value recognized by the market.

Considerations about the applicability to different typologies of the sector

Strictly speaking, Blockchain technology can be applied to any typology of building in the operation phase, as long as smart meters are installed related to each consumed or produced asset and formally established relationships between stakeholders (mediated by smart contracts). However, considering that it is still an evolving market, it is more easily applied between units that share the same set of infrastructure, such as multifamily, public and commercial and service buildings, fundamentally those with public capital and sustainability requirements for listing in exchange, which use certifications of origin to prove the use of clean energy.

Building Management Systems (BMS) [15; 39; 81; 84; 85; 87; 88; 90; 91; 93; 94; 98; 102; 107]

In conjunction with sensors and actuators, it is an efficient system to reduce energy consumption in the HVAC and lighting domains, while maintaining user comfort. Such a system has the autonomy to take specific measures in response to demand at peak times of energy consumption, being advantageous mainly in scenarios with dynamic tariff. Examples of actions taken are the generation of consumption profiles based on the occupancy of the room, turning off equipment after vacating after a certain time and, in the case of lighting, turning it on/off according to external conditions. It can also manage on-site energy generation in an integrated manner with its demand, maximizing microgeneration at times with higher demand from its own generation or from the surroundings to maximize economic return. However, it should be noted that Building Management Systems are not limited to electrical equipment, it can also manage, for example, heating and water supply, in addition to predicting the need for maintenance of equipment and structures based on usage profiles.

One issue with BMS, since it operates on a considerable amount of data, is its security. Through the use of Blockchain, it has the potential to store the data obtained from the building in a dispersed, encrypted, and in a secure way.

Considerations about the applicability to different typologies of the sector

Like BEM, which also requires a network of sensors to provide data, BMS have greater applicability in commercial, service and public buildings. In multifamily residential buildings and social interest housing, the units are autonomous, making it difficult to use BMS. Finally, it is a very expensive system to implement in single-family residences, but it is sometimes used in high-end homes.

Smart sensors, actuators and switches

In this phase, the use of sensors and actuators is intensive. In smart buildings, smart switches are gradually becoming more common. Most of the energy in buildings is consumed at this phase, the use of these technologies enables a drastic reduction in the consumption of energy inputs to be achieved. The smart and sustainable use of these technologies varies according to the typology, economic level of space users and their awareness.

Considerations about the applicability to different typologies of the sector

In newly built commercial buildings, it is common to find motion detectors, automatic control of the pumping system, climate control, water control sensors in faucets and urinals, dimming and lighting control, among others. These technologies constitute some of the building automation systems that maximize the efficiency of equipment, based on continuous monitoring with online data and enabling on-time decision making and the interconnection of various devices. Most of these elements can also be found in large public buildings, due to eventual campaigns to combat waste. Regarding social interest housing, digitalization is still moving slowly due to purchasing power. They enter gradually as a particular product becomes cheaper with the mass production. The typologies of single-family and multifamily homes have a wide variety of economic standards and awareness regarding energy efficiency and its impact on the environment, these issues guide the level of presence of these technologies in these typologies. It is a trend the increasing penetration of commercial smart switches that make home automation more practical to install and more affordable.

Digitally Addressable Lighting Interface (DALI) [14; 108-114]

Automation with DALI works as an interface where information flows from an electronic controller to lighting fixtures or other controlling devices, which execute commands or respond to requests for information, allowing these to be coded or recoded individually and assigned to groups through Software (no cabling required). Precisely with regard to LED lighting systems, DALI is especially interesting when there are combinations of lights with varying colors, in addition to which the control is digital and integrated directly into the lamps, without the need for complex connections compatible with LED power supplies.

The DALI information flow is bidirectional. It controls the lighting in order to configure and synchronize different scenarios when it regulates colors and luminous fluxes to match the entrance of natural light, and creates adaptations for occupancy and programmed shutdown (time, presence, etc.). It is also possible to obtain information about the maintenance status of each equipment with DALI. This is done by returning individual messages from each component (burned out lamp, for example).

Easy to install, the Digital Addressable Light Interface (DALI), integrated with motion or light sensors and with Building Management Systems (BMS), enables numerous energy efficiency solutions at an affordable cost besides being adjustable to layout changes.

The DALI Alliance is the global industry organization for the DALI Protocol, responsible for maintaining testing and licensing programs as well as DALI-2 and D4i certifications. The goal is to increase confidence in the interoperability of products and enable DALI for smart, Internet of Things (IoT)-ready lighting fixtures. In an effort to standardize lighting control protocols, many manufacturers have joined the group and only certified products can carry the DALI logo.

Considerations about the applicability to different typologies of the sector

The application of DALI takes place in commercial, service and public buildings, where it benefits the day-to-day operation of the building. In the case of Social Interest Housing and Multifamily Residences, implementation is possible in common areas, but in general it is not used often enough and a simpler system, using only sensors, present a best value for money.

Smart Facades and other systems [15; 81; 83]

Although smart facades are installed on the envelope, their influence is extrapolated to other domains of the building. Through the design of dynamic shading systems, for example, it is possible to optimize the generation of photovoltaic energy at peak times in response to demand. When an integrated project between dynamic shading elements and building management is carried out, it is possible to configure a smart facade in order to maximize the storage of thermal energy through water that can be used later in other areas of the building. The main application of dynamic shading systems, however, is to improve indoor light and temperature conditions therefore reducing the demand for artificial systems for lighting and HVAC.

Another aspect of smart facades is the automatic control of openings. Such control requires sensors to identify the state of the window and a motor/actuator to open or close it. Its benefits are related to a more efficient hybrid functioning building: when the HVAC is on, it allows for no unwanted or accidental openings; however, when the weather conditions are favorable, it allows the building to function with natural ventilation alone.

Considerations about the applicability to different typologies of the sector

Smart facades have a high cost associated with maintenance, especially due to their moving parts. Therefore, they are predominantly found in commercial and service buildings, where their cost is justified by the building's operating hours. Residences, whether single-family, multifamily or social interest housing tend to be unoccupied during the day (except weekends and holidays), which are the periods when smart facades have the most benefits, so it does not justify their investment. Public buildings, despite having an occupation profile similar to commercial and service buildings and consequently being able to have dynamic systems on the facades, tend to use static facades - such as, for example, *brises soleil* - to reduce maintenance costs. Therefore, they are not characterized as Smart facades. With the reduction of maintenance costs or the increase in the durability of the parts, it is believed that penetration into residential and public buildings would be facilitated, which would contribute considerably to their energy efficiency and environmental comfort.

Virtual Assistants [115]

The main advantage of using Virtual Assistants for the energy efficiency of buildings is the ease of control of small equipment, such as lamps, even electronics and appliances. Some of the factors that contribute to its popularization, in addition to its convenience, is the reduction of barriers to learning to use, through voice control and not with platforms and/or apps. Alternatives for Virtual Assistants to have grown recently, but they have focused on controlling ambient lighting of smart electrical and electronic equipment connected to the grid, security systems, and thermostat/HVAC control. One of its differentials from the perspective of energy efficiency is the creation of routines, such as, for example, to turn appliances on and off, change the temperature, etc.

Considerations about the applicability of virtual assistants to different typologies of the sector

The penetration of Virtual Assistants has grown considerably in the residential sector in the last year with special focus on the autonomous unit. Lighting controls and entertainment systems are some of the uses, but the sector lacks applications that take advantage of the large-scale usage and control the building almost like a Building Management/System Control. In public, commercial and small service buildings, as well as in common areas of multifamily buildings, it is not common to have Virtual Assistants integration with building automation, being generally used as a platform of smart apps and controls, eventually tweaked by gamification.

Smart apps and controls

Such equipment may have more general functions in the operation of a building, such as entertainment equipment, for watering plants and configuration of vacuum robots. However, with smart controls, it also has more robust and specific troubleshooting capabilities. In the case of lighting, they are able to turn the lights on and off according to their use or the conditions of the environment in order to save energy. They also can control external shading, such as, with the use of smart curtains that aim to optimize visual comfort and energy efficiency simultaneously. In HVAC systems, by means of smart thermostats, it is possible for users to control the internal conditions of the building, turning it off or on remotely and generating routines for idle situations. For building safety, it contributes to real-time monitoring of suspicious movements in the building even when unoccupied. It is possible to configure sensors for the management of building infrastructure, in order to automatically detect water, gas and other leaks.

Considerations on the applicability of apps and smart controls to different typologies of the sector

As displays and apps have a more intuitive interface for the general public, they can be applied in all typologies, but are less used in those where there are large centralized systems, such as public, commercial and larger service buildings. On the other hand, as smart controls tend to present more complete reports and require some knowledge of the platform domain for their use, their implementation tends to focus on commercial, service and public buildings.

Smart sockets and chargers for electric vehicles [81; 84; 94]

It is at this phase of the life cycle that these technologies are used and can be an important agent of energy efficiency. Smart sockets enable energy management in order to reduce energy consumption and demand at certain times, which can have a relevant impact on the operating costs of buildings. The form and intensity of the use of these technologies are associated with the operational form of the building and the financial capacity of the user to acquire, install and maintain these technologies. The International Energy Agency presented in its 2021 report that, by the end of 2020, 10 million electric cars were transiting the world, after a decade of rapid growth. Electric vehicles accounted for a 4.6% share of car sales, representing around 3 million units sold globally. Electric buses and trucks also expanded in key markets, reaching global inventories of 600,000 and 31,000, respectively. This growing sale will impact commercial, public and residential buildings in a niche with more purchasing power.

Considerations about the applicability to different typologies of the sector

In this work, he considered that for social interest housing in Brazil, the costs of products with this technology would make their use unfeasible. It should be noted that smart sockets are increasing in price and may be a future option if, to implement energy efficiency actions, the cost of non-smart appliance plus smart socket is lower than the cost of smart appliances. In both single-family and multifamily residential typology, the use of smart sockets increases proportionally to the economic standard of its residents. In the commercial and public sector, more intensive use is expected and depends solely on managers. These technologies can serve as a low-cost, modularized entry for commercial automation of existing buildings of these typologies. In new buildings, it is expected that the intelligence of the operation is included in the project, so there will be no need for these adapters. Electric vehicle charging sockets may contain different charging technologies due to the lack of standardization of this kind of transport and may be AC or DC depending on the vehicle. If the vehicle is powered by DC, the charger needs a rectifier to transform the electrical energy from utility companies from AC to DC, although DC technology has an advantage in terms of fast charging.

Smart electrical and electronic equipment connected to the grid

The use of smart electrical and electronic equipment connected to the grid has a significant impact on reducing the energy demand of socket loads, prioritizing the use of smart equipment for those with higher energy consumption (depending on the use of the building). Such devices vary considerably in size and application but tend to be concentrated in the residential sector. Examples of smart electrical and electronic equipment connected to the grid are robot vacuum cleaners, smart refrigerators, water heaters, air filters, and washing machines.

Other systems, however, are larger and have wider uses in the building sector. This is the case of HVAC and refrigerators, through the installation of smart thermostats, and the security part related to the entry and exit of users of the building. From an energy perspective, it is beneficial to use this equipment in areas that are often idle - such as common areas of multifamily buildings and meeting room - aiming to reduce waste and consequently unnecessary costs during the operation. Another potential application is its linkage to demand response programs, allowing for the load shifting at peak times.

Considerations about the applicability to different typologies of the sector

Most commercially available grid-connected smart electrical and electronic equipment are aimed at homes, thus resulting in greater applicability in single-family, multifamily and social interest housing typologies. However, smart electrical and electronic equipment connected to the grid aimed at HVAC and security can also be adapted for implementation in commercial, service and even public buildings. Bearing in mind that depending on the size, a Building Management System can be more advantageous.

Demand response, awareness and gamification apps

In the operational phase, the improvement of information provided to the consumer is an important and evident benefit. It relates to the use of Building Management Systems (BMS), apps and smart controls, which show energy consumption and quality. This feedback can be done in real time (direct feedback) or periodically, with data processing and reports that can show trends (indirect feedback). It is essential to provide visibility of consumption, using a user-friendly interface (according to their “energy literacy”), providing the necessary information, without overloading the user with a large amount of data. Important information to show include load curves, minimum and maximum demand, comparisons with previous periods, cost information, CO_2 emissions, etc. Another possibility is to use meters that replicate a part of this operation, without the need to install new smart meters.

Demand response involves the performance of end-user equipment as a tool to reduce demand peaks. The proposal is not to change the total energy consumption, but to reduce it during peak hour and, therefore, lower the generation costs and energy distribution. There are simple and analog forms of DR, such as thermoaccumulation in cold water tanks to avoid the use of chillers at peak times, for example. Integration with smart meters, associated with restrictions related to flexible pricing models, opens up the possibility of automated demand control by users at several levels. One of them is the simple use of a dynamic and interactive display so that users can manually respond to energy cost changes (which requires smart meter bi-directional communication functionality); another is interactive dynamic of stimulus with gamification strategies; as well as the interconnection of electronic equipment with the meters and, through the use of smart protocols, to schedule shutdowns when the tariff value is above a pre-determined parameter. Another way is to create direct automation, in which the energy company takes control of some large loads and has the possibility of acting on the systems in a way that does not require user intervention, to control and stabilize the loads on the electrical grid, which requires some obvious financial compensation for the user.

Considerations about the applicability to different typologies of the sector

Automated demand response can be applied to all building typologies, as long as there is a legal basis, dynamic pricing, compatible smart meters and smart devices (or smart sockets) that allow remote shutdown managed by some system, from smart apps and controls up to BMS. Of course, larger buildings (multifamily, public, commercial and service) and with more energy assets, such as distributed generation systems, thermoaccumulation tanks, battery banks, etc. are more resilient and can absorb multiple peak hours or longer periods of unfavorable pricing.

Cloud Computing

During operation, the option of using IaaS means that it is not necessary to have datacenters in the building. Datacenters consume a lot of energy (mainly related to specific temperature control systems), require a lot of maintenance and infrastructure control, which are provided by information technology teams. They need replicated structures for backup and require additional care with digital and physical security, as they store sensitive information. In this way, hiring cloud computing, in addition to transferring risks, allows specialized companies to build their datacenters with highly specialized and energy efficient projects that are located far from urban centers. The combination of these factors reduces heat islands in cities and provides considerable energy savings and a lower carbon footprint not only for the building, but for the system. In addition, having a secure service to host all the software that governs the hardware that make up the digital layer of the building is of paramount importance to enable any energy efficiency gains arising from the technology, as well as allowing a higher level of automation with more flexibility and less need for cabling because the control platform does not need to be local, what is necessary is a good quality wireless network and a digital interface device to obtain information and, eventually, carry out commands.

Considerations about the applicability to different typologies of the sector

Cloud Computing, emerging as an alternative to datacenters, has greater applicability to commercial, service and public typologies, however, due to its current low cost of implementation, it can also be advantageous for multifamily homes and social interest housing, facilitating the management between the multiple owners. In single-family residences, because there is less control, it is not so necessary, except in cases where some certification is sought and a backup in the cloud becomes a guarantee that such data will not be lost.

2.1.4 LIFE CYCLE PHASE: Renovation

The renovation phase refers to the adaptation of the building to a specific demand, and it has grown in importance in recent decades, whether driven by concern for sustainability and energy savings or by the movement of the real estate sector to change the purpose of buildings due to new business opportunities. For example, commercial buildings and hotels are being changed to multifamily residential buildings, notably in more central regions of the big cities. This phase uses both the technologies associated with design and construction and the aggregated information obtained during the operation.

The morphological matrix of the digital solutions for the renovation phase is presented below. Next, the technologies and their applicability regarding the typologies of buildings and domains covered in this study are described.

Table 4 – Morphological matrix of digital solutions for the renovation phase. Source: Made by the authors.

Renovation					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Envelope	• Building Information Modeling (BIM) [5-10; 117] • Building Energy Modeling (BEM) [117] • Computational Fluid Dynamics [CFD] • Simulation of natural and artificial lighting • Software for Life Cycle Assessment (LCA) • 3D printing • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 74] • Building Energy Modeling (BEM) [117] • Computational Fluid Dynamics [CFD] • Simulation of natural and artificial lighting • Software for Life Cycle Assessment (LCA) • 3D printing • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 117] • Building Energy Modeling (BEM) [117] • Computational Fluid Dynamics [CFD] • Simulation of natural and artificial lighting • Software for Life Cycle Assessment (LCA) • 3D printing • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [117] • Building Energy Modeling (BEM) [117] • Computational Fluid Dynamics [CFD] • Simulation of natural and artificial lighting • Software for Life Cycle Assessment (LCA) • 3D printing • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 117] • Building Energy Modeling (BEM) [117] • Computational Fluid Dynamics [CFD] • Simulation of natural and artificial lighting [116] • Software for Life Cycle Assessment (LCA) • 3D printing • Augmented Reality • Blockchain
HVAC	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems [83] • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 104] • Building Energy Modeling (BEM) [104] • Computational Fluid Dynamics [CFD] • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 104] • Building Energy Modeling (BEM) [104] • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 104] • Building Energy Modeling (BEM) [104] • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain

Table 4 – Morphological matrix of digital solutions for the renovation phase. **(Following part of previous table)**

Renovation					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Lighting	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Simulation of natural and artificial lighting • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Simulation of natural and artificial lighting • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 104] • Building Energy Modeling (BEM) [104] • Simulation of natural and artificial lighting • Software for Life Cycle Assessment (LCA) • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 104] • Building Energy Modeling (BEM) [104] • Simulation of natural and artificial lighting • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain • Cloud Computing	• Building Information Modeling (BIM) [5-10; 104] • Building Energy Modeling (BEM) [104] • Simulation of natural and artificial lighting [116] • Software for Life Cycle Assessment (LCA) • Blockchain
Water heating	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) • Blockchain • Augmented Reality	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) • Blockchain • Augmented Reality
Equipment, socket loads	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Software for Life Cycle Assessment (LCA) • Blockchain
Building infrastructure	• Building Information Modeling (BIM) [5-10; 116; 117] • Building Energy Modeling (BEM) [117] • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 116; 117] • Building Energy Modeling (BEM) [117] • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) [83] • Augmented Reality • Blockchain	• Building Information Modeling (BIM) [5-10; 116; 117] • Building Energy Modeling (BEM) [117] • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) [83] • Blockchain	• Building Information Modeling (BIM) [5-10; 116; 117] • Building Energy Modeling (BEM) [117] • Energy portfolio management systems • Software for Life Cycle Assessment (LCA) [83] • Blockchain	• Building Information Modeling (BIM) [5-10, 74] • Building Energy Modeling (BEM) [117] • Software for Life Cycle Assessment (LCA) [83] • Blockchain

Table 4 – Morphological matrix of digital solutions for the renovation phase. **(Following part of previous table)**

Renovation					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Energy supply, generation and storage	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy Portfolio Management Systems [21] • Life cycle assessment software (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems [21] • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems [21] • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy portfolio management systems [21] • Software for Life Cycle Assessment (LCA) • Blockchain	• Building Information Modeling (BIM) [5-10] • Building Energy Modeling (BEM) • Energy Portfolio Management Systems [21] • Software for Life Cycle Assessment (LCA) • Blockchain

Building Information Modeling (BIM) [5-10; 103; 116; 117]

The BIM model and its associated databases are kept up-to-date during the building's operation and have an extremely useful set of information for the designer, as well as a rich performance history that can be used as a basis for the renovation project, whether aiming at adapting to specific requirements, such as energy efficiency, sustainability, accessibility or even changing the purpose of the building. In addition, it carries all the advantages already described for the design phase.

Considerations about the applicability to different typologies of the sector

BIM technology in the renovation phase is also at a mature stage, mainly due to the ease of the platform in “phasing” the construction and explaining the elements to be built and demolished. Some platforms can even generate this technical drawing automatically, which makes the renovation process faster and with less chance of errors. It presents some advantages like the design phase, such as the ease of compatibility of complementary projects and making quotations Its application is also more focused on larger projects, whether commercial and service, public, multifamily residences and social interest housing. In cases of listed buildings (regardless of the instance), its use can be a crucial tool for increasing energy efficiency, reducing errors and ensuring the preservation of heritage. For small constructions, such as single-family residences, despite the visible benefits of using the BIM platform, commercial viability needs to be evaluated. Influencing factors are the size and the fact that single-family home renovations usually involve only one professional or a considerably smaller team, often not requiring such a detailed compatibility, which would not justify the costs associated with the use of BIM.

Building Energy Modeling (BEM) [23]

With the use of BEM in a renovation, it is possible to measure the energy consumption of the existing building (baseline) and compare it with proposed modifications to be carried out, in order to validate the improvements in the energy performance of the building. This method can also be applied to evaluate the benefits brought to users' thermal comfort.

In relation to the other domains in which the Energy Modeling of Building has application, these are considerably similar to the design phase. One highlights the simulation of electricity consumption in groups or individually, in order to show those with the greatest potential for improvement. There is also the possibility of integration with Machine Learning for single or multi-objective optimization.

Considerations about the applicability to different typologies of the sector

As in the design phase, the use of thermoenergetic simulation helps in the design of envelopes with greater energy efficiency, thermal and lighting comfort for users. However, it is necessary to emphasize the limitation of the scope of renovation projects, which varies from case to case. It is smaller when it comes to a change of purpose or when it involves major alterations to the facade and HVAC. Due to the need for knowledge regarding not only simulation software, but also having a lot of fluency related to civil construction, professionals trained to carry out energy modeling of buildings for renovation are scarce, limited to larger projects, high standard or professionals that aim to obtain some environmental certification. It can be considered that the typologies that present the greatest interest in technology are commercial and services, and residential, for which certifications and a lower operating cost can be used as a strategy for valuing the property.

Computational Fluid Dynamics (CFD) [26-32; 34; 36-38]

CFD optimizes the development of renovation projects based on criteria such as optimal flow distribution, efficient thermal management, and minimal load losses. It does so by enabling the comparison of different alternatives for decision making in diagnostics, process improvements and validation of rates of air renewal, speed, and temperature in projects. It allows the 3D visualization of the distribution of the hot or cold fluid with regard to the desired variable, being possible to analyze the flow through videos and observe the critical points.

Considerations on the applicability of CFD to different typologies of the sector

CFD is an important methodology to predict the natural ventilation of buildings, which is especially useful in multifamily, single-family and social interest housing buildings that mostly use such ventilation and not HVAC. It can also be used to study the distribution of air conditioning in complex or high-performance environments (such as datacenters). However, its high costs and lack of trained personnel are seen as barriers and are more adopted by multifamily residential typologies. In Social Interest Housing, replicability can make the adoption of such a tool viable.

Simulation of natural and artificial lighting [39; 41-45; 47-55]

Lighting software offers a wide range of features and functions, facilitating assessments for the revitalization of these systems in existing buildings, whether due to the need to adapt lighting to new standards and norms, to improve occupant comfort or because they are systems with a more immediate economic return to reduce energy costs.

Often, in large buildings, lighting renovation could be part of a broader combination of energy efficiency strategies and, due to the large amount of data needed that must be considered in lighting calculations and the various possibilities of solutions, it is necessary to use faster and more assertive tools for decision making on which option to implement, especially when it involves the use of natural light. In addition, they contribute to achieving financial balance between renovation costs and expected energy savings.

Considerations on the applicability of lighting simulation to different typologies of the sector

The simulations of natural and artificial lighting, as in the design phase, can have a considerable impact on energy efficiency and light comfort throughout the subsequent operation, being more applicable to large projects or related to labeling/certifications, mainly commercial and services, in addition to academic research. Unfortunately, considering the scarcity of trained professionals, there is still low application in public building projects, multifamily residences, single-family and social interest housing.

Energy portfolio management systems [21; 57-60; 83]

Sometimes, the lack of understanding about the costs and benefits of renewable energy, energy efficiency and cogeneration projects in existing buildings constitutes barriers to their implementation and integration, which can be overcome with the help of project analysis software that brings together all aspects to be evaluated in a single platform. Digital tools especially contribute to the development of studies and optimized solutions for HVAC systems, water heating, building infrastructure and energy supply, generation and storage.

Once the renovation projects with proven technical and financial feasibility have been carried out, through integrated management programs (balance between consumption and energy production) it is also possible for facility managers to work holistically for the continuous monitoring of energy performance of the building. They can also establish clean energy production, greenhouse gas reduction and energy efficiency targets, among others, and program abnormality alerts (if renewable energy production is below forecast, for example), which provides immediate information for the operational sector to take action and ensure that the planned investments are maintained in the long term.

The displays on these platforms can also serve as information for employees and visitors about the environmental quality of spaces, both inside and outside the building.

Considerations about the applicability to different typologies of the sector

It basically applies to buildings of any typology that have or are in the process of evaluating the implementation of distributed generation systems and solar thermal water heating. However, they have an expanded scope for larger buildings that are interested in installing other energy-consuming or producing assets, such as large HVAC systems, tanks, heat pumps, cogeneration systems, etc., that is, fundamentally for the typologies of public, commercial and service buildings.

Software for life cycle assessment (LCA) [2; 13; 61; 62]

It is important to highlight that the option for a renovation instead of a demolition followed by a new project can already be the product of a Life Cycle Assessment, as well as the definition of which parts of the building will be maintained and which will be demolished. Regarding the domains, there is generally more limitation in the intervention of the envelope and a prioritization of the modification of thermal insulation and glass than the sealing materials themselves. Lighting systems, building infrastructure and HVAC in general have great potential for intervention in all typologies.

Considerations about the applicability to software for LCA to different typologies of the sector

The use of life cycle assessment (LCA) is more associated with the characteristics of the renovation and unrelated to the typology of the sector in the project. This is because the decision to maintain a building, instead of demolishing it, should already be the subject of an LCA. However, it is observed that it is generally assumed that the renovation will have less environmental impact than demolition and a project from scratch, which is not necessarily true in all cases. In the assessment of the life cycle during the renovation, there are great similarities with the design phase: its current high cost to be carried out limits its applications to larger projects, such as commercial and services, as well as high-end residential projects. Its replicability becomes even more complex at this phase, as it not only considers place variations but also the different needs of reforms, which makes extrapolation from just one large-scale LCA complex. This complexity grows even more if there is a change in the purpose of the building.

3D printing

In renovations on-site printers allow specific approaches for the best use (and reduction of local demolition) of the existing parts of the building, given that each piece can be unique, just by being three-dimensionally modeled. This impacts on the direct reduction of waste generation and on the reduction of the use of large machinery.

Considerations on the applicability of 3D printing to different typologies of the sector

Due to its high cost, its current application is restricted to high-end projects or those in which its cost can be reduced, such as commercial and services or in shared service centers for multiple units. The use in multifamily residential buildings, social interest housing, single-family and public buildings is still low due to the financial issue, despite the technology being able to respond to the demands of these markets. It is noteworthy that 3D Printing is very useful in renovation projects of listed heritage sites, where it is necessary to recreate an element exactly as it was before, due to its precision.

Augmented Reality [17; 66; 73]

It allows the superposition of guidelines in the view of employees, such as the elements which will be built and demolished through the visualization of the construction and demolition plan, which considerably reduces the chances of error and additional costs. It can also be used for communication among workers and show potential hazards, such as gases, besides increasing the safety of the construction site. Due to its relationship with multiple domains and the need to visualize different technical drawings of the building, its integration with Building Information Modeling (BIM) has several benefits.

Considerations about the applicability to augmented reality to different typologies of the sector

Augmented Reality allows greater control of what will be done in the renovation, both in demolition/construction and in the installation of complementary ones, which proves to be very useful in large projects such as commercial and service buildings, public and multifamily residences. Although social interest housing (SIH) varies in size, its replicability makes the use of Augmented Reality viable. All these typologies allow for the reduction of the cost of implementing the technology, which is caused both by the creation of the technical drawings to be visualized, and by the equipment used for the visualization of Augmented Reality by the employees. In smaller projects, as the control of the renovation is easier, there is no need to adopt technology that justifies its cost.

Blockchain [64]

In renovations, the uses are similar to those in the design phase. In buildings already built and operated using the technology, there is the additional benefit of having a recorded history and, consequently, important information on the integrity of the materials and systems installed, and that facilitates decision-making on what is possible or not to keep in the building.

Considerations on Blockchain applicability to different typologies of the sector

Since Blockchain is associated with obtaining data from the building throughout its operation to create a renovation project, its main application is in commercial and service buildings where there is greater control and management of the building, such as the use of BMS.

Agile Management Software

This phase can be as complex as the construction phase depending on the level of renovation that is desired to be implemented in the existing construction, especially considering the national and international trend of retrofitting existing buildings.

Considerations on the applicability of Agile management software to different typologies of the sector

The use of agile management methods collaborates with the same characteristics already mentioned in the construction phase, focusing on commercial, public and multifamily typologies. However, one does not expect these methods to become popular in small renovation projects typically in single-family and social interest housing typologies.

Cloud Computing

During the renovation phase, cloud computing services provide the same benefits described for the design phase, with the additional feature that, in case it is already used prior to retrofitting, they contain the information, parameters and programs used to manage the building as well as the record of all its history. This makes it possible to analyze what worked and what did not work well from an energy point of view, providing valuable information for designers and quantitative parameters for comparison, whether for obtaining financing or for predicting the average fixed cost of maintenance.

Considerations about the applicability of cloud computing to different typologies of the sector

Cloud computing is very important in the renovation as it demands greater work in terms of compatibility of installation projects and, in some cases, control of heritage preservation agencies. However, there is more concentration in more complex projects, such as commercial and service, multifamily and public residential projects and in social interest housing projects. Its adoption is advantageous because it allows the connection between project teams in different parts of the country, which enables the exchange of knowledge if the renovation is not replicable.

2.1.4 LIFE CYCLE PHASE: Demolition

The incorporation of digital technologies at this phase is still at a very early stage, both in Brazil and in other countries. However, some technologies can be used to provide more quality, organization, better targeting and reuse of waste, increase safety and cost reduction in the demolition phase.

The morphological matrix for this phase is shown below. It can be seen that the relationship with the domains fundamentally refers to the existence of information collected during the other phases, which enable evaluations of the destination of waste, from an economic and environmental point of view.

Table 5 – Morphological matrix of digital solutions for the demolition phase. **Source: Made by the authors.**

Demolition					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Envelope	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain
HVAC	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]
Lighting	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]
Water heating	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]
Equipment, socket loads	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]

Table 5 – Morphological matrix of digital solutions for the demolition phase. **(Following part of previous table).**

Demolition					
Domains	**Commercial and Services**	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Building infrastructure	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67] • Blockchain
Energy supply, generation and storage	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]	• Building Information Modeling (BIM) [5-10] • Life cycle assessment (LCA) software [61, 62; 67]

Building Information Modeling (BIM) [5-10]

For demolition, the BIM model gathers information on construction methods, as well as indications on what can be dismantled and reused or recycled, quantities and volumes, which can help to decide the most appropriate way to proceed with a demolition or disassembly. It also attributes commercial value to usable or recyclable elements, which tends to drastically reduce the generation of non-usable solid waste and to reinsert materials, mainly from the envelope, into the civil construction market. The volumetric information of recyclable material (mainly Construction and Demolition Waste - CDW) helps in the mobilization of the construction site, allowing to more adequately dimension and quantify equipment to be used, services and suppliers to be mobilized.

Considerations on the applicability of BIM to different typologies of the sector

The use of the BIM model in demolition is a consequence of its use throughout the previous phases. Therefore, its applicability is more common in large projects, such as commercial and service buildings, public, multifamily residences, and even social interest housing, when multifamily or modular are considered together.

Software for Life Cycle Assessment (LCA) [61, 62; 67]

In the demolition phase, the LCA is a useful tool to measure the environmental impact of the operation of the construction site. It can also be used to make more conscious choices regarding the end of lifecycle of inputs, with a closed-loop approach (recycling or reuse) always being preferable to disposal. One of the factors to pay attention to is the distance between the construction site and the place where the material will be sent due to the high polluting potential of diesel trucks.

Considerations about the applicability to software for LCA to different typologies of the sector

The Life Cycle Assessment is a viable tool in multifamily, single-family, social interest housing, commercial, service and public housing typologies. However, as large buildings generate a more environmental impact in their demolition, they should be more attentive to carrying out LCAs at the end of their life, regardless of their use.

Augmented Reality [17; 66; 73]

It enables communication and guidance between workers during the execution of tasks, being able to indicate which elements to demolish first and which are structural. It can also indicate which are the best routes to follow to leave the building and allocate each category of materials in the construction site. Finally, it increases safety for workers by showing potential hazards at the construction site. Due to its relationship with multiple domains and the need to visualize different technical drawings of the building, its integration with BIM adds quality to this phase.

Considerations about the applicability to augmented reality to different typologies of the sector

Augmented Reality on a construction site is mainly applicable to large developments such as commercial, service, multifamily residential and public buildings. Despite its cost, it is also feasible in Social Interest Housing projects by reusing used equipment, as long as there is guidance and care. Due to its small size, its use in single-family residences is not feasible.

Blockchain

Similar to what was reported in renovations, it is possible to verify the quality and integrity of the existing materials in the building, in order to guide decision-making on what can be reused, what can be recycled, and what actually needs to be discarded. Intense use of reusable items provides energy efficiency, to the extent that such constructive elements, such as metal profiles, will not need to undergo industrial reprocessing or energy-intensive conformation steps, hence reducing the carbon footprint of the company that uses them.

The use of Blockchain follows two paths at this phase: (i) in those buildings that already used the technology for the management of materials, analyses can be carried out for the best decision-making in relation to the destination, and (ii) for those that had or had not adopted the technology before, for those it is possible to categorize the origin and general composition of each material extracted from the construction and regulate the transactions made to remove them from the construction site (recording pieces of land, quantities and characteristics as evolution tokens), processing and conformation (recording processes, energy consumption and other resources) and market orientation (recording physical and mechanical characteristics, pieces of land, quantities and destination).

Considerations on Blockchain applicability to different typologies of the sector

It fundamentally applies to large construction sites, where there is a large amount and added value in the demolition waste. They are public, commercial and service buildings and multifamily residential buildings.

Agile Management Software

For large demolition projects, the issue of logistics is crucial, especially in the management of construction and demolition waste. At this phase, this technology can be associated with BIM technologies that store information about construction methods, materials and their dismantling and should help in the most appropriate way of carrying out such activities with reduced waste generation.

Considerations on the applicability of Agile management software to different typologies of the sector

The potential for using this technology at this phase is in commercial and public typologies, notably in the niche of large buildings and in highly regulated areas in terms of demolition and waste.

2.2 *Status quo* of digitalization in the building sector in Brazil and worldwide

The summary tables presented in the following items refer to the *status quo* of the commercial availability of technologies that can be used in each phase of the building's life cycle, stratified by typology. Each table refers to a phase of the life cycle and lists, for each typology of building, a series of technologies which are evaluated and classified according to their availability in the Brazilian and international markets. The theoretical basis for framing the *status quo* and the fundamental distribution of technologies in relation to building typologies and their life cycle phases are consolidated in a synthetic table (in Appendix 3). in addition to searches for academic references, searches for commercial references were carried out in order to find products, solutions, software, apps, tools, web apps, service providers, specialized companies, or other sources of information relevant to the establishment of the market *status quo*. These references are organized in Appendix 4. With the cataloged references, it was possible to understand and assess the current status of each technology and classify them with the following scale of colors and meanings:

Color	Status	Meaning
Green	Commercially available	It means that enough references were found to consider the available technology from a commercial point of view.
Yellow	Under development	It means that not enough references were found to consider the available technology from a commercial point of view, but there are mentions in academic literature which highlights the interest and imminent development from a commercial point of view.
Red	Commercially unavailable	It means that not enough references were found to consider the available technology from a commercial point of view, not citations in academic literature that explain the use of the technology at hand, considering the analyzed context (building type versus life cycle phase). This classification also includes digital solutions not relevant to certain association between life cycle phase and building typology.

It is important to emphasize that the availability of a given solution, which translates into the *status quo* classification, is not related to the need or obligation to use the technology in the phase/typology of the building analyzed in a specific context, but related to availability in the market. The classification did not take into account aspects related to the costs involved and possible restrictions related to the acquisition of inputs and services necessary for the use of a certain digital solution in the analyzed contexts. The effective penetration of digital solutions will be addressed in the scenario studies, contemplating additional criteria.

In the building design phase, Software, apps and tools used, as well as the associated services, are mostly found related to the following digital solutions: Building Energy Modeling, Urban Energy Modeling, Computational Fluid Dynamics, Simulation of natural and artificial lighting and Energy Portfolio Management Systems, Software for Life Cycle Assessment, Augmented Reality and Agile Management Software. When these solutions are analyzed in the context of the *status quo* matrices, and when in fact relevant to the association between life cycle phase versus building typology, are available both in the national market and in other countries in all analyzed contexts. Among these, the positive highlights regarding the availability of suppliers, which can be translated into market maturity, are for solutions in BIM, CFD and Simulation of natural and artificial lighting. The initiatives using Blockchain are a reality, but for the most part, the digital solution is provided and performed in partnership with foreign companies.

In the construction phase of buildings, digital solutions using software are widely used. However, digital solutions that employ BEM/UBEM, CFD, computer simulation for evaluating light performance and simulation, and renewable energy management systems were not identified at this phase. Solutions were identified in BIM, LCA, augmented reality and tools for agile management, available both in the national market and in other countries in all analyzed contexts. Specifically, for 3D Printing and Blockchain digital solutions, it is possible to find numerous initiatives abroad, while in Brazil they are still under development, mostly offered by startups.

In the building operation phase, digital solutions are more frequently found involving devices and systems capable of promoting the control and automation of processes and services, mainly involving the following digital solutions: Sensors and Actuators, Digital Addressable Lighting Interface (DALI), Virtual Assistants, Smart Apps and Controls, Smart Sockets, Electric Vehicle Chargers, Smart Switches and Grid-Connected Smart Electronics. These are available both in the national market and in other countries in all analyzed contexts. Specifically, for digital solutions related to Smart Facades and demand response actions, it is possible to find numerous initiatives abroad whereas in Brazil they are still under development. In terms of demand response, examples can be found in pilot projects initiated by energy distribution companies and by ANEEL. At this phase, solutions were also identified using software such as BIM, LCA and energy portfolio management systems.

In the building renovation phase, because of the presentation format of these results, the classifications and the considerations present in the matrix have great similarity with the conclusions drawn from the results matrix for the design phase. Except for the presence of 3D Printing solutions, which, as in the construction phase, are available internationally and under development domestically.

In the building demolition phase, in the solutions in which software and related services are used, the following digital technologies are mostly used: BIM, Software for LCA and Augmented Reality. When analyzed in the sphere of *status quo* matrices, they are available both in the national market and in other countries in all analyzed contexts. Specifically, for digital solutions on Blockchain, it is possible to find numerous initiatives at an international level while in Brazil they are still under development.

Below, we present the summary tables with the *status quo* of the main digital solutions available in Brazil and in the world, by phase of the building's life cycle, considering all the typologies addressed in this study.

2.2.1 *Status quo* of digital solutions for buildings in the design phase

Table 6 presents the *status quo* of the main digital solutions available in Brazil and in the world for the design phase, considering the five typologies addressed in this study.

Table 6 – *Status quo* of digital solutions for the design phase. **Source: Made by the authors.**

Digital solution	*Status quo*									
	Commercial		Public		SIH Residences		Multifamily		Single-family	
	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries
Building Information Modeling (BIM)										
Building Energy Modeling (BEM) / Urban Energy Modeling (UBEM)										
Computational Fluid Dynamics (CFD)										
Simulation of natural and artificial lighting										
Energy Portfolio Management Systems										
Software for Life Cycle Assessment (LCA)										
3D printing										
Augmented Reality										
Blockchain										
Agile Management Software										
Building Management / System Control										
Sensors and actuators										
Digitally Addressable Lighting Interface (DALI)										
Smart facades / Systems of dynamic shading										
Virtual assistants										
Smart apps and controls										
Smart sockets and electric vehicle chargers										
Smart switches										
Smart electronic equipment connected to the grid										
Demand, awareness and gamification response apps										
Cloud Computing										

2.2.2 *Status quo* of digital solutions for buildings in the construction phase

Table 7 presents the *status quo* of the main digital solutions available in Brazil and in the world for the construction phase, considering the five typologies addressed in this study.

Table 7 – *Status quo* of digital solutions for the construction phase. **Source: Made by the authors.**

Digital solution	*Status quo*									
	Commercial		Public		SIH Residences		Multifamily		Single-family	
	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries
Building Information Modeling (BIM)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Building Energy Modeling (BEM) / Urban Energy Modeling (UBEM)	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Computational Fluid Dynamics (CFD)	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Simulation of natural and artificial lighting	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Energy Portfolio Management Systems	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Software for Life Cycle Assessment (LCA)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
3D printing	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green
Augmented Reality	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Blockchain	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green
Agile Management Software	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Building Management Systems (BMS)	Yellow	Green	Red	Red	Red	Red	Red	Red	Red	Red
Sensors and actuators	Red	Red	Yellow	Green	Yellow	Green	Yellow	Green	Red	Red
Digitally Addressable Lighting Interface (DALI)	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart facades / Systems of dynamic shading	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Virtual assistants	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart apps and controls	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart sockets and electric vehicle chargers	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart switches	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart electronic equipment connected to the grid	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Demand, awareness and gamification response apps	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Cloud Computing	Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Green

2.2.3 *Status quo* of digital solutions for buildings in the operation phase

Table 8 presents the *status quo* of the main digital solutions available in Brazil and in the world for the operation phase, considering the five typologies addressed in this study.

Table 8 – *Status quo* of digital solutions for the operation phase. **Source: Made by the authors.**

Digital solution	*Status quo*									
	Commercial		Public		SIH Residences		Multifamily		Single-family	
	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries
Building Information Modeling (BIM)										
Building Energy Modeling (BEM) / Urban Energy Modeling (UBEM)										
Computational Fluid Dynamics (CFD)										
Simulation of natural and artificial lighting										
Energy Portfolio Management Systems										
Software for Life Cycle Assessment (LCA)										
3D printing										
Augmented Reality										
Blockchain										
Agile Management Software										
Building Management Systems (BMS)										
Sensors and actuators										
Digitally Addressable Lighting Interface (DALI)										
Smart facades / Systems of dynamic shading										
Virtual assistants										
Smart apps and controls										
Smart sockets and electric vehicle chargers										
Smart switches										
Smart electronic equipment connected to the grid										
Demand, awareness and gamification response apps										
Cloud Computing										

2.2.4 *Status quo* of digital solutions for buildings in the renovation phase

Table 9 presents the *status quo* of the main digital solutions available in Brazil and in the world for the renovation phase, considering the five typologies addressed in this study.

Table 9 – *Status quo* of digital solutions for the renovation phase. **Source: Made by the authors.**

Digital solution	*Status quo*									
	Commercial		Public		SIH Residences		Multifamily		Single-family	
	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries
Building Information Modeling (BIM)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Building Energy Modeling (BEM) / Urban Energy Modeling (UBEM)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Computational Fluid Dynamics (CFD)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Simulation of natural and artificial lighting	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Energy Portfolio Management Systems	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Software for Life Cycle Assessment (LCA)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
3D printing	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green
Augmented Reality	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Blockchain	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green
Agile Management Software	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Building Management Systems (BMS)	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Sensors and actuators	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Digitally Addressable Lighting Interface (DALI)	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart facades / Systems of dynamic shading	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Virtual assistants	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart apps and controls	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart sockets and electric vehicle chargers	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart switches	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Smart electronic equipment connected to the grid	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Demand, awareness and gamification response apps	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Cloud Computing	Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Green

2.2.5 *Status quo* of digital solutions for buildings in the demolition phase

Table 10 presents the *status quo* of the main digital solutions available in Brazil and in the world for the demolition phase, considering the five typologies addressed in this study.

Table 10 – *Status quo* of digital solutions for the demolition phase. **Source: Made by the authors.**

Digital solution	*Status quo*									
	Commercial		Public		SIH Residences		Multifamily		Single-family	
	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries	Brazil	Other countries
Building Information Modeling (BIM)										
Building Energy Modeling (BEM) / Urban Energy Modeling (UBEM)										
Computational Fluid Dynamics (CFD)										
Simulation of natural and artificial lighting										
Energy Portfolio Management Systems										
Software for Life Cycle Assessment (LCA)										
3D printing										
Augmented Reality										
Blockchain										
Agile Management Software										
Building Management Systems (BMS)										
Sensors and actuators										
Digitally Addressable Lighting Interface (DALI)										
Smart facades / Systems of dynamic shading										
Virtual assistants										
Smart apps and controls										
Smart sockets and electric vehicle chargers										
Smart switches										
Smart electronic equipment connected to the grid										
Demand, awareness and gamification response apps										
Cloud Computing										

2.3 Digitalization policies in the building sector in Brazil and instruments implemented or under development

This section presents the results of the document analysis on the main policies and regulatory instruments implemented or under development in Brazil, which relate to the *status quo* of digitalization in the building sector aiming to increase energy efficiency in this sector. In this sense, the reference documents were separated into three large groups, namely:

- **i.** Energy efficiency policies that may impact the building sector;
- **ii.** Regulatory instruments related to smart electric grids that can expand digitalization in this sector;
- **iii.** Policies directly linked to the digitalization of the building sector.

Regarding energy efficiency policies, the instruments that defined the regulatory framework for equipment labeling in Brazil were evaluated using the Energy Efficiency Law as a backdrop. In addition, the main energy efficiency programs that exist in the country were described, with emphasis on the National Electric Energy Conservation Program, the National Program for the Rationalization of the Use of Petroleum and Natural Gas Derivatives and the Energy Efficiency Program of Electricity Distributors. Subsequently, there was focus on energy efficiency in buildings through the description of the Brazilian Labeling Program for Building. Finally, still in this group, a description was made of the plans that consider energy efficiency in the context of Energy Planning, with emphasis on the Ten-Year Plan for Energy Efficiency.

With regard to regulatory instruments related to smart electrical grids that can somehow expand digitalization in the building sector and, thus, achieve greater energy efficiency, regulatory instruments related to smart meters, distributed generation and demand-response tariff mechanisms (white tariff, for example) stand out. In addition, it discusses how the agenda of modernization of the electricity sector can expand the adoption of new technologies in the building sector.

Regarding the policies that can encourage the use of digital technologies in the building sector, these were divided into three sections:

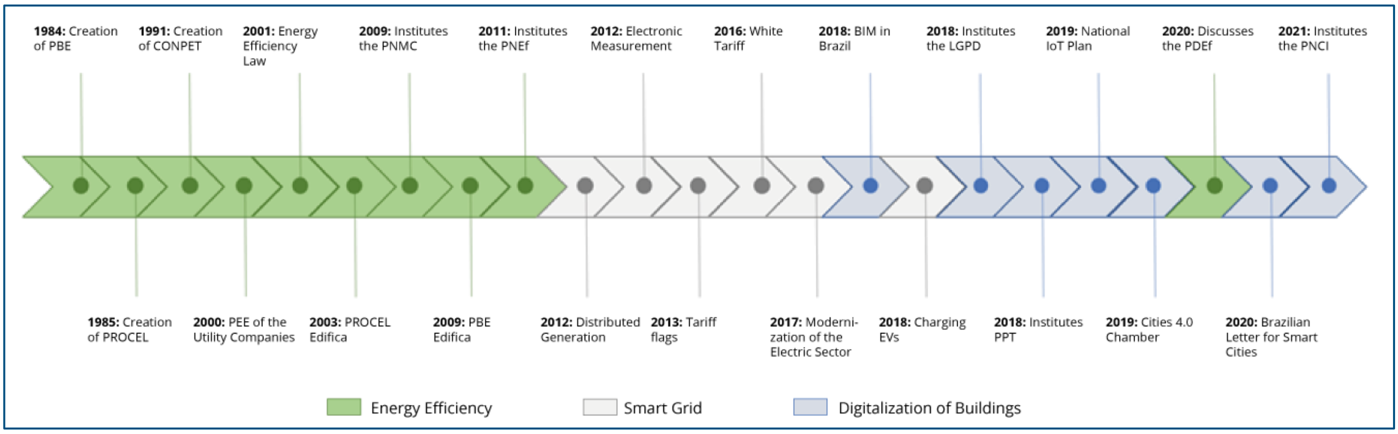
- **i.** One that deals with connecting devices in buildings, such as the National Plan for the Internet of Things;
- **ii.** Another addressing policies related to smart cities, with emphasis on the National Smart City Plan;
- **iii.** One that addresses the issue of the data life cycle, where the National Strategy for the Dissemination of Building Information Modeling (BIM) was described.

The policies discussed in this section are summarized in Table 11. In addition, a timeline is presented with the main regulatory instruments aggregated into three groups, according to the color legend:

- Energy efficiency (green);
- Smart electrical grids (gray);
- Digitalization of buildings (blue).

It is worth mentioning that most policies listed have already been implemented, with the exception of the Ten-Year Energy Efficiency Plan (PDEf) and the National Policy for Smart Cities (PNCI).

Table 11 summarizes the main policies and regulatory instruments implemented or under development in Brazil related to the objective of this study. Picture 1 schematically shows the timeline of digitalization policies in the building sector in Brazil and instruments implemented or under development.



Picture 1 – Timeline of policies implemented or under development in the country. **Source: Made by the authors.**

Table 11 – Summary of policies implemented or under development in the country. **Source: Made by the**

Code	Predominant area	Policies and instruments implemented or under development	Regulatory instruments
1	Energy Efficiency	Brazilian Labeling Program - PBE	Program created by Inmetro in 1984
2	Energy Efficiency	National Electric Energy Conservation Program - PROCEL	Interministerial Ordinance No. 1.877/1985
3	Energy Efficiency	National Program for the Rationalization of the Use of Petroleum and Natural Gas Derivatives - CONPET	Presidential Decree of July 18, 1991
4	Energy Efficiency	Energy Efficiency Program for Electric Energy Distributors - PEE	Law No. 9,991/2000 and Law No. 13,280/2016
5	Energy Efficiency	Energy Efficiency Law	Law No. 10,295/2001, Decree No. 4,059/2001 and Decree No. 9,864/2019
6	Energy Efficiency	Procel Edifica	Launched in 2003 by ELETROBRAS/PROCEL
7	Energy Efficiency	National Policy on Climate Change - PNMC	Law No. 12,187/2009, Decree No. 7,390/2010 and Nationally Determined Contribution (NDC Brazil, 2015)
8	Energy Efficiency	PBE Edifica	Inmetro Ordinance No. 372/2010, No. 17/2012, No. 18/2012 and No. 42/2021, and ABNT NBR 15.575-1/2021
9	Energy Efficiency	National Energy Efficiency Plan - PNEf	MME Ordinance No. 594/2011
10	Smart Electric Grids	Distributed Generation	ANEEL Normative Resolutions No. 482/2012, No. 687/2015, 786/2017 and Bill No. 5,829/2019
11	Smart Electric Grids	Regulation of Electronic Measurement	ANEEL Normative Resolutions No. 502/2012 and No. 863/2019
12	Smart Electric Grids	Tariff Flags	ANEEL Normative Resolution No. 547/2013
13	Smart Electric Grids	White Tariff	ANEEL Normative Resolution No. 733/2016
14	Smart Electric Grids	Modernization of the Electricity Sector	Public Consultation No. 33/2017, MME Ordinance No. 187/2019 and 403/2019
15	Digitalization of Buildings	National Strategy for the Dissemination of Building Information Modeling (BIM)	Decrees No. 9,983/2019 and No. 10,306/2020
16	Smart Electric Grids	Charging Electric Vehicles (EVs)	ANEEL Normative Resolution No. 819/2018
17	Digitalization of Buildings	General Personal Data Protection Law - LGPD	Law No. 13,709/2018 and No. 13,853/2019
18	Digitalization of Buildings	Public Telecommunications Policies - PPT	Decree No. 9,612/2018
19	Digitalization of Buildings	National Plan for the Internet of Things (IoT)	Decree No. 9,854/2019
20	Digitalization of Buildings	Chamber of Cities 4.0	Launched in Dec/2019 by MCTI
21	Energy Efficiency	Ten Year Energy Efficiency Plan - PDEf	Approved by the 2nd Resource Application Plan of PROCEL (2nd PAR)
22	Digitalization of Buildings	Brazilian Charter for Smart Cities	Launched Dec/2020 at Smart City Session 2020
23	Digitalization of Buildings	National Smart Cities Policy - PNCI	Bill No. 976/2021

2.3.1 Energy efficiency policies that impact the building sector

This item describes the energy efficiency policies that impact the building sector, being subdivided into four groups, namely:

i. Equipment labeling;
ii. Energy efficiency programs;
iii. Energy efficiency in buildings;
iv. Energy efficiency in the context of the country's energy planning.

Equipment labeling

In 1984, the National Institute of Metrology, Quality and Technology (Inmetro) started the debate on the creation of performance-focused conformity assessment programs, with the objective of contributing to the rationalization of energy use in the country. Thus, in the same year, the Brazilian Labeling Program (PBE) was created, which adopts the National Energy Conservation Label (ENCE) to provide information on the performance of products with regard to their energy efficiency. Currently, the PBE comprises 27 conformity assessment programs in different phases of implementation, ranging from the labeling of household appliances, such as stoves, refrigerators and air conditioners, to vehicles and buildings.

The PBE programs are coordinated in partnership with the National Electric Energy Conservation Program (PROCEL), established by Interministerial Ordinance No. 1877 of December 30, 1985, [118] and the National Program for the Rationalization of the Use of Petroleum and Natural Gas Derivatives (CONPET), created by Presidential Decree of July 18, 1991 [119]. CONPET and PROCEL, originally operated, respectively, by Petrobras and Eletrobras, which reward the most efficient products in the Inmetro Labeling Program. CONPET is provisionally being coordinated directly by the MME. PROCEL, according to law nº 14.182/2021, must be coordinated by the Brazilian Company of Participations in Nuclear and Binational Energy S.A. (ENBPar).

Until 2001, the equipment labeling process was voluntary, but on October 17 of the same year, Law 10,295, known as the Energy Efficiency Law, was enacted and it became mandatory for the performance of some pieces of equipment [120]. Thus, the Executive Branch is responsible to establish minimum levels of energy efficiency or maximum levels of specific consumption of energy-consuming machines and equipment.

Both Decrees No. 4059, of December 19, 2001 [121] and No. 9,864, of June 27, 2019, regulate Law No. 10,295 [120], which provides for a National Policy for the Conservation and Rational Use of Energy. But it was Decree nº 4.059/2001 that created the Energy Efficiency Indicators and Levels Management Committee (CGIEE), which is responsible for establishing the minimum efficiency levels and the respective Target Programs indicating the evolution of these levels for each equipment regulated. In addition, it created the Technical Building Group responsible for promoting energy efficiency in buildings. By virtue of the application of Decree No. 9,759, of April 11, 2019, Decree No. 4,059, of 2001, was replaced by Decree No. 9,864, of June 27, 2019, which updated the composition of the CGIEE to the new ministerial structure and its work procedures, as well as incorporating new competencies into the collegiate body, giving it more legitimacy in the implementation of the National Energy Conservation Policy. The composition of the Technical Group for Energy Efficiency in Buildings – the Buildings GT – was also updated.

A lot of equipment that are used in buildings are those with compulsory labeling established in the PBE and, therefore, can contribute to increasing energy efficiency in this sector.

Energy efficiency programs

In addition to PROCEL and CONPET, another very important instrument to promote energy efficiency in the country is the Energy Efficiency Program for Electric Energy Distributors, the PEE, created by Law No. 9,991 of July 24, 2000 [122]. This law provides for investments in both research and development and energy efficiency by energy providers, permit holders and authorized companies in the electricity sector, which includes electricity utility companies. These companies must invest part of their net operating revenue (NOR) in energy efficiency (PEE) and research and development (R&D) projects.

Currently, the total percentages for each of the programs are 0.5% for PEE and 0.5% for R&D. In the case of the PEE, Law No. 13,280, of May 3, 2016, allocated part of the energy efficiency money to PROCEL, 20% of this resource [123]. Thus, PROCEL receives from this account 0.1% of the utility companies' NOR and PEE 0.4% of this revenue.

Another regulatory instrument worth mentioning is the National Policy on Climate Change – PNMC, established by Law No. 12,187, of December 29, 2009 [124]. This policy determines that there must be measures to encourage the development of processes and technologies that can contribute to the reduction of greenhouse gas (GHG) emissions. In addition, proposals must be defined that provide more savings in energy, water and other natural resources, as well as the reduction of the emission of these gases and waste.

Decree No. 7,390, of December 9, 2010, regulates some articles of Law No. 12,187/2009, with emphasis on Brazil's voluntary target plan to reduce GHG emissions [125]. With the Paris Agreement, signed at the 21st Conference of the Parties (COP 21) in 2015, the GHG reduction targets by the Brazilian government were redefined. In the Nationally Determined Contribution (NDC) that was ratified by Brazil in 2016, in relation to the energy sector, the country committed to expand the domestic use of non-fossil energy sources by 2030 by increasing the share of renewable energy (in addition to energy from hydropower sources), and to achieve 10% efficiency gains in this sector [126].

Energy efficiency in buildings

The Energy Efficiency Law, in its article 4, mentions the responsibility of the Executive Branch to develop mechanisms that promote energy efficiency in buildings built in the country. This may be the government's first initiative with the objective of bringing greater efficiency in the building sector.

It was through the National Program for Energy Efficiency in Buildings - PROCEL Edifica - established in 2003 by PROCEL, that clearer objectives were defined to encourage the conservation and efficient use of natural resources (water, light, etc.) in buildings, thus reducing waste and impacts on the environment, including GHG reduction [127].

Within the scope of the WG-Buildings created in 2001, at the end of 2005, the Technical Department of Buildings (ST-Buildings) was created and had the competence to discuss technical issues involving energy efficiency indicators. In 2005, Inmetro became part of the process through the creation of the Technical Committee for Buildings, in which the processes for obtaining ENCE in this sector are discussed and defined. Thus, within the scope of the PBE, the Technical Requirements of the Quality for the Energy Efficiency Level of Commercial, Service and Public Buildings (RTQ-C), Inmetro Ordinance No. 372/2010 and No. 17/2012 and Residential Buildings (RTQ-R), Inmetro Ordinance No. 18/2012, as well such as the Building Energy Efficiency Conformity Assessment (RAC) Requirements.

In 2017, PROCEL/PBE Edifica, together with the Brazilian Center for Energy Efficiency in Buildings (CB3E), launched a proposal for a new method for evaluating the energy performance of buildings considering primary energy consumption. It was only on February 24, 2021, thanks to Ordinance nº 42/2021, that the criteria and methods for the classification of commercial, service and public buildings in terms of energy efficiency were approved [128]. The regulatory instrument established for this purpose is the Inmetro Normative Instruction for the Energy Efficiency Classification of Commercial, Service and Public Buildings (INI-C), which improved the Technical Quality Requirements for the Energy Efficiency Level of Commercial, Service and and Audiences (RTQ-C).

From the perspective of improving the performance of buildings, the ABNT NBR 15,575 standard was created with the objective of defining the minimum requirements for quality, durability, safety and performance for Brazilian housing constructions. Among these requirements, there are requirements for thermal, lighting and acoustic performance, which are totally related to the energy efficiency of buildings. This standard was published in February 2013 and its application became mandatory in July of the same year. In addition, to correct some limitations of this version of the standard within the thermal performance requirements, revisions and updates were made, which were published in 2021 [129].

In relation to public sector buildings, there are many laws to have a better management of resources in these buildings, in particular, water and energy. Normative Instruction No. 2, of June 4, 2014, of the Ministry of Planning, Budget and Management (MP), makes it mandatory to obtain ENCE class “A” in projects of new federal public buildings or those undergoing renovations. In addition, Ordinance SPU nº 202, of November 11, 2015, of the Secretariat of Federal Assets linked to MP, provides for the obligation of contractual clauses that deal with accessibility, safety and sustainability, including new works, in the instruments of destination of federal real estate. This legislation can help federal buildings to be an example of efficiency, even making use of digital technologies that aim to achieve higher levels of energy efficiency.

Energy efficiency in the context of Energy Planning in Brazil

In the context of Brazilian energy planning, the creation of two plans highlights the importance of energy efficiency for the country: the National Energy Efficiency Plan – PNEf [130] and the Ten-Year Energy Efficiency Plan – PDEf [131].

MME Ordinance No. 594, of October 18, 2011, which approved the PNEf, serves as a guideline for achieving energy saving goals in the context of national energy planning [130]. Thus, thanks to this regulatory instrument, the National Energy Plan 2030 (PNE 2030) and the Ten-Year Energy Plans (PDEs) began to incorporate energy efficiency policies defined by the government. In this sense, in relation to buildings, this plan proposed lines of action in four areas, namely: training; technology; dissemination; regulation; and housing. Specifically, in relation to technology, this plan highlighted the need to develop computer simulation systems focused on thermodynamic aspects, with a view to simplifying the evaluation procedures of buildings.

Regarding the PDEf, proposals were presented that covered a review of existing energy efficiency mechanisms in Brazil, as well as the indication of new transversal and specific actions in sectors considered relevant, such as public service, buildings, transport, industry and agriculture. In the building sector municipal regulatory instruments, technical standards aimed at this sector, as well as initiatives aimed at the public sector and real estate credit lines were evaluated. In addition, the creation of an energy efficiency program for natural gas was proposed, considering the potential for growth in the consumption of this energy vector in buildings [131].

Regarding the performance of buildings, the PDEf proposes to simplify the methodology of the PBE Edifica Label, which could be based on a checklist, which, in the view proposed by the Plan, would facilitate the adoption of this label, especially for small and simple buildings. In addition, the need to define an energy benchmarking for different categories of buildings was pointed out.

Another proposal put in the PDEf was the creation of a subprogram ('Procel Eficiência Digital') related to IoT (Internet of Things), more geared to the residential sector. In addition, this program would be responsible for obtaining energy efficiency gains associated with the insertion of digitalization in processes involving, for example, the industrial and commercial sectors, which includes buildings [131].

2.3.2 Smart electrical networks and digitalization of buildings: regulatory instruments

The regulatory instruments related to smart grids that can contribute to the digitalization of Buildings are described below, with the objective of increasing energy efficiency in this sector. This item is subdivided into four topics, namely:

i. Smart meters;
ii. Distributed generation;
iii. Demand response tariff instruments;
iv. Modernization of the electricity sector.

Smart meters

One of the first digitalization actions focused on homes in Brazil took place in 2003 with the installation of electronic meters in the DAT Network (Transversal Aerial Distribution) of the distributor Ampla (today Enel Distribuição Rio). The construction of this network was aimed at mitigating the problem of non-technical losses (energy theft) in low-income communities and, for that electronic meters were used, in which displays with energy consumption information were installed inside homes. Although this action took place in 2003, it was only in 2010 that Inmetro approved electronic meters [132].

Subsequently, on August 7, 2012, due to the deployment of electronic meters in the electricity distribution market in the country, ANEEL launched Normative Resolution (NR) No. 502/2021, aiming to regulate electric power metering systems for consumer units of Group B (low voltage) [133]. Thus, the price of active electricity consumed accumulated by billing time unit was regulated, as well as the identification of the billing time unit when it existed. This resolution also contributes to the regulation of the white tariff could happen later in 2016. On December 10, 2019, NR nº 502/2012 [133] was revoked, and the measurement and reading procedures were improved by Resolution nº 863/2019. [134].

Also, from the point of view of electronic and smart metering, NR nº 819, of July 5, 2018, established the procedures and conditions for carrying out activities for recharging electric vehicles by electric energy utility companies and other interested parties [135]. This resolution can bring a great advance to smart metering, since charging stations have a set of software and equipment used for the supply of alternating or direct current to electric vehicles, being installed in one or more enclosures, with special control and communication functions. This measuring equipment, in addition to being installed in specific charging stations, are often integrated into buildings.

Distributed generation

Another policy that benefited from the guidelines defined by NR nº 502/2012, as they allow measurements at billing time units, was distributed generation. NR nº 482, of April 17, 2012, regulates distributed micro and mini generation, which are justified by the potential benefits that distributed generation can provide to the electrical system [136]. Some of the benefits are the postponement of investments in the expansion of the transmission and distribution systems, the low environmental impact, the reduction in grid loading, the minimization of technical and non-technical losses, and the diversification of the energy matrix. One of the distributed generation technologies that managed to create a large market, after the publication of this Resolution, was photovoltaic solar energy, which is often directly integrated into buildings.

ANEEL published Normative Resolution No. 687 on November 24, 2015, revising NR No. 482/2012, with the aim of reducing costs and time for connecting microgeneration and mini-generation and increasing the target audience of consumers who have distributed generation. [137]. In addition, NR nº 786, of October 17, 2017, increased the power of generation systems from water sources [138].

An important contribution of this regulation was the possibility for consumers to generate their own electric energy and transfer the excess energy through free 'loan' to the local distributor and this energy would be later compensated with the consumption of active electric energy. This system is called a compensation system and the consumer has up to 60 months to consume this energy 'loaned' to the distributor.

To make this compensation system technically viable, it is necessary for the utility company to adapt the metering system for these consumers, as it is essential that a bidirectional meter be installed. This new measurement technology enables the adoption of distributed generation in buildings in Brazil, modernizing the way of consuming energy. It is worth mentioning the publication of Law No. 14,300/2022 on January 7, 2022, which established the legal framework for microgeneration and distributed mini-generation, the Electric Energy Compensation System (SCEE) and the Social Renewable Energy Program (PERS). In addition to staggering the compensation of some tariff components [139].

Demand response tariff instruments

There are two demand response instruments that deserve to be mentioned, as smart meters can contribute to higher effectiveness of this policy. These are: the Tariff Flags, regulated by NR nº 547, of April 16, 2013 [140]; and the White Tariff, regulated by NR nº 733, of September 6, 2016 [141].

The Tariff Flag is a demand response mechanism that associates the tariff increase to the dispatch of thermal generation, caused by the reduced availability of water in the reservoirs of hydroelectric power plants. While the green flag does not imply additional tariff collection, the yellow or red flag, when activated, imply higher tariffs, due to the higher cost of generating thermal power plants.

The White Rate is an hourly rate that is intended for Group B, on an optional basis. This tariff has three billing time units according to the hourly demand of the utility companies, namely:

- **i.** Off peak;
- **ii.** Peak hours;
- **iii.** Intermediate.

While the cost of off-peak energy is cheaper than the conventional tariff, at peak and intermediate times, the tariff is more expensive. This tariff requires measuring instruments that can measure these billing time units. Thus, there is a need to install electronic meters in consumer units demanding this tariff. With the help of electronic or smart meters, it is possible for consumers to monitor their consumption and control the use of the equipment, contributing to energy conservation.

In addition to these two already consolidated instruments, discussions were opened on the Binomial Tariff for low voltage consumers, in Public Hearing No. 59/2018 [142], and the modality of Pre-payment of Electricity, in Public Consultation No. 16/2017 [143].

Modernization of the electricity sector

Through Public Consultation No. 33, of July 5, 2017 [144], discussions were opened to improve the legal framework for the Brazilian electricity sector, given that the bases of the regulatory model of the Brazilian electricity sector in force date back to 2004 (Law No. 10,848/2004) [145]. With the results of this consultation, it was up to the Ministry of Mines and Energy, through Ordinance MME 403, of October 29, 2019 [146], to institute the Committee for the Implementation of the Modernization of the Electricity Sector in this Ministry, to enable the effective execution of the action plan to improvement the electric sector, topic of MME Ordinance No. April of the same year [147].

One of the lines of action of the work groups created by the MME related to the modernization of the electric sector concerns the “Insertion of New Technologies”. Among the technologies analyzed, there are storage solutions, hybrid power plants, wave power, offshore wind power and distributed energy resources, in addition to auxiliary services. Thus, for each of these sources and technologies, we sought to identify the current barriers to their adoption, as well as to point out action plans to encourage the participation of these technologies in the Brazilian electricity matrix.

Some of these technologies are distributed energy resources (distributed generation, electric vehicles, demand response and energy efficiency) and energy storage solutions (especially batteries and hydrogen) that have full intersection with the building sector and increasingly demand digital technologies.

2.3.3 Policies that influence the increase in digitalization in the building sector

The policies that influence the increase in digitalization in the building sector are presented below, around three themes, namely:

- **i.** Device connection;
- **ii.** Smart cities;
- **iii.** Data life cycle.

Device connection

Decree No. 9,612, of December 17, 2018, provides for Public Telecommunications Policies (PPT), whose main objectives are to promote access to telecommunications under economic conditions that enable the use of services, especially for the expansion of Internet access and digital inclusion, which will guarantee the access to telecommunications networks. This Decree defines one of the bases for the 5G auction, whose public bid was approved by the National Telecommunications Agency (ANATEL) in September 2021 [148].

The introduction of 5G technology will be important, as it can spread and diversify the Internet of Things (IoT), in sectors such as public security, telemedicine, remote learning, smart cities, buildings, industrial and agricultural automation, among others. As with 4G, 5G should introduce different business models and create many opportunities in the digitalization market including buildings.

Regarding the IoT, Decree No. 9,854, of June 25, 2019, established the National Plan for the Internet of Things (PNIC), which aims to implement and develop the IoT in Brazil, based on free competition and free movement. data, in compliance with information security and personal data protection guidelines. With this Plan, it will be possible to improve people's quality of life and promote efficiency gains in services, increase productivity and foster the competitiveness of Brazilian companies developing IoT [149].

Smart cities

Smart cities use IoT to collect real-time data to better understand how resource demand patterns are changing and respond to these demands with faster, lower-cost solutions. 5G can increase the potential of IoT and become a driving force for cities to become smarter and smarter.

According to the Ministry of Science, Technology and Innovation, smart cities are cities committed to sustainable urban development and digital transformation, in their economic, environmental and sociocultural aspects. These cities act in a planned, innovative, inclusive and networked way, promoting collaborative governance and management. In addition, they use technologies to solve concrete problems, create opportunities, offer services efficiently, reduce inequalities, increase resilience and improve the quality of life for all people. As much of the emission of Greenhouse Gases (GHG) in cities is a consequence of the energy consumption of buildings, smart cities need to have increasingly sustainable buildings that use smart and digital technologies [150].

With the objective of raising the quality of life in cities through the adoption of technologies and practices that enable the integrated management of services for citizens and the improvement of mobility, public safety and use of resources, the Chamber of Cities 4.0 was launched in December of 2019. It is a forum coordinated by the Ministry of Regional Development (MDR) and the MCTI, with the participation of public and private business, government and academic institutions [150]. Thus, to debate and present solutions to the Cities, four Working Groups (WG) were created, one of them aims to discuss, elaborate and consolidate proposals for the development and technological innovation applied to the Cities.

Another relevant initiative, the result of collective efforts to build a “national strategy for smart cities”, is the “Brazilian Charter for Smart Cities”, which was launched on December 8, 2020, during the Smart City Session 2020 [151]. One of its strategic objectives is to integrate digital transformation into sustainable urban development policies, programs and actions. There should be development of projects that use mechanisms and technologies (including digital ones), aiming to increase the energy efficiency of urban infrastructure and buildings [151].

Finally, it is worth noting that the Bill 976/2021 which establishes the National Smart Cities Policy (PNCI) is being processed in the House of Representatives and its goal is to encourage the development of smart cities in the country. Based on this policy, municipalities must adopt smart city plans approved by municipal law and integrated into the cities' master plan. Citizens should participate to make these plans, showing the digital transformations they wish to see implemented in their cities. This proposal also provides for federal support in the implementation of measures defined by the municipality, since a funding must be created [152].

Data life cycle

Decree No. 9,983 of August 22, 2019 provides for the National Strategy for the dissemination of Building Information Modeling (BIM) and establishes an appropriate environment for investment in this technology. This decree also creates the Management Committee to coordinate the implementation of this strategy. In this way, the level of reliability of the projects and planning processes can be raised, since a lot of data is stored and managed which in turn improves the control of the construction work. This would generate an increase in productivity and economy in the construction of buildings and infrastructure in the country [153].

Decree No. 10,306, of April 2, 2020, establishes the use of BIM in the direct or indirect execution of engineering works and services carried out by agencies and entities of the federal public administration, within the scope of the National Strategy [154].

In any smart or digitalized system (BIM included), the data cycle is well defined, namely: generation, acquisition, storage and processing which includes data analysis. With the increase in digitalization, particularly in buildings, special care must be taken with data, especially that of individuals. In this sense, the General Personal Data Protection Law (LGPD) was passed, and it provides for the processing of personal data, in digital media, including by a natural person or by a legal entity governed by public or private law. The purpose of this law is to protect the fundamental rights of liberty and privacy of individuals.

Complementing the LGPD, on July 8, 2019, Law No. 13,853 was enacted, creating the National Data Protection Authority, which is a public administration body that is responsible for ensuring, implementing and monitoring compliance with LGPD throughout the national territory [155].

2.3.4 Final considerations on regulatory instruments

It can be concluded that, in Brazil, there are relevant regulatory instruments that can leverage the process of digitalization of buildings in the country with a focus on energy efficiency. However, digitalization requires huge investments in new technologies, infrastructure and training. An example of this is 5G technology that will have a specific auction in 2021/2022.

Labeling policies, whether for equipment or buildings, may consider the use of digital technologies to achieve higher levels of energy efficiency. Furthermore, in the Ten-Year Energy Efficiency Plans, more emphasis should be given to digital technologies, with the same purpose.

In addition, policies related to smart metering should be aligned with policies regarding smart cities. Energy measurement instruments should be introduced to systems that connect the various objects (IoT), in order to improve the energy management of buildings in cities.

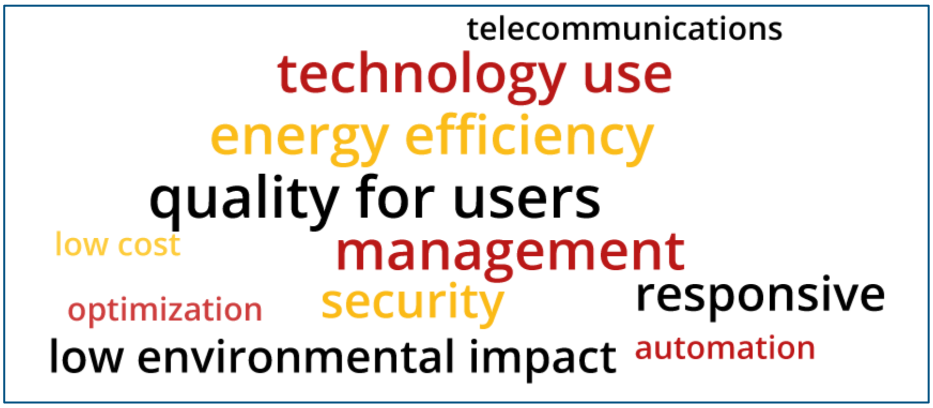
2.4 "Intelligence" adopted in the operation of buildings in Brazil and worldwide

Although the term "intelligent buildings" is gaining in popularity, its definition can be ambiguous or even vague. More than thirty variations for the term were already accounted for [156] at the beginning of the century and this number has been increasing recently. Therefore, a more in-depth investigation into its definition was deemed necessary. A bibliographic survey of the main existing definitions was carried out, which are presented below:

- "Production of a smart architecture as a whole, instead of using smart components. Response to climatic conditions through bioclimatism, but with a technological bias" [157];
- "A building with complex telecommunications, management and automation systems" [260];
- "One that is designed and built to give quality environments to meet the user's long-term needs" [158];
- "Any building that allows an agile and effective response to obtain its commercial objectives" [159];
- "It is the one that has an interdisciplinary effort to integrate and optimize its structures, systems, services and management in order to generate a comfortable environment, with low environmental impact and with the best cost-benefit" [160];
- "One that integrates technology to create a safer, more comfortable and productive environment for its occupants, while simultaneously being more efficient during operation for its owners" [160];
- "They are able to obtain information and respond to their own demands in an integrated manner" [161];
- "They link the physical and virtual environments through technology, resulting in environments that are energy efficient, comfortable and safe for users" [162].

The definitions vary widely. Some emphasize the need for a comfortable environment for users, but do not to mention the use of technologies [158; 160]. Although intelligent buildings need individual elements for their operation, what characterizes intelligence is its operation in an integrated manner [157]. The role of technologies is emphasized to achieve safer, more comfortable and productive buildings with benefits for both users and owners. It is noticed that some characteristics stand out as common points. A word cloud with the most recurrent characteristics found in the definitions of "intelligent buildings" is presented in Picture 2.

The analysis of the different definitions allows us to perceive the common guidelines that define the intelligence adopted in buildings, both in Brazil and in other countries. They are good architectural design quality considering the simulations of local climatic conditions, automation and integration of equipment and systems management, technology placed at the customer's service in terms of information and control, energy efficiency, reduced consumption of energy inputs, energy sustainability and, to a lesser extent, integration with the surroundings and the electricity sector.



Picture 2 – "Intelligent buildings" word cloud. Source: Made by the authors.

3. Analysis of technologies applied to the management of building demand and surroundings

This chapter addresses the technologies used in four issues related to building demand management and building surroundings. The management of energy-consuming equipment and connected buildings that deal with management and control technologies, smart meters that connect to the electrical grid of electric energy utility companies, showing international experiences in the implementation of monitoring and smart management systems (smart metering).

Finally, the assessment by third parties of the actual use of energy and the level of efficiency/sustainability of the building through certification is presented, with special emphasis on the application of remote inspection technologies, according to guidelines established in the ABNT NBR ISO 19011 Standard: 2018 [4].

3.1 Management of household appliances, lighting and air conditioning

The form and amount of energy consumed in a building depend on several factors such as the behavior of users, the technologies of the equipment and its controls, the performance of the administration of the building, external factors that interfere in the impact of this consumption, such as different electricity tariffs among other factors. The purpose of a building is to carry out the activity for which it was built with adequate environmental comfort for its users and service with the lowest possible energy consumption.

The management of home appliances, lighting, and air conditioning systems can be directed by two different purposes. They depend on the regulatory environment to which the buildings that contain them are subject.

The first is management to reduce energy consumption, in this case three technology families stand out: those aimed at energy measurement; those aimed at energy management; and the technology of the equipment itself, if they are efficient and manageable.

Within the scope of the first two families, the technologies already presented in item 2.1 and detailed in item 2.1.3 stand out:

- Building management systems (BMS) [14; 39; 81; 84; 85; 87; 88; 90; 91; 93; 94; 97; 102; 107];
- Smart sensors, actuators and switches;
- Virtual Assistants [115];
- Smart apps and controls;
- Smart sockets [81; 84; 94];
- Digitally Addressable Lighting Interface (DALI) [14; 108-114].

Such digital technologies enable the control of home appliances, lighting and air conditioning to consume less energy, and help change users' habits. Smart apps and controls give visibility to information of consumption and help users to save energy. Smart controls, virtual assistants and smart switches facilitate control of these devices. Management of more complex buildings such as commercial and public uses the technologies of Building Management Systems (BMS) and Digital Addressable Lighting Interface (DALI).

Regarding the technologies of equipment and systems themselves, we often see the availability of increasingly efficient technologies in the market. These technologies are supported by a vast literature and are outside the scope of this study. They are driven by various public policy instruments, such as the PROCEL Seal. The emerging technology of grid-connected smart electrical and electronic equipment combines communication technology and remote control in home appliances, making them smart. They can be easily controlled by such management technologies or by the user himself. Smart switch and smart socket technologies make it possible for appliances and systems that are not built with embedded intelligence to be controlled as well.

The management of home appliances and lighting systems in order to save energy is strongly boosted by digital technologies, making it possible to change user habits, automatic manage of loads and monitor online important quantities in consumption.

The second purpose is demand management to minimize electricity bill costs. The volumes of power and energy required become important. This issue strongly depends on the regulation of the electricity system to which the building is inserted. Currently in Brazil, tariff group B for consumers served at voltages below 2.3 kV has a monomial tariff, that is, it has a constant value at any time of the day, unless you opt for the white tariff that differentiates the tariff price throughout the day which was explained in item 2.3.3. Consumers in tariff group A receive electricity at voltages equal to or higher than 2.3 kV (high voltage), using three-phase branches, or are served by an underground secondary voltage distribution system. These consumers do not have the same tariff price throughout the year, they are subdivided into several classes that may have demand and energy values that vary according to the time of the year. In group A, there are large shopping malls and commercial and public buildings.

For commercial and public buildings in group A, it is essential to use technologies that allow the user to manage their load, especially air conditioning, which in these buildings generally corresponds to more than 30% of consumption, so that during the most expensive tariffs they can minimize the demand and the energy required. The technologies of Building Management Systems (BMS) and sensors, actuators and smart switches are essential for this management. See item 2.1.3.

With the digitalization of the electricity sector, through the adoption of digital technologies such as smart meters and smart grids, associated with the regulatory change in this sector in order to make it more flexible, infinite possibilities for interaction between buildings and the electricity sector opened up. Especially if this flexibility extends to the residential sector.

In this future context, smart metering can be used to work closely with demand response technology and interact with smart grids. This interaction provides real-time pricing information that helps building managers implement specific policies to reduce energy usage during peak periods, thereby reducing costs and leading to better energy usage. It also allows utilities to manage demand and supply in a balanced and effective way, which is good for the functioning and operation of the entire grid.

Demand response technology can link to the smart grid for mutual negotiation between demand providers and dynamic pricing of public services. This would mean that building energy consumers would actively monitor the grid side, power supply conditions and prices, and shut down some loads to reduce some of the energy consumption to avoid expensive energy usage during peak hours, or drive your own power generators to meet real demands.

In several developed countries such as the USA, utility companies offer differentiated tariffs if both industrial and residential users allow the utility company to remotely turn off some of its load under certain conditions. In the residential case, the use of IoT in these devices is common.

Demand management adds another cost reduction vector to energy saving management that seeks to improve energy efficiency in buildings.

3.2 Management of connected buildings and smart districts

The previous items elucidated the use of technologies in buildings, in the different phases of their life cycle, and how they can help in improving energy efficiency as well as in the management of other resources. However, when the buildings are analyzed together, there are new possibilities for optimization and sharing. They range from the adoption of specific technologies and the integration between them, as well as the possibility of shared management of assets, aided by digital artifacts [11; 101].

Therefore, it is important to verify possibilities for buildings to operate together and the most appropriate restrictions and conditions to obtain greater benefits for the district. By restrictions, one means the limitation to share installations between buildings (for example, in many cities there is a prohibition of sharing installations between buildings under or on public roads), sectors of cities whose Master Plans do not allow different uses, availability or not of infrastructure and services such as gas, water, sewage, electricity, structured telecommunications networks (telephone, cable, fiber optics, cellular and 4G/5G signals), etc. More suitable conditions are considered the occupation with multiple uses because needs are heterogeneous and, consequently, the consumption pattern of each asset is not concentrated (between the units), favorable weather conditions for the installation of distributed generation with renewable energies, local availability of electrical energy storage systems, space to create specific reservoirs for different categories of water, etc.

There are, however, several possible approaches to defining a smart district, depending largely on who is starting the initiative. When the starting institution is the government (city halls, for example), in general larger areas, such as small neighborhoods can be covered, and shared systems are managed by incubated companies and specific service providers. In these cases, there is more flexibility regarding legislation, zoning and infrastructure distribution, as well as the scope of action is expanded to more general urban issues, including smart mobility, public lighting systems, urban equipment, etc.

In this context, each building can remain connected to the grids of the utility companies and the companies providing additional services with smart metering for each asset and with specific rules and criteria for sharing it with the surroundings and utility companies.

The balance of the district's assets may or may not be taken into account in the management optimization process. To consider it (and thereby increase the benefits of this strategy) it is necessary to adopt a fractal measurement structure, in which a large-capacity smart meter is installed at the entrance to the district, others are installed to serve more restricted sets of buildings, each building adopts its own meters, and each building unit is also measured. Eventually, depending on the building typology, the sub-measurement and control strategy, such as smart apps and controls, smart sockets and smart electrical and electronic equipment connected to the grid, can still be adopted in the context of the units, which is fundamental for the contractual apportionment (proportional) and the composition of costs and benefits among users.

With a hierarchically defined structure, the asset balance closest to zero is the target. That is made using automation models and smart contracts, in real time, from the smallest instance to the largest. That is, first the unit seeks to maintain a neutral balance, compensating only what is necessary with the immediately superior instance, and then balance the needs and offers of each unit, its areas and common infrastructure [16], only then exchanging surpluses and demands with the subset of buildings it integrates (a block, for example). The set of buildings then seeks a neutral balance between the buildings that comprise it, then moving on to exchanges between sets; the district pursues the balance between the assets of the complexes and their common infrastructure (distributed generation, public lighting, integrated transport systems, qualified cogeneration systems, heat pumps, etc.); and only then does the district consume or release its surplus to the utility companies, taking into account issues related to dynamic tariff and demand response programs. This type of approach favors more autonomy for each of the sharing spheres and causes the demand for external services to be naturally lower. Furthermore, it allows the utility companies to communicate actively with the district, allowing the displacement of load without loss of functionality and relieving peak hours.

Other possible drivers include the sphere of management of large condominiums with their own urban structure, in which a logic similar to the one detailed above is repeated; and, to a lesser extent, managers of buildings located on the same block, respecting the fractal logic of the instances involved.

Although the main focus of this item is the treatment given to demand management and the technological solutions that are possible and, therefore, to the operation of the district, it is important to consider that the means for such management must be provided for in specific integration projects, as well as the careful monitoring of renovations or new constructions so that they do not negatively affect its operation. It is also important to foresee the infrastructure for assets that provide resilience to the set as shared services [117], such as renewable energy generation systems, solar thermal heating, shared hot water supply systems, thermoaccumulation tanks, water supply systems, cold water and/or refrigerant fluids (for air conditioning), collection systems, treatment and storage of rainwater and/or wastewater, etc. For that, the classes of solutions related to simulation, such as Urban Energy Modeling, Computational Fluid Dynamics, Simulation of natural and artificial lighting, Software for life cycle assessment and energy portfolio management systems are essential.

For the operation phase, information management itself is essential, as well as automation protocols and associated technologies. This means that technologies for transversal provision of IT infrastructure, such as cloud computing; integration, such as BIM and energy portfolio management systems; transaction registration and automation, such as Blockchain, its smart contracts, artificial intelligence and associated hardware (sensors, actuators and smart switches); those that support demand response [11], enhanced by user information tools [163] and gamification, such as smart sockets and (two-way) chargers for electric vehicles (which can function as batteries or no-breaks to assist in the displacement of vehicles load), are essential. The main digital solutions and strategies that influence the management of connected buildings and smart districts are presented below.

Building Information Modeling (BIM) [41; 58; 94; 153; 164 – 167]

BIM technology has the potential to be applied to districts (and even entire cities, in which case it is called City Information Modeling – CIM), as long as there are shared facilities and equipment for community use, thereby creating additional layers of information, whose people in charge may be different from those responsible for the BIM models of each building, as long as they share the same CDE, so that they remain common to all buildings in the District. In this context, it describes in detail community infrastructure systems, such as: district lighting (analogous to public) and sings; information and communication systems; water storage and treatment systems; sewage treatment systems; solid waste processing stations; power generation systems; centralized water heating and cooling systems, as well as their distribution lines; management and control rooms and systems. Energy efficiency is also similar to that described for buildings.

Urban Energy Modeling (UBEM) [63; 115; 168]

When performing the Building Energy Modeling on an urban or district scale, the term Urban Energy Modeling (UBEM) is often used. This method allows the study of the thermal behavior of the buildings envelope in order to measure the impact of the entire district on urban heat islands. Such simulation has become increasingly used in the context of mitigating climate change and increasing thermal comfort on an urban scale. It is also possible to simulate a set of buildings located in the district, in order to minimize their impact on energy consumption according to legal guidelines.

Computational fluid dynamics (CFD) [26-29; 33; 34; 36-38;169- 171]

Considering climate change and the rapid trend towards urbanization, computational fluid dynamics has gained importance in the modeling of natural ventilation with interest in the surroundings of buildings, aiming to analyze the interference of buildings' characteristics and the effects of verticalization on air flow in urban networks, indoor environments and energy demand. CFD has been used, above all, for investigations regarding the formation of stagnant areas (wind shadows), identification of "heat islands" or urban temperature forecasts, geometric optimization of buildings, air recirculation zones, turbulence, acceleration or reduction of wind speed, delays in the transfer of heat from surfaces to the air, among other possibilities.

Simulation of natural lighting [55; 172-175]

Among the factors that can impair the performance of lighting systems and cause discomfort due to glare to the user are those related to the built environment, such as verticalization, geometry and reflectance of exterior surfaces (floors, facades and roofs), especially glazed surfaces. Computer simulation provides guidelines to improve the distribution of light intensities within environments because it enables more in-depth studies on the availability and quality of natural light received by a building, not only because of its orientation in relation to the solar trajectory, but also as a function of the occupation of the land and surrounding urban morphology.

Urban modeling programs also help to reduce energy consumption and achieve environmental comfort for different types of users by considering other issues in lighting simulations, such as the need, in hot climates, to protect pedestrians from solar radiation (vegetation), but without interfering with the photovoltaic generation potential of the roofs (self-shading between buildings, for example) and the entrance of natural lighting into the buildings. This dynamic is opposed to conventional design processes, where many of the decisions are based on investigations and assumptions derived from professional experience or supplier indications, and not related to performance analyses.

Energy Portfolio Management Systems [44; 70; 71; 176]

Energy portfolio management and simulation programs are applicable and useful to institutions that have several assets that consume or generate energy and other resources and can be viewed in different ways, depending on the cluster instance in which they are managed. Municipalities or large corporations can use the technology to manage the energy balance and other resources of buildings, as well as other equipment of common use, such as renewable distributed generation assets, water, sewage and waste treatment plants, electric transport grid, public lighting and sings, and others which make up its portfolio. Buildings connected on the same block can use the tool to manage their joint balance and each building manage the balance between its units. The analyses are useful to identify unexpected variations, indicate maintenance, suggest improvement measures or larger interventions aimed at energy efficiency and in the management of other resources.

Software for Life Cycle Assessment (LCA) [61; 62]

The influence of LCA in the district starts with the choice of its location, with preference being given to those that favor a low-carbon lifestyle, with plenty of public transit or with a prioritization of electric vehicles. The potential for integrated operation stands out both in the construction phase, reducing the environmental impacts of transporting materials, equipment and the construction site, and in renovation and demolition. Concerning operation, the district can benefit mainly from optimizing the generation and demand of renewable energy through bidirectional meters, which in some cases can minimize or eliminate the need for batteries.

Blockchain [20; 177]

In districts, similarly to what was reported in the operational phase, the main application of Blockchain is at the level of dispatch of energy produced and consumed by the buildings that integrate it, facilitating the internal balance before the exchange with the supply grid which increases the efficiency of the system and reduces possible costs for the use of utility companies' infrastructure (grid cost in different modalities). Dispatch control also applies to other assets, with or without embodied energy and with different fungibilities, such as: rainwater for non-potable purposes; cold water (for air conditioning systems); hot water, etc.

Smart sensors, actuators and switches [33,39, 49, 50, 99]

Smart districts must actively manage energy consumption and the flow of energy between buildings, consumers in public space, and possible generation of electricity and other energy inputs. The districts demand the use of hundreds of sensors and actuators that work as part of the hardware that operationalizes the flow of assets, governed by specific rules in software platforms, equipped with artificial intelligence, capable of processing big data and recording transactions and dispatches via Blockchain.

Smart sockets and chargers for electric vehicles [181; 182]

The search to implement the philosophy of smart districts can also boost the penetration of this technology in the building sector. Electric vehicles can also act as energy storage devices, demanding better communication, measurement and management of the energy consumed and offered in relation to the buildings that are part of the district. In the future, the management of the charging stations in the districts will be an important demand management tool, both for consumption and for energy generation.

Demand response, awareness and gamification apps [11; 13;46; 113; 114; 183]

In districts, demand response may involve balancing the district's energy in a planned way to reduce demand at peak times before switching with the energy provider or utility company, adopting common infrastructure (generation, storage, thermoaccumulation, etc.) to enable demand flexibility without loss of functionality. For this, smart meters need to be programmed together to optimize dispatch in the district, which can be enhanced using Blockchain in addition to sensors and actuators. The practice of increasing information related to energy demand and consumption and the use of gamification strategies (with local financial benefits or not) can be very interesting to stimulate competition between the units that make up the district, creating a culture of reduction of demand.

Cloud computing [47; 48; 98; 99; 163]

In districts, cloud computing can work to integrate information from the various buildings that are part of it, however, the infrastructure for signal replication is considerable. This issue is expected to be definitively resolved with the advent of 5G. On the other hand, it is essential to guarantee the scalability of an integrated system, without the need for extensive planning to build a compatible IT infrastructure just by increasing the contracted storage and processing capacity, as more digital applications start to be produced.

3.3 Smart meters and their role in building management

In order to obtain more energy efficiency gains in buildings, energy meters, especially electricity meters, play a decisive role in ensuring better energy management in the building. However, there are other smart metering technologies that can and should be used in buildings, in order to obtain more energy efficiency gains. In this way, the technologies used in the management of other resources, such as water and waste, for example, must also be considered, since there is a causal relationship between energy consumption and some use of these resources. An example is the increase in consumption of water which will also increase consumption of electric energy used by water pumps.

In addition, the smart metering technologies used to measure the various parameters of buildings are not restricted to electricity meters. In fact, a smart metering infrastructure must be composed of equipment that measures energy quantities (smart meters included), of systems and software that store, manage and analyze the data measured. In this section, the following smart metering technologies are covered:

i. Smart meters;
ii. Building Management Systems (BMS);
iii. Virtual assistants;
iv. Smart sockets;
v. Electric vehicle chargers;
vi. Blockchain;
vii. Building Information Modeling (BIM).

These technologies are described below by life cycle phase and by building typology. Next, an overview of the smart meter market in Brazil is presented. Finally, some international experiences in the implementation of monitoring and smart management systems are discussed.

3.3.1 Smart metering technologies and their use by life cycle phase and building typology

All of the smart metering technologies discussed in this section can be used in the operating phase of buildings. Among these, only two - Blockchain and Building Information Modeling (BIM) - can measure quantities to be carried out in other phases of the life cycle besides the operation. It is worth mentioning that, although the focus of this section is on smart metering technologies, the business models that such technologies can enable are discussed as whole which is the Energy-as-a-Service (EaaS) business models. They are centered on the consumer, which emerged to share and monetize the value created by the increased digitalization and decentralization of the energy system [186; 187].

Smart meters

There is no formal definition for smart meters. These can be considered as electronic meters that have more advanced functionality [177], especially related to two-way communication. In Brazil, INMETRO classifies energy meters into two types: electromechanical and electronic [177]. Therefore, all smart meters are electronic meters, but not all electronic meters are smart meters, the latter use a communication infrastructure [177; 188].

The smart meter must be able to measure and store data at specific intervals, as well as act in the interface between energy suppliers and consumers, through two-way communication. This communication becomes feasible due to the implementation of AMM (Automated Meter Management) devices. The most simplified versions of electronic meters, AMR (Automated Meter Reading) offer simple one-way communication, from customers to utilities. However, a more comprehensive concept is the AMI (Advanced Metering Infrastructure), which uses embedded AMM-type smart meters and a communication structure which is characterized as the measurement system of a smart electrical grid [189]. Among the communication technologies most adopted to integrate the meter to this network, ZigBee, Power Line Communication (PLC) and Mesh grid stand out.

Smart meters must have memory for storing consumer information, as well as an interface so that information can be exchanged between the consumer and the utility company, the gateway. The security and control of communication via this gateway is essential to guarantee the integrity and privacy of the data exchanged. Another way to establish a secure communication is the use of VPN (Virtual Private Network), as this network can guarantee a secure communication path, in addition to encrypting transmitted/received data [106; 190].

In its minimal version, the meter can provide consumption data for the past hours, days, weeks, months or year. In addition, through apps or systems of energy providers, it is possible to present the data per consumer unit, transmit them to the utility company for billing purposes or make them available to a third party for value-added services that might be defined [106].

The magnitudes that some more modern meters are capable of measuring are: active and reactive energy; active and reactive power; quality indicators (records of the frequency and duration of power outages, voltage, and current information). In addition, this equipment must have a user-friendly interface for consumers, to be able to monitor and manage their consumption, as well as the tariffs related to various measured quantities. Monitoring and management may use other technologies such as building management systems (BMS) and virtual assistants.

Some smart meters are capable of enabling real-time pricing by linking electricity price signals directly to “smart” appliances. Thus, consumers are provided with information about their consumption pattern, which makes it possible to manage their consumption. However, additional functionalities go beyond measuring energy consumption of end users, i.e. allowing them to be used in demand-side management apps. Depending on the application and payment methods, there is a variety of meters that can be used.

The smart meter can be used in any typology of building to replace the electromechanical meter, which is still being widely adopted in the Brazilian market. Basically, this meter will be used in the operation phase of the building and can improve the interface between the user and their equipment. In addition, the smart meter must be able to measure in both directions, measuring not only the energy consumed by the consumer unit, but also the amount of energy injected into the electrical grid. This functionality allows consumers to have their own generation, known in the electricity market as distributed generation [136]. As a result, consumers are able not only to consume energy from the utility company but can also install his own generation system in his building (solar photovoltaic, for example), thus being called a prosumer.

The digitalization process is not only happening in the electricity market, but also in those sectors that sell other utilities, such as water and gas. In the case of water supply companies, a natural advance for more conservation of this important natural resource is the use of digital water meters, which can be installed in buildings.

In the same way as smart electricity meters, digital meter technologies used in other utilities can be used in any typology of building in the operating phase. This may enable the use of shared communication networks between the various utility companies (electricity, gas, water, etc.) [191].

Building Management Systems (BMS)

Building management and control systems are smart management systems, responsible for controlling and monitoring mechanical and electrical equipment/systems in a building [58], such as HVAC, lighting, power generation systems, fire systems, and security, among others. These systems allow the integration of various smart metering technologies so as to reducing the building's energy consumption, improving comfort and increasing productivity [192; 193].

Management and control systems can be used in the operation phase in any typology of building, with the goal of improving the management of its resources. In addition, these systems can and should be integrated with other smart metering technologies that will be described in this section, in order to further improve the management of building operations. It is important to highlight that, for social interest housing, there is a restriction from an economic point of view and not of the use of technology in itself.

Virtual assistants

A virtual assistant is a software that can perform tasks or services for an individual by using voice command [194]. This kind of software can interpret human speech and respond with synthesized voices. Using voice commands, users can ask questions to their virtual assistants, control home automation devices and manage other basic tasks [194].

The use of virtual assistants in buildings takes place in the operation phase and they are often used in residential buildings to control devices such as smart sockets, which can even measure electrical energy consumption. This functionality enables better energy management by the user in their home.

Although the greatest use of this technology occurs in residential buildings, nothing prevents the use of these devices in public and commercial buildings. In social interest housing, a low penetration of this technology is expected, considering the other priorities of its users.

Smart sockets

Smart sockets are electrical devices that allow ordinary appliances to be connected to the internet, becoming "smart". They also enable people to monitor energy use and, in turn, manage how they use this resource [196]. This monitoring is done via Software, including virtual assistants, which can be used on smartphones or computers.

The use of such technologies in buildings takes place in the operation phase and it is more used in residential buildings. Although the greatest use of this technology is in homes, nothing prevents its use in public and commercial buildings. This technology, regarding social interest housing, is expected to have low penetration since its users have other priorities.

Electric vehicle chargers

The EV Charger is an electric vehicle charging station capable of providing electrical energy to charge the batteries of plug-in electric vehicles (including hybrid vehicles, trucks, buses and others) [197]. Since batteries can only be charged with direct current (DC), most electric vehicles have a built-in AC-DC (Alternating Current – Direct Current) converter, making it possible for these vehicles to be plugged into a common household AC electrical outlet. As a result, electric vehicle chargers can be present in public or private charging stations in various types of buildings, including residential ones. Many commercial and service buildings, as well as public ones, have electric vehicle chargers in their parking lots and these devices are used in the building operation phase.

In addition, there are several business models that allow the integration of the electric vehicle into the building, thanks to electric vehicle chargers. Brazilian legislation only allows the G2V (Grid to Vehicle) business model, in which the vehicle is connected to the electrical grid and consumes energy, and the electric car is prohibited from supplying energy to the grid. In this case, the energy measurement direction is unidirectional.

In some countries, however, in addition to G2V, V2G (Vehicle to Grid) is allowed. In this case, the electric vehicle battery can be a backup for the electrical system, enabling the car to send energy into the electrical grid at times of greater demand by the system. In some countries, it is not allowed to inject energy directly into the grid, but into buildings (V2B or Vehicle to Building). In both business models, the direction of energy measurement must be bidirectional [197], so that the mode of injection of electrical energy into the system can be enabled.

With a regulatory environment that allows V2G or V2B, electric vehicles can get a larger share in the automotive market in Brazil. Furthermore, a policy in this sense would bring flexibility to the electric power system, making it much more efficient [197].

Blockchain

Blockchain technology can be used in smart contracts and that means that this technology can be used the operation, in the construction, and renovation phases. This allows tracking of various processes in these phases of the life cycle, such as material inventory control, workforce, available technologies and environmental conditions, which could impact the physical progress of the work. Thus, along with other technologies such as IoT and Big Data, Blockchain and smart contracts create an integration environment that can streamline the construction and bidding supply chain (for purchase, procurement and provisioning) [198]. This technology can be used in any of the five typologies of buildings analyzed and as also in the construction, operation and renovation phases.

In addition, in the operational phase of the building, Blockchain can revolutionize the way energy is consumed, since it makes it possible to establish a hierarchy of priorities in relation to the generation sources at its origin. This allows renewable energy certification processes to be streamlined and automated, as there is a greater degree of traceability of where the energy consumed by the building comes from, if it is supplied by a 100% “green” source. These agreements play a key role today, as they promote the growth of renewable energy by encouraging the purchase of this type of energy by large corporations [199].

Through smart contracts, the use of Blockchain technology also guarantees the transparency and security of the transactions carried out, as the data is permanently recorded on a platform, which allows all parties to audit the information defined by the contract.

Building Information Modeling (BIM)

BIM can be used in all typologies of buildings and in all phases of the life cycle. However, in single-family residences and social interest housing (SIH), the cost-effectiveness of adopting BIM at all phases of the life cycle must be evaluated. Perhaps in SIH, if the technology is used in subdivisions, it may make economic sense for construction companies.

In the design phase, with the use of BIM it is possible to measure the design parameters (costs, for example), the characteristics of the place where the project will be built (environmental and zoning) and the attributes related to the shape of the building (architecture and structure of the building). This makes it possible to estimate the quantities of materials and the prices of the equipment of the systems [5]. In the construction phase, the entire process of acquiring services and goods from suppliers, as well as the assembly of equipment, can be measured and monitored [5]. In the operational phase, commissioning (eg, equipment testing), occupancy and maintenance management may have their own indicators that can be measured and monitored [5; 7]. In the renovation phase, the designer can, with the help of BIM, evaluate the impact of using different energy efficiency measures on energy consumption and the final cost, using the Performance Measurement and Verification (M&V) process [9]. Finally, in the final phase of the building's life cycle, the entire inventory of planning, budgeting, work control, commissioning and operation activities can be used to help define the most appropriate destination for the waste generated in the demolition phase of the building [7].

3.3.2 National smart meter market

Smart meters can be used in any typology of building and basically in the operation phase. The potential for energy savings in existing buildings is often cited as one of the great benefits that this equipment can offer [177]. The energy benefits generated by smart metering vary according to the building typology, tariff structure and other associated systems and infrastructure. Furthermore, the reasons for installing smart metering in the various typologies of buildings are different.

Regarding applications by typology, electronic meters were initially installed in Brazil in single-family buildings, especially those of social interest with the motivation of reducing non-technical losses or energy theft. This first initiative was carried out by Ampla utility company (today, Enel Distribuição Rio). The company, in order to obtain significant and lasting results in reducing these losses, decided to adopt a structural solution based on the implementation of a new electrical grid topology, that is, a “shielded network” that the company called the DAT grid (Transversal Aerial Distribution), whose meter used was electronic [132]. Since then, the use of electronic meters has become a reality in many energy distribution concession areas in the country.

The theft of energy created the first and, perhaps, the most important market for smart metering in Brazil. Electric power utility companies must invest in tools that can reduce non-technical losses in their concession area, as ANEEL establishes maximum levels of these losses (target regime), which must be recognized in the electricity tariff [201]. It is worth mentioning the importance of this regulatory instrument for increasing energy efficiency, since consumers who steal energy are not concerned with its conservation, when compared to those who pay their light bill on time [200].

Another important initiative in the electricity distribution market are the pilot projects to implement these networks/grids. They aim to implement smart electric grids and, consequently, smart metering in Brazil [189]. The pilot projects used resources from the Research and Development Program of the National Electric Energy Agency (ANEEL). 43 projects registered in this Agency's information bank refer to the development of smart networks and cybersecurity for networks, smart metering, communication or processing intelligence [106]. These projects were started in 2010 and completed in 2016, totaling an investment of around BRL 276 million, according to their budget estimate [106]. Some of the pilot projects focused on the consumer and the main purpose was to study the different conditions of operation of a network with minimal digitalization in the meters.

Since 2012, when ANEEL's Normative Resolution No. 482/2012 [136] came into force, consumers were able to generate their own electricity, including supplying the surplus to the distribution network in their location (prosumer). Thus, the consumer of any type of consumption, including residential, government, products and services, can install mini and micro distributed generation. This resolution also establishes the energy compensation system, which is a system in which the active energy injected by a consumer unit is transferred to the local utility company, generating credits for the consumer. Subsequently, this energy is compensated, when the consumer needs this amount of energy [136].

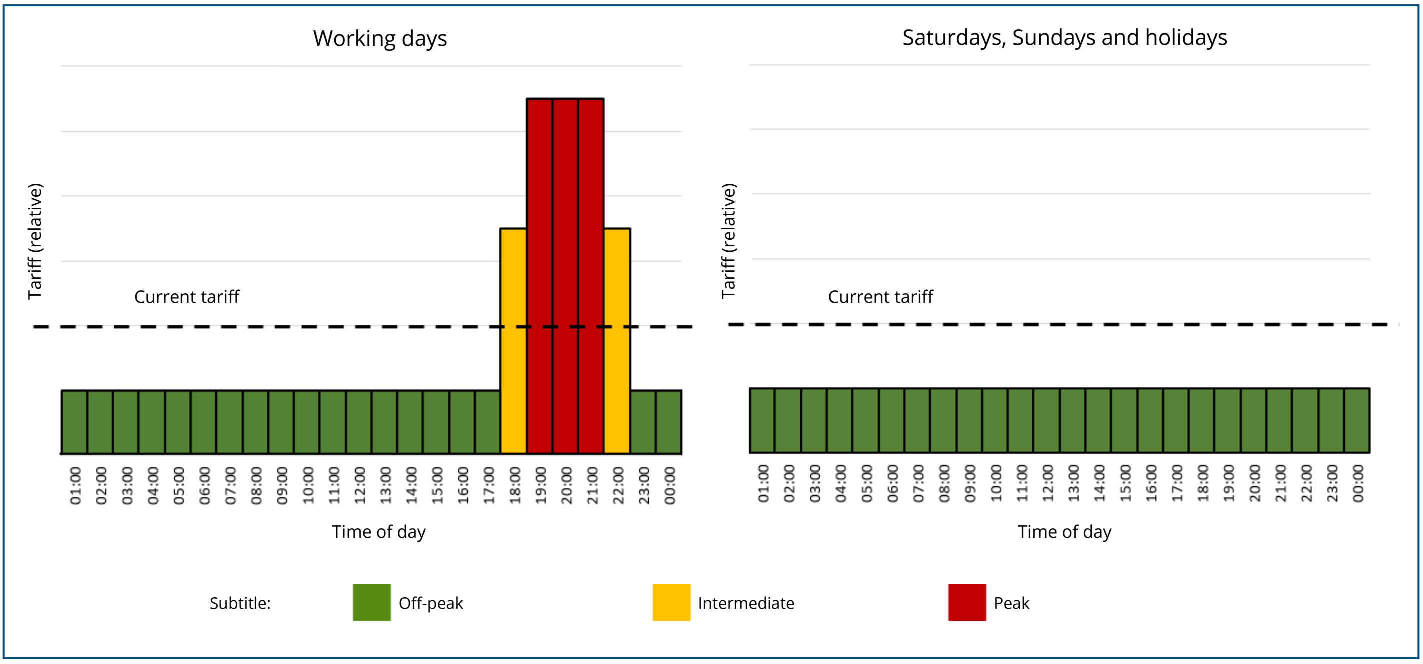
To make this compensation system technically feasible, it is necessary for the utility company to install a bidirectional meter or two unidirectional meters in the consumer unit. Thus, it is possible to measure the energy that the consumer gives to the utility company and consumes from it. There is a tendency to use electronic or smart meters in compensation systems, but these meters are not necessarily used in all utility companies in the country. As the distributed generation market has grown strongly since 2012, thanks to the photovoltaic energy, there is an expectation that smart meters that are used in energy compensation systems will be increasingly adopted.

Smart grids have several benefits in the control and operation of the Brazilian electrical system. They create new products and functionalities that can open up a range of new services which will require a more active posture on the part of the consumer, and a better understanding of their consumption habits and more power of analysis for decision making. These new services are made possible with the installation of smart meters in buildings, allowing the consumer to manage their electricity consumption in real time, the remote activation and disconnection of loads from their residence and, perhaps the most relevant, the possibility to choose between different tariffs or energy prices throughout the day [201]. In this manner the consumer is empowered because he becomes no longer a passive agent in the process of energy consumption, but a fully active agent, and this is due to the fact that it significantly increases the power of choice of products that can be offered by electrical energy providers [201].

One of the first initiatives in this regard was the establishment of an hourly tariff for low tension consumers, called the white tariff, which is regulated by NR nº 733/2016. This fare has different values at peak and off peak, in addition to an intermediate value. Picture 3 shows the tariff structure for low voltage consumers in Brazil, showing the peak, off-peak and intermediate billing time units. Note the differences in these rates on working days (graph on the left of the picture) and on Saturdays, Sundays and holidays (graph on the right).

When it offered this new tariff structure, ANEEL's objective was to encourage a more efficient use of the electrical system, using price signaling as a mechanism to induce load modulation. In other words, it is more expensive to use energy at times when it is most demanded, that is, at intermediate and peak times [201].

It is worth noting that the adoption of the white tariff is optional and, therefore, a significant number of smart meters have not been installed in Brazil. In addition, it can be seen that there is no dissemination of information on this policy by competent agencies, which translates into its low effectiveness so far.



Picture 3 – Tariff structure for low voltage consumers in Brazil. Source: Made by the authors.

However, this presents the opportunity to increase the coverage of the smart metering market in the country, if a policy of dissemination of information on the white tariff is adopted.

In addition to this policy, two policies that can leverage the smart meter market in Brazil are being discussed within the scope of public hearings and consultations: the energy prepayment modality and the binomial tariff [142; 143]. In addition, with the growth of the electric vehicle market in the country, there is yet another opportunity for the growth of smart metering in buildings.

The recent study "Use of new digital technologies to measure energy consumption and energy efficiency levels in Brazil" [106], launched in 2021, addressed this issue highlighting that the opening of the electricity market, which has been discussed since Public Consultation nº 33 of 2017 started, can expand the smart meter market in Brazil. In this sense, the creation of the energy aggregator, agents that bring together different Distributed Energy Resources (DER) and form virtual plants, can also contribute to the expansion of smart metering in the country [106].

In summary, the smart meter market has great growth potential in the country, thanks to the current regulatory framework, and it also presents the opportunity to leverage the market for other smart metering technologies addressed in this item. In a scenario of adoption of these technologies, energy efficiency gains in buildings can be achieved, since, with the information generated by a process of digitalization of the energy sector and the building sector, consumers will be able to make more rational decisions regarding the use of electricity and other resources.

3.3.3 International experiences in implementing smart metering and monitoring systems

At the end of the first decade of this millennium, investment decisions in smart electric grids were motivated by international agreements to mitigate the impacts caused by greenhouse gas (GHG) emissions. At that time, the Kyoto Protocol was in effect. Thus, the adoption of renewable sources, the development of electric vehicles and the increase in energy efficiency were some of the measures that could impact the reduction of GHGs. In addition, another reason was that some countries decided to adopt smart grids to modernize their electrical grids which were aging and obsolete. Table 12 summarizes the main drivers for implementing smart grids in the US, European countries, China and Japan.

Table 12 – Summary of the main drivers for the deployment of smart grids in different countries. Source: [189].

Country/Region	Main motivators
USA	Technological agenda for economic recovery
	Obsolete infrastructure
	Distributed generation
	System reliability, security and efficiency
	Use of electric and hybrid vehicles
Europe	Integration of various renewable energy sources
	Aging infrastructure
	Use of electric vehicles
Japan	Energy diversification (nuclear accidents)
	Use of electric vehicles
	Implementation of "Smart Cities"
China	Implementation of "Smart Cities" and global leadership in IoT
	Energy efficiency
	Energy diversification (renewable sources)

Smart meters are enabling technologies that provide more energy savings, as they enable more efficient management and operation of energy resources and changes in consumer behavior [106;203;187]. The process of dissemination and implementation of smart meters in European Union countries was basically due to the publication of Directive 2009/72/EC [203]. According to this Directive, the implementation of smart meters, subject to a positive economic analysis, should be used by at least 80% of consumers in the bloc's member countries by 2020 [190]. Most member countries managed to reach the target of 80% of meters installed by 2020, with some reaching the target before the 5-year deadline (Sweden, Italy, Finland and Malta) [204].

Regarding the basic functionality of the measurement systems, the publication of Recommendation 2012/148/EU established the basic characteristics of smart meters that should be present in the market of the bloc countries. [205]. However, it was observed that 80% of EU member countries wanted to have all ten features available to their electricity consumers and 50% wanted to do so for free [204]. In addition, all member countries have provided information on the functionality of their smart meter systems so that they can at least provide direct reading to consumers, allow readings to be updated frequently enough to utilize energy conservation schemes, and support more advanced tariff systems [204]. In addition to these features, Recommendation 2012/148/EU suggests that meters should be able to provide secure data communication and prevent or detect fraud [205].

With the introduction of renewable energies and the growth of the smart meter market in some European Union member countries (Germany, for example), the requirements for safe and efficient operation of electrical networks have increased [106]. Thus, cybersecurity becomes a topic of the utmost relevance and requires standardization, with specific security standardization for smart grids [106].

In the case of the United Kingdom, there is commitment by multiple stakeholders involved in the whole process of spreading smart meters, including the government. Thus, the British government recommends active social monitoring based on the following objectives [189]:

i. Develop consumer confidence in smart meters;
ii. Conduct campaigns so that there is a more understanding by the consumer about the operation and the information, which is made available by these types of equipment;
iii. Increase the willingness of users to use this equipment in such a way that they can change their behavior in order to reduce energy consumption;
iv. Help vulnerable, low-income and prepaid customers to realize the benefits of smart metering systems without compromising adequate levels of comfort or other energy needs.

In the US, the implementation of technologies related to smart electrical grids started to happen in 2007 with the enactment of the Energy Independence and Security Act. In the specific case of implementation of smart grids, this measure aimed to:

i. Increase the digitalization of the electrical grid for greater reliability, safety and efficiency;
ii. Dynamically optimize operations;
iii. Implement distributed resources;
iv. Develop demand response mechanisms;
v. Deploy smart (real-time) technologies for operation;
vi. Improve the integration of smart devices and consumer devices;
vii. Deploy and integrate storage technologies, including plug-in electric vehicles and electric hybrids;
viii. Provide consumers with more information and options to control their consumption;
ix. Develop communication and interoperability standards for appliances and equipment connected to the electrical grid, including infrastructure;
x. Identify and reduce irrational or unnecessary barriers to the adoption of smart grid technologies and practices [206].

Following the smart metering trajectory of the European Union, the US installed by 2019 around 98 million units of smart meters, around 70% [330] and the forecast is that they will install by the end of 2021, around 115 million, which shows this country's commitment to the Energy Independence and Security Act [207].

During 2018, demand response measures in the United States provided more than 785 MW of flexible capacity, with 2.7 million participants [209]. A successful example of this measure was the city of Baltimore, being the largest of its kind in the United States, with 1.1 million registered households and more than 70% participation in the load change during peak hours. Thus, any customer who installs a smart meter is automatically enrolled in the program and can opt out. Subsequently, participants are notified the day before the "Energy Saving Days" (typically hot summer days) and if they manage to reduce consumption on those days, they receive a credit in the account of US$ 1.25 for each kilowatt-hour that they save compared to normal usage.

International experience in installing smart meters in buildings has allowed all the features of this equipment to be implemented in any building, regardless of typology. This enables better management and operation of energy resources in these countries. Furthermore, it is evident that the energy management functionality in the prepaid category is applicable more vulnerable families (a measure of a social nature). It is expected that these families will not experience a loss of comfort.

3.4 Digital technologies for building certification

Environmental certification is a method of recognized effectiveness to improve the use of natural resources in a country, it provides consumers with information on the environmental and energy performance of a given product (building) and helps to create a shared vision of the practical meaning of sustainability issues and energy efficiency. Building certification is granted according to the building's performance when compared to pre-established criteria, organized by categories. The categories referring to energy have relevant importance.

Advances in technologies for capturing and transmitting images and documents, Blockchain, data security, among others, have made it possible to digitalize various certification processes and create digital platforms that are safer and nimbler. Item 3.4.1 generically addresses building certifications, technologies currently used and those with potential and item 3.4.2 focuses on the application of remote inspection technologies, according to the guidelines of the ABNT NBR ISO 19011:2018 - Guidelines for audit of management systems [4].

3.4.1 Digital technologies used in the certification process

In the last 30 years, several certifications were created for buildings that, through outsourced and impartial assessments from different institutions, verify sustainable aspects of a construction. Each one focuses on different approaches, some of them consider energy efficiency aspects more relevant, others seek to optimize the consumption of building materials. There are those that seek to emphasize the executive phase, while others focus on the design phase, and are often more relevant in certain regions of the world.

In Brazil, the PBE Edifica Label and the Casa Azul + Caixa Seal stand out, which are of national origin, and there are several seals based on international ones and mostly align with the PBE Edifica in terms of the energy category. Some of them are: LEED (Leadership in Energy and Environmental Design); EDGE (Excellence in Design for Greater Efficiencies); WELL Building Standard, of American origin; BREEAM (Building Research Establishment Environmental Assessment Method), of English origin; DGNB (*Deutsche Gesellschaft für Nachhaltiges Bauen*), of German origin, and AQUA-HQE (High Environmental Quality - *Haute Qualité Environnementale*) of French origin [209-217].

It is worth noting that in Category 6 (Innovation) of the Blue Seal + Caixa, additional scores are awarded for the use of Building Information Modeling (BIM) in the integrated management of the project, efficient building automation systems and digital tools aimed at sustainability practices and that facilitate the collaborative management of the enterprise.

In line with efforts to digitalize the building sector, the main environmental certifications for buildings have or are developing digital systems and platforms to support their assessment processes, described below:

- Webprescriptive PBE EDIFICA [218] - this is a tool for assessing the Energy Efficiency of Commercial, Service and Public Buildings using the INI-C Prescriptive Method. The purpose of this tool is not to obtain an energy conservation label, but to automate building assessment procedures in accordance with current regulations. On the web, the user provides the design parameters of the building and obtains the classification level of the partial label for the envelope, lighting, air conditioning and for the general label of the building. Webprescriptive is still under development, but a preliminary version can be accessed for testing;
- ARC SKORU / LEED [219] – the Green Business Certification Inc. (GBCI) launched this platform and integrated the parameters of the LEED O+M certification for building operation and maintenance, presenting a new concept to measure the operational performance of buildings in the scope of different categories such as water, energy, waste and air quality. The platform allows professionals, facility managers and other users to add data from their buildings and generate scores, exploring metric relationships as to their current efficiency and possible reductions, based on LEED certified buildings around the world, be it to achieve the desired certification level, be it to obtain better comparable indicators in the market (benchmark analysis);
- LEED ONLINE [220] - the US Green Building Council (USGBC) has launched new tools for LEED BD+C (new construction) and LEED ID+C (indoor) certification on LEED Online, in order to support pre-certification and certification of projects submitted to these certifications, consisting of documentation forms in Web format, offline calculators based on Excel for documenting the most complex credits (medical equipment, demolition waste, avoided emissions, etc.), among others;
- EDGE 3.0 [211] - EDGE certification is a pioneer in the digitalization process and was born as a fully digitalized and online system. In addition to the traditional electronic upload of documents, which already exists in other certifications, at EDGE all performance calculations are performed through this system in real time. EDGE 3.0 is therefore a cloud-based platform to calculate sustainability and energy efficiency projects in buildings, which includes a sophisticated set of cost and climate data based on consumption patterns and algorithms to predict performance outcomes. Being open and free to use, a global network of accredited EDGE certifiers and experts uses this platform to simulate the environmental performance of their projects/buildings, even if one does not want the certificate;
- BREEAM In Use v6 [212] – this is an online platform that has been in existence since 2009 and is constantly being updated with new digital resources, where evaluators, managers and building owners can register and submit evidence of their installations (in use) for certification. Users instantly simulate scores based on BREEAM criteria and can compare their results with other certified buildings of the same typology by accessing the sustainability benchmarking that is available. BREEAM's digital tools also allow interaction between users of the platform through forums and the BREEAM Wiki.

The use of digital technologies can leverage the certification market by adding important improvements to processes such as more agility in granting certification with smart contracts, reducing verification times and more reliability with Blockchain technology, providing security and traceability to each transaction, as well as increased information flow and hierarchical transparency with personalized access according to the sphere of competence of each party involved.

The data is permanently recorded in a distributed manner, allowing access to the history of transactions carried out by all parties, whether for checking or auditing. As mentioned earlier, a pioneering initiative coordinated by Procel is under development in Brazil, called Projeto Smart Selo Procel – Applications in Blockchain Platform for Energy Efficiency Certification, which aims to add a Blockchain layer to the Procel Seal for equipment and can be extended for Buildings. It will be applied to all typologies of buildings in their subsystems considered in the evaluation for the Seal (envelope, HVAC, lighting and water heating) as well as for equipment with the Procel Seal.

From the analysis of the digital technologies discussed in Chapter 2 and from the perspective of the certifying body (capable of making thermal-energy simulations at the request of the applicant, for example). In table 13 one can see the technologies considered for application in the main building certification processes, according to the life cycle phase.

Although some of the technologies listed also have potential for application in certification processes for blocks, neighborhoods and districts, they were not mentioned here as they are outside the scope of this section 3.4.

Within the scope of certifications of national origin, the operation phase can be understood here as the certification of the built/existing building. In Brazil, there is still no specific national certification for the operational energy performance (OEP) of buildings (based on actual/measured performance) as found in some international certifications.

The foundations for such a program are still under construction, with the creation of consumption benchmarks by building typology. However, if there was an energy labeling program “in use”, smart metering technologies would be applicable to remotely and periodically provide information in order to facilitate, automate and make the data collection process more accurate and, consequently, increase the impact of the certification of buildings in operation. The Smart Meter is understood here as an equipment in favor of the energy user and not as an integrating element of the functionalities of a smart grid nor as the guarantor of the control and supervision interests of energy utility companies.

The physical and structural information about the building (for example typology, floor area and address) do not vary much from one year to the next. However, energy performance may vary. In this sense, the PBE Edifica Label for built buildings would work as a basis for a certification of operational energy performance and create the possibility of evaluating inappropriate uses, loss of performance of certain systems, susceptibility of changing the properties of the envelope due to lack of maintenance, among others. This type of information would allow a decision to be taken in favor of simple energy efficiency measures, which have a great impact on consumption, to the detriment of large and expensive reforms [177].

3.4.2 Technologies and remote inspection for building certification

With regard to remote inspections, technologies for capturing and transmitting images and documents, Blockchain, data security and digital contracts withing computing platforms, make it possible to comply with following guidelines in a more transparent, traceable and agile manner. These platforms can materialize in a range of devices and various products on the market.

The remote inspection (or audit), carried out partially or completely remotely, can use mobile or computer apps and cover everything that a face-to-face assessment would normally include, following the standard audit process when using technology to verify compliances. The auditee (building) and the audit team (certifier) should use previously agreed protocols, including required devices, software, etc. They should also ensure appropriate requirements for remote access, which may include video conferencing and collaborative work through interviews and meetings, synchronous (real-time) interactive communication, online access to records and documents, and recording of audit evidence through photos and videos.

After being published by the International Organization for Standardization (ISO) in July 2018, the ISO Standard 19011:2018 was published in Brazil by ABNT in December 2018. It made its third updated edition official, which canceled and replaced its 2012 edition. One of the changes in the revision of the Standard was precisely the inclusion of the possibility of remote auditing techniques, in line with advances in technological resources that make these activities viable. The Standard defines an audit as a

Table 13 – Main digital technologies used in building certification. **Source: Made by the authors.**

Design	Construction	Operation	Renovation
Building Information Modeling (BIM)	Building Information Modeling (BIM)	Building Information Modeling (BIM)	Building Information Modeling (BIM)
Building Energy Modeling (BEM)	Software for Life Cycle Assessment (LCA)	Energy Portfolio Management Systems	Building Energy Modeling (BEM)
Computational Fluid Dynamics (CFD)	Blockchain	Software for Life Cycle Assessment (LCA)	Computational Fluid Dynamics (CFD)
Simulation of natural and artificial lighting	Cloud Computing	Blockchain	Simulation of natural and artificial lighting
Energy Portfolio Management Systems		Cloud Computing	Energy Portfolio Management Systems
Software for Life Cycle Assessment (LCA)		Smart Meters	Software for Life Cycle Assessment (LCA)
Blockchain			Blockchain
Cloud Computing			Cloud Computing

systematic, independent and documented process for obtaining objective evidence and objectively evaluating it to determine the extent to which audit criteria have been met. The ABNT NBR ISO 19011:2018 Standard includes in its Annex "A" guidelines for conducting virtual/remote audits in any location other than the auditee's location to name a few [4]:

- Never record people without their permission and request permission in advance to make screenshots and documents of any kind;
- Request and use, for your understanding of the site layout, floor plans/site diagrams in digital format;
- Have contingency plans and communicate them (e.g. interruption of access, use of alternative technology);
- Auditor and auditee must take steps to ensure that security and confidentiality are maintained during the time of activities.

Remote audit performance, as well as face-to-face audits, is based on the engagement between the auditor and the auditee (with or without human interaction) and the technology used to conduct the audit. If an audit requires the use of a team with multiple members, face-to-face or remote methods can be used simultaneously. Applying a variety and combination of different audit methods can optimize the efficiency and effectiveness of the audit process and its outcome, as recommended by the aforementioned standard.

Interactive remote audit activities are carried out using communication technologies integrated with data security in conducting interviews, remote observation of the work performed, filling in checklists and questionnaires and conducting critical document analysis with the participation of the auditee. Non-interactive audit activities do not involve human interaction with people representing the auditee, but involve document review. Document and office audits are often considered part of a larger audit. The Project Inspection phase (either by the prescriptive method or the simulation method) of the PBE Edifica Label, carried out by the inspectors of the OIA - Inspection Bodies Accredited by Inmetro, could be considered as a remote document analysis audit.

The ABNT NBR ISO 17021-1:2016 Standard establishes the requirements for a certification body to perform its certification audits. This Standard provides for remote auditing in three requirements: operational control, preparation of the audit plan and generalities [222; 223].

According to the International Accreditation Forum (IAF) [223], as digital technologies become increasingly sophisticated, it is important to be able to use them to improve the effectiveness and efficiency of audits/assessments and to support and maintain the integrity of the entire process. These technologies may be used for the collection, storage, retrieval, processing, analysis and transmission of information. Example of software and hardware are smartphones, portable devices, laptops, desktops, drones, video cameras, technologies used coupled with the human body (wearables), artificial intelligence and others. The IAF document MD 4:2018, published by the IAF, cites examples of technologies for audits (example list and description) [223]:

- Meetings through teleconferencing, including audio, video and data sharing;
- Audit/assessment of documents and certification/accreditation processes through remote electronic access, synchronously (in real time) or asynchronously (when applicable);
- Recording information and evidence using still cameras, or audio/video recordings;
- Permission to access video and audio in remote or potentially dangerous locations.

On a large scale, the bureaucratic costs of gathering and validating energy consumption information for a large number of buildings every year (or every month) can be very high. Thus, it would be interesting to consider automating the process of sending data to the auditors/inspectors of the accreditation companies. Smart meters with standardized communication protocols could enable this functionality and enable automatic monthly or annual renewal of certificates with minimal costs [177].

On a smaller scale, it is already possible to use apps and software to automate and streamline energy inspection and audit processes that, compared to a conventional audit approach, greatly reduce the evaluator's time in data collection, in the development of various types of analysis and reporting. Software has been configured to manage different types of assessment, from a simpler mini audit, where quick gains are identified, to more complete investigations that analyze equipment and services in buildings [224-229].

Several features can be inserted into energy audit apps in order to assist and support audits/inspections in buildings, remote and on-site, for the purposes of certification of buildings:

- Registration of various types of equipment, quantities and hours of use;
- Use of device's camera to add photos of the area under inspection;
- Inserting floor plans or manual sketches to visually mark device data;
- Transcript of field audit data in order to upload it to the cloud;
- Solutions stemming from predefined “kits” or customized solution;
- Reports of estimated cost savings according to the building's life cycle phase.

To perform measurements and capture details of construction elements, it is worth mentioning the possibility of using advanced technologies, with laser scanning equipment that speeds up the metric survey of environments and facades and include thermal scan. The information collected is stored in a point cloud that joins all the mapped parts and from which a parametric three-dimensional model can be built to record the situation found. Drones could also be used to collect dimensional data through aerial photographs. With the aid of photogrammetry techniques, the images are vectorized for incorporation into the three-dimensional models (stereo-photogrammetric rendering). In the construction phase, the laser scanner could also be very useful for recording the progress of the work and meeting the sustainability criteria required by certifications, reducing on-site visits and improving safety in the work process of auditors/inspectors (risks physical or contamination) [16; 231-233].

Paper records are completely eliminated, as the evaluator can survey and analyze the collected data using calculation models already built into the apps. It can be used on site or in the office, and a report generation feature allows recommendations and adaptations of the results for the customer, resulting in a customized audit report. Data such as greenhouse gas emission factors, site weather conditions, specific regulatory requirements, building materials library and renovation costs can be updated regularly.

Specific modules can also be explored and that would substantially increase the quality of audits/inspections, such as the inclusion of budget modules in the platforms and Software for the creation and comparison of different proposals for each type of energy source, modules for individual evaluation of the different systems (lighting, air conditioning, water heating etc.) and modules with features linked to the benchmark, with the ability to show the current performance of the building in comparison with typical reference data for similar buildings (by typology and/or size).

The implementation of benchmarks can be carried out through building labels, recording the building's normalized consumption and comparing it with an appropriate indicator, in order to classify its efficiency. The European Directive 2010/31/EU has as its key principle the implementation of benchmarking and energy labeling of buildings in all member countries of the European Union. With a holistic approach and aiming to demonstrate the effectiveness of energy assessments of buildings in the operational performance certificates and fill in the absence of adequate protocols for the inclusion of smart and innovative technologies, through the H2020 ePANACEA Project – Smart European Energy Performance Assessment & Certification, a platform was developed for the evaluation and development of a new generation of European building certification that integrates advanced dynamic simulation techniques, big data analysis, inverse modeling, among many other functions [221;230].

In Brazil, in relation to this matter, it is worth highlighting the work being carried out by the Brazilian Council for Sustainable Construction (CBCS) regarding the construction of the Energy Benchmarking Platform, developed for specific typologies (bank branches, corporate offices, public buildings, gated communities, etc.) [234].

4. Conclusions

This study achieved its objective of analyzing different topics related to digital technologies applied to the building sector in order to strengthen energy efficiency actions.

The topics covered were: main technologies applied by phase and by typology; the *status quo* of these technologies in Brazil and in other countries; the normative and legal instruments that support energy efficiency policies in buildings, smart grids and meters and digitalization in the building sector; the concept of intelligence adopted in the operation of buildings; demand management for home appliances, lighting and air conditioning; demand management for connected buildings; the market for electronic meters linked to building management, international experience in the implementation of monitoring and smart management systems; and technologies for building performance certifications and remote inspection based on the ABNT NBR ISO 19011:2008 - Guidelines for auditing management systems.

Each theme carries its own complexity as the building sector is composed of different realities and agents such as developers, construction companies, project offices, building administrators, users, suppliers and manufacturers of materials and service providers. Each actor brings its own diversity, whether in terms of size, specific objectives, financial conditions, specific challenges such as adopting technologies in their daily lives. This complexity increases because it is still inserted in a very heterogeneous regulatory environment, high level of informality and the civil construction sector is known worldwide for being conservative in the adoption of digital technologies.

An example of this complexity was the stratification of the residential sector that has several definitions and classifications. An additional study was prepared for this and found in Appendix 2 that divided it into a few categories and in a broader way, establishing the stratification in single-family residential, multifamily and social interest housing. This indication was approved by the sponsors of this study and does not discriminate differences in purchasing power that interfere with the adoption of technologies.

The buildings called social interest housing have peculiar characteristics: their projects are usually replicated and built by medium or large construction companies in large construction works, this allows these construction companies to adopt various design and construction technologies; the absence of a builder-client relationship in the projects and the low purchasing power of the residents limits the applicability of technologies in the operation and renovation phases, as well as those technologies that provide customer engagement in the design phase.

In the evaluation of digital technologies by phase of the building life cycle and by typology, twenty technologies were identified, described and analyzed by building phase and typology. Items 2.1.1 to 2.1.5 show the technologies by phase, distributed in seven domains of activity and the description of their application, in addition to considerations about their use among the five typologies. The commercial availability of each technology is shown in the tables in items 2.2.1 to 2.2.5. Appendix 3 shows a synthetic picture of the relationship between these technologies, the project phases and typologies, the districts, as well as their relationship with Industry 4.0.

In the design phases, the agents that are most involved are architecture and design offices or departments and the client in the typology of commercial, public and high-end residences and high-end condominiums. This characteristic leads to an accelerated adoption of technologies. It can be said that technologies such as Building Information Modeling (BIM), Computational Fluid Dynamics (CFD) and Natural and Artificial Lighting Simulation are already at a higher phase of maturity and are commercially available both in Brazil and in other countries. Other technologies such as Blockchain are used in other countries, but not in Brazil.

In the construction phase, the most involved agents are construction companies, developers and engineering companies. Solutions were identified such as Building Information Modeling (BIM), Software for Life Cycle Assessment (LCA), Augmented Reality and Agile Management Software which are available both in the national market and in other countries. For 3D Printing and Blockchain digital solutions, numerous initiatives were identified at an international level, while in Brazil they are still under development, being mostly offered by startups. The potential for using digital technologies at this phase is great, especially in Brazil. At construction sites, there is plenty of space for training and environmental education, energy savings and other types of input.

Managers of commercial and public buildings and large condominiums, as well as consumers in general, are the active agents in the operation phase. The uses of technologies vary in intensity with size, purpose, regulation with utility companies and the purchasing power of the person responsible for managing the building. Technologies associated with the control and management of equipment and systems are the most used, simulation and modeling programs are also used in more complex buildings. The dissemination of digital technologies and controls is mainly facilitated by mobile devices and purchasing power is a strong indicator of the intensity of use in the residential sector.

In the building renovation phase, for large buildings in the commercial, public and high-end residential sectors, design offices, engineering firms and construction companies are the major players. Because of that the technologies used bear close resemblance to the conclusions for the result matrix for the design and construction phase. Except for the presence of 3D Printing solutions, which, as in the construction phase, are available at internationally and under development domestically. For the renovation of medium and low standard buildings and residences, and social interest housing, the use of digital technologies is incipient.

With regard to the demolition phase, for large commercial and public buildings, digital solutions related to Building Information Modeling (BIM), Software for Life Cycle Assessment (LCA), Blockchain, Agile Management Software and Augmented Reality Increases have been used by construction companies and specialized firms both in the national market and in other countries. In relation to solutions on Blockchain, there is no record of use in Brazil, only in other countries. The demolition of small buildings and small size residences hardly uses digital technologies.

In terms of the normative and regulatory framework related to energy efficiency that may impact the building sector, the regulatory instruments related to smart electrical grids that can expand digitalization in this sector stand out, and policies directly linked to digitalization in buildings. Based on the analysis of this framework presented in section 2.3 of this document, it can be said that the regulatory instruments are at different phases of maturity and implementation. Although this framework is consolidated with the attributions established between the various actors and the insertion in energy planning, with regard to encouraging digitalization in buildings, there is a long way to go which involves discussions about the establishment of new construction standards, mandatory certifications, promotion of operational energy performance, change of culture in the civil construction sector and its most diverse customers. There will be a strong incentive to disseminate these technologies when the regulation of smart grids and meters and distributed generation, move towards making the electricity sector and other energy input sectors more flexible in the sense of pricing throughout the day and inclusion of new sources of power generation, mainly distributed. Digitalization policies in buildings have made significant progress since 2018 with decrees, laws and bills in the areas of device connection, smart cities and data lifecycle.

It can be concluded that there are, in Brazil, relevant regulatory instruments that can leverage the process of digitalization of buildings in the country with a focus on energy efficiency. However, digitalization requires huge investments in new technologies, infrastructure and training. An example of this is 5G technology that had a specific bidding process in 2021. The policies in the three areas mentioned are at different levels of maturity, but they all need improvement to effectively boost this market.

Digital demand management technologies linked to the reduction of energy consumption have gradually become popular due to advances in terms of comfort and ease of use of control by cell phones, tablets and computers and because of the reduction in the price of smart equipment such as smart electronics equipment connected to the grid or devices that can add intelligence such as technologies like smart switches and smart sockets. In terms of typologies, it is a reality in the management of large commercial and public buildings, and in high-end residences. Concerning demand management, it is required by regulation of the electricity sector for consumers in tariff group A and digital technologies also improve the management. For residential consumers, except for those who opt for the white tariff, demand management is not mandatory, so the penetration of these digital solutions is very small for this purpose. In several developed countries such as the USA and European Union countries, energy utility companies offer differentiated tariffs if users, both industrial and residential, allow them to remotely turn off some of their loads under certain conditions. In the residential case, the use of IoT in these devices is common.

In terms of smart districts, when buildings are analyzed as a group, a new layer of possibilities for optimization and sharing can be seen, starting with the adoption of specific technologies and the integration between them, as well as the possibility of shared management of assets, aided by digital devices. It is important to verify possibilities so that buildings can operate together, also to find the most appropriate restrictions and conditions to obtain greater benefits for the district. Examples of areas impacted by digital solutions can be shared services, such as renewable energy generation systems, solar thermal heating, shared hot water supply systems, thermoaccumulation tanks, cold water supply systems and/or refrigerant fluids for air conditioning, collection systems, treatment and storage of rainwater and wastewater, etc. To this end, the classes of solutions related to simulation, such as Urban Energy Modeling (UBEM), Computational Fluid Dynamics (CFD), Natural and Artificial Lighting Simulation, Software for Life Cycle Assessment (LCA) and Simulation and Energy Portfolio are essential. For the operation phase, information management itself is essential, as well as automation protocols and associated technologies, which makes the following technologies essential. And they are technologies of transversal provision of IT infrastructure, such as cloud computing; integration, such as Building Information Modeling (BIM) and energy portfolio management tools; transaction registration and automation, such as Blockchain, its smart contracts, artificial intelligence and associated hardware (sensors, actuators and smart switches); and those that support demand response, enhanced by user information and gamification tools, such as smart sockets and (two-way) chargers for electric cars (which can function as batteries or breaks to assist in shifting load).

Smart meters in building demand management are used to measure the various parameters of buildings and are not restricted to measuring of electricity. In fact, a smart metering infrastructure must be composed of equipment that measures energy quantities (smart meters, including), by systems and Software that stores, manages and analyzes the measured data. The applied smart metering technologies are: smart meters, building management systems (BMS), virtual assistants, smart sockets, electric vehicle chargers, Blockchain, and BIM. The uses of the technologies cover all typologies of building, with the exception of social interest housing, which can only use electronic meters that are suitable to a differentiated tariff regime. As it is a measurement, the use of these technologies refers to the operation phase. However, the use of smart meters with the goal to get more response to demand is incipient in the country, and the main function in the use of this equipment is for energy billing.

The international experiences of installing smart meters in the buildings studied in the USA, EU, Germany and the UK show the success in the use of this equipment and it was realized that all the features of this equipment can be implemented in any building, regardless of typology. This enables better management and operation of energy resources in these countries. Furthermore, it is evident that the energy management functionality in the prepaid modality is applicable to families with that are more vulnerable (a measure of a social nature). However, there is concern that these families do not experience a loss of comfort.

The third edition of the ABNT NBR ISO 19011:2008 Standard - Guidelines for auditing management systems brings the innovation of inclusion of the possibility of remote audit techniques, in line with the advances in technological resources that make these activities possible and in Annex "A” presents guidelines for conducting virtual/remote audits at any location other than the auditee's location.

There are several applications and software being used to automate and streamline audit processes that, compared to a conventional audit approach, greatly reduce the evaluator's time in collecting data, developing different types of analyses and issuing reports.

Regarding building typologies, certification, its digital platforms and remote inspections can be used for all typologies. Adoption of a certification is generally driven by a mandatory regulatory framework. This is not the Brazilian case. Due to digital technologies agility, reliability and reduction of human and financial resources, notably in remote inspections, there can be a great booster of voluntary certifications in the country that today is not massively adopted because of various barriers such as lack of knowledge and high cost for small buildings.

As a final conclusion, one can say that there is a great and growing potential for the use of digital solutions in buildings. For each phase of the building life cycle and typology there are different agents involved with different barriers and challenges. Agents are also intrinsically differentiated by size, purchasing power, knowledge and technology adoption culture. The complexity of this area increases with a complex regulatory framework that involves several levels of government. The global trend of increasing use of digital technologies in buildings drives the national market. The main factors driving the use of these technologies for energy efficiency in the near future are the reduction in the consumption of energy inputs, the flexibility and ease of energy and demand management that are part of the context of the modernization of the electric sector, the reduction of service costs and equipment of digital solutions, the more attentive behavior of consumers in relation to energy efficiency with ease of access to information and better control of equipment, less fear of using digital technologies and digitalization in other sectors of society such as the electricity sector.

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Appendix 1 – Methodological note

The general methodology adopted in this study is presented in this first appendix [1]. It comprises three main phases:

i. Exploratory/descriptive phase;
ii. Prospective phase;
iii. Propositional phase.

The activities in each phase of the study are detailed below.

A1. Exploratory/descriptive phase

Initially, bibliographic research and document analysis were carried out on the central themes of the study, i.e, digitalization and energy efficiency in the building sector. The bibliographic research was conducted by searching documents in Scopus, Web of Science, Science Direct, Engineering Village and Google Scholar databases, covering the period from 2010 to 2021. Once the documents of interest for the study were selected, the technique of content analysis was used for the meta-analysis of the documents and synthesis of the bibliographic review [2].

In addition to the bibliographic research, a detailed analysis of technical and normative documents was carried out, such as reports from international, regional or national agencies, applicable technical standards and regulations by searching institutional websites and identifying references cited in scientific and reference documents. The following were objects of the document analysis:

i. Overview of international experiences in the implementation of mechanisms and strategies for the sustained penetration of smart buildings;
ii. Description of the current situation of digitalization in the building sector in Brazil, including public policies and instruments implemented or under development;
iii. Description of the current situation of public policies on energy efficiency in Brazil, that is, instruments implemented or under development.

The bibliographic review and document analysis supported the mapping of existing digital solutions, distinguishing the solutions for each phase of the life cycle (design, construction, operation and renovation, and demolition) and by building typology (commercial, public and residential, social interest housing). For this mapping, we chose to use the morphological analysis technique [3; 4]. The basic premise for choosing this technique was that a complex problem, such as the one addressed in this study, can be decomposed into variables, which undergo a systematic analysis of the possible states that these may assume, thus generating a set of states or values that refer to them. The logic of the problem decomposition is to deal with less complex issues than the original system, thus enabling a deeper analysis of the parts (in this study, subsystems with indication of digital solutions by phase of the buildings life cycle).

Morphological analysis is an analytical-combinatorial technique, which is based on the decomposition of a problem, or object of analysis, into its attributes. Zwicky [3] proposed the application of this technique in five steps:

i. Formulation and definition of the problem (question to be answered);
ii. Identification and characterization of all problem variables;
iii. Construction of a multidimensional matrix, filled with the possible states that each variable can take;
iv. Identification of plausible combinations of the states generated for each variable, depending on the question to be answered;
v. Analysis of alternatives dismissing those intrinsically inconsistent, unsustainable or economically unfeasible.

Using this technique, it was possible to build five multidimensional morphological matrices, one for each phase of the building's life cycle (design, construction, operation, renovation and demolition), with the definition of seven domains (envelope, HVAC, lighting, water heating, equipment, socket loads, building infrastructure, energy supply, generation, and storage) and five typologies of buildings (commercial and service, public and residential – single-family, multifamily and social interest housing - SIH).

The domains and building typologies were defined based on a literature review and document analysis, and were later validated by representatives of GIZ and MME. Thus, the five matrices were formatted, as illustrated in Picture 4.

For each of the five matrices (design, construction, operation, renovation and demolition), plausible combinations of existing digital solutions were generated by type of building (commercial and service, public and residential, multifamily, single family and social interest housing). Intrinsically inconsistent, unsustainable or economically unfeasible combinations were discarded. Thus, five multidimensional morphological matrices were consolidated (one per phase of the life cycle), which were filled with the combinations of existing digital solutions applicable to each building typology (filled out matrices are presented in section 2.1 of Chapter 2 of this report).

Specifically in relation to the other topics of Chapters 2 and 3 of the Preliminary Report, the questions were considered in a textual form and the analyses were conducted based on the results of the bibliographic and document review using content analysis, as proposed by Bardin [2].

Based on the results of the exploratory/descriptive phase, the first version of the Preliminary Report was prepared, which should be revised based on the comments and recommendations of the MME, MDR and GIZ. After consolidating the review, with comments and recommendations from GIZ, the final version of the Preliminary Report is sent.

The activities planned for the prospective and propositional phases, respectively, are described below.

A2. Prospective phase

For the purposes of developing this phase, a prospective scenario is defined as a coherent set of hypotheses that describe a future situation and the course of events that allow the transition from the original situation to that future situation. The game of hypotheses of a scenario must simultaneously fulfill five conditions: relevance, coherence, likelihood, importance and transparency [4; 5].

The construction of alternative prospective scenarios is foreseen at this phase, and this construction refers to the main issues of the study regarding the penetration of efficient buildings and the potential for energy efficiency in the building sector in Brazil, considering different levels of digitalization.

To answer this question, a mixed methodological approach will be used to build alternative prospective scenarios, which combines the methodology of the Global Business Network [6] with tools proposed by Godet [4; 5].

Building life cycle phase					
Domains	**Typologies**				
	Commercial and Services	**Public**	**SIH Residences**	**Multifamily Residences**	**Single-family Residences**
Envelope	Digital solutions	Digital solutions	Digital solutions	Digital solutions	Digital solutions
HVAC	Digital solutions	Digital solutions	Digital solutions	Digital solutions	Digital solutions
Lighting	Digital solutions	Digital solutions	Digital solutions	Digital solutions	Digital solutions
Water heating	Digital solutions	Digital solutions	Digital solutions	Digital solutions	Digital solutions
Equipment, socket loads	Digital solutions	Digital solutions	Digital solutions	Digital solutions	Digital solutions
Building infrastructure	Digital solutions	Digital solutions	Digital solutions	Digital solutions	Digital solutions
Energy supply, generation and storage	Digital solutions	Digital solutions	Digital solutions	Digital solutions	Digital solutions

Picture 4 – Representation of a multidimensional morphological matrix applicable to each phase of the building's life cycle.
Source: Made by the authors.

This approach consists of seven steps described below:

i. Determination of the scope of analysis and time horizon for the construction of scenarios;

ii. Definition of fundamental variables through the use of structural analysis and the MICMAC tool, available on the institutional website "La Prospective" [7];

iii. Identification of the main actors, stakeholders and influencers of the scenarios;

iv. Analysis of the Brazilian context in relation to the main question, description of the situation of origin and identification of future conditions in the considered horizon. In addition to the results of the documental research to be carried out in the exploratory/descriptive phase, some semi-structured interviews may be conducted with representatives of sector institutions, government programs, professional associations related to civil construction and building automation in addition to S&T institutions. This is done in order to get information on penetration, barriers to efficient buildings and impact of digital technologies in the measurement of energy efficiency, as well as define premises for the intended scenario. The interview script can be previously validated with GIZ. After these individual interviews, an online form will be developed to collect information from a larger number of specialists. The list of respondents interviewed individually and the ones interviewed by form will receive indications from the MME and GIZ;

v. Construction of alternative prospective scenarios, based on multidimensional morphological matrices, and definition of premises to establish plausible future configurations of the potential for energy efficiency in the building sector in Brazil, considering different digitalization paces. The MORPHOL tool, available on the institutional website "La Prospective" [7] will be used;

vi. Definition of logic of the three most likely scenarios of penetration in Brazil of efficient buildings with use of digital technologies in their life cycle phases, in the considered horizon. These scenarios will be chosen jointly with representatives of GIZ and MME and, based on this definition, the trajectories of the fundamental variables over the period at hand will be narrated and requirements for a successful implementation in Brazil will be defined, including technical, legal requirements or regulations relating to the provision of data by energy consumers;

vii. Checking of consistency and plausibility of the three scenarios, by carrying out consistency tests and adjustments, if necessary, as well as analyzing the interests of the main actors and influencers in each scenario with the use of MACTOR tool i.e. "Matrix of Alliances and Conflicts: Tactics, Objectives and Recommendations", available on the institutional website "La Prospective" [7].

In this phase there will also be the identification of case studies, detailing the energy savings due to the implementation of digital solutions, considering the three implementation scenarios that are going to be defined with representatives of GIZ and MME. If the set of information is not sufficient to identify case studies in Brazil, this topic should be transferred to the propositional phase.

A3. Propositional phase

After describing the three most likely scenarios, it is necessary to return to the main question and verify the possible implications for the formulation of public policies in each scenario. These policies are aimed at increasing energy efficiency in the building sector in Brazil, considering different levels of digitalization. The use of the MACTOR tool and the analysis of the conditions of the future in the prospective phase will allow investigating the strategic purposes of the actors involved in this issue and identify the driving forces that will shape the trajectories in each scenario.

To formulate recommendations for future steps, a webinar is planned to validate the results and conclusions of the study, from the perspective of implementing public policies and strategies associated with scenarios of sustained penetration of digital technologies in buildings in Brazil.

The steps planned for the finalization of the Final Report are:

i. Preparation and delivery of the first draft of the Final Report;

ii. Review of the draft Final Report, aiming to incorporate the comments and contributions of the GIZ team;

iii. Delivery of the Final Report, after reviewing and incorporating the comments and contributions of the GIZ and MME teams.

It should be noted that during the execution of the prospective and propositional phases, periodic meetings are scheduled for monitoring the project and decision-making between MME/GIZ/Growing Energy.

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Appendix 2 – Definition of building typologies

The Project's Term of Reference provides for the analysis of digital solutions and applications **for each typology of buildings (residential - in relation to different market sectors - commercial and public)** [1].

At the presentation meeting of the Work Plan (Product 1 of the Contract), held on 09/02/2021, between MME/GIZ/Growing Energy, it was decided that the specifics of each typology for the commercial and public sectors will not be discussed. For the residential sector, the following stratification is proposed: Social housing, Single-family residential building and Multifamily residential building.

This subdivision proposal, in a few categories and in a broader way, will effectively be enough to develop this study and can be confirmed through initial bibliographic research that was carried out in the main housing reference bases in the country, whose list is presented below.

11 national and 4 international references were analyzed. It appears that there is a mismatch between the classifications used in the documents, both on the part of civil construction / real estate sector and in relation to energy consumption (in the residential sector these are stratified mainly according to social class, according to family income), which complicates an analysis from the perspective of the theme of digitalization and energy efficiency in buildings. Part of this mismatch refers to the different objectives of the documents. In a complementary way and to reinforce the stratification proposal that is being presented, consultations were also carried out with the IEA (International Energy Agency) and European Commission platforms. Two German studies were also selected, in order to have international references on how the subdivision of the residential sector in other countries. The international references were an important guideline as it has the closest objectives stipulated in the ToR.

In addition, from our experience, one can conclude that the classification of buildings in many types will not contribute, and may even harm, the achievement of the final objective of the study, which is to "provide a basis for the formulation of public policies aimed at increasing the energy efficiency in the building sector, through digital transformation".

Summary of research conducted in the main reference bases of the Residential Sector

ABNT NBR 12721 – Assessment of unit construction costs for real estate development and other provisions for condominiums (2007) [2]

Rule that helps compliance with Law 4,591/64, on real estate development and condominiums, and presents eight tables with the most important information about the project, which are essential for obtaining the Registration of Incorporation (RI).

To represent the different types of Residential Building, the main characteristics of the architectural project are taken into account (such as number of bedrooms, bathrooms, etc.), as well as the standard of finishing material and areas, with the subdivision as follows:

- Single family residence (low standard, normal standard and high standard);
- Popular residence (low standard);
- Multifamily residence / apartments;
    - Project of social interest;
    - Popular building (low standard and normal standard);
    - Multifamily residence (low standard, normal standard and high standard).

Available at:
https://www.abntcatalogo.com.br/norma.aspx?ID=4743

ABNT NBR 15.575 - Performance of Housing Buildings (2013) [3]

It brought to the development of residential projects concerns about the expected useful life, performance, efficiency, sustainability and maintenance of buildings. For this, it adds to its content an extensive list of existing norms, from the most diverse subjects related to the theme.

It is focused on the behavior of building elements and systems to meet user requirements rather than prescribing how systems are built. From this point of view, it is organized using the elements of the building, defining the requirements (qualitative characteristics) to which it is intended to meet and establishing criteria (quantitative amounts) for this service.

In this sense, there is no subdivision of types of residential buildings.

Available at:
https://www.abntcatalogo.com.br/curs.aspx?ID=157

CAU/BR – Table of fees for architecture and urban planning services in Brazil (2013) [4]

Prepared based on the Manual of Procedures and Hiring of Architecture and Urbanism Services, approved at the 138th COSU-IAB/SP, in 2011. The buildings are classified into four categories (I, II, III and IV) according to the criteria: complexity of the previous research necessary for their design, functional, technical and aesthetic differentiation of the spaces and environments to be designed, composition sophistication of the work, technological complexity, especially for complementary projects, complexity of the development of project detail, intensity of customer participation in the design process.

In item 7.3.1 - Typology of buildings, the building for Housing use is subdivided into:

- Residential;
    - Social interest housing;
    - Apartment buildings, housing complexes and buildings, condominiums and villages (normal and high standards);
    - Simple residences (low standard, medium standard and high standard).
- Accommodation;
    - Hostels, inns, simple hotels and motels;
    - Luxury hotels.
- Collective;
    - Dorms, retirement homes, orphanages, boarding schools, convents and monasteries;
    - Barracks;
    - Prisons and jails.

Available at: https://honorario.caubr.gov.br/download/

PBE EDIFICA - Inmetro Normative Instruction for the Energy Efficiency Classification of Residential Buildings (INI-R) (2021) [5]

Residential Building is considered to be one used for housing purposes, containing spaces for rest, food, domestic services and hygiene, and the following cannot be predominant: sales, schools, associations or institutions of various types, provision of services, etc. In the case of mixed-use buildings, which have occupancy encompassing more than one use, these are evaluated separately for energy efficiency classification purposes.

Subdivides Residential Buildings into:

- Housing unit (HU) - Real estate property intended for housing and with independent access. Corresponds to a unit of a multifamily building (apartment) or a single-family building (house);
- Single-family building - Building that has a single housing unit (HU) on the plot of land;
- Multifamily building - Building that has more than one housing unit (HU) on the same lot, in a condominium, which can be configured as an apartment building, two-story house or group of buildings. Terraced houses, when located on the same lot, fall into this classification. Hotels, motels, inns, residential hotels and similar places are excluded from this category.

Available at: http://www.pbeedifica.com.br/nova-ini/inir

PPH/PROCEL – Survey of Possession and Habits of Use of Electrical Equipment in the Residential Class (2019) [6]

The main objective is to know the behavior, habits and characteristics of consumption, in addition to the level of knowledge about energy efficiency of the Brazilian population. Considering the 2010 census as a reference, with a face-to-face and household approach, the interviews were conducted with a questionnaire aimed at people living in households officially connected to the electricity distribution grid, in capitals and cities with 100,000 (one hundred thousand) or more households.

The types of electrical equipment considered in the survey are: Lamps, Refrigerators, Air Conditioners, Televisions, Microwave, Washing Machine, Cell Phone, Internet Modem, Wireless Router (Wi-Fi), Cable TV Receiver, External Digital Converter for Non cable TV, Water Heating. There were also questions regarding awareness / energy saving measures.

The characterization of households is presented in five ways, through:

- Socioeconomic Class to which the family belongs – Social Classes according to income (Class A, B1, B2, C1, C2 and D/E);
- Type of residence (House, Apartment[1] and Others) – along the same lines as the PNAD;
- Constructed (in m^2) Area of the House (Average, Median, Mode etc.);
- Origin of Electric Energy Used at Home (General distribution grid /Electricity Utility company, generated at home, Mixed/general distribution network and generated at home and Don't know/did not answer);
- Average of the Household's Monthly Electricity Consumption, in kWh, consulted directly on the electricity bill presented by the resident of the household.

Available at: https://eletrobras.com/pt/Paginas/PPH-2019.aspx

[1] The “Apartment” typology considers the location of the home in the building (ground floor, first floor, top floor...) and whether the building is exclusively residential or has another activity.

National Survey by Household Sample - Continuous PNAD /IBGE (2019) [7]

Its purpose is to produce basic information for the study of the country's socioeconomic development. The PNAD Continua, implemented in 2011, produces indicators on the workforce and supplementary topics (household chores, information and communication technology, etc.), investigated quarterly and accumulated to generate annual results.

Its research unit is a residence[2], which is intended to serve as housing for one or more people or is being used as such, defined as a structurally separate location (associated with a spatial limitation of floor, sides and roof that allows its residents to isolate themselves) and independent (relates to the characteristics of access, which allow entry and exit without the need to go through other people's residence).

Households are classified as private (permanent or improvised) or collective, according to the location area (urban or rural) and occupation condition (own, rented, given or other), subdivided into the following types:

- House;
- Apartment;
- Tenement house.

Available at:
https://www.ibge.gov.br/estatisticas/sociais/populacao/9171-pesquisa-nacional-por-amostra-de-domicilios-continua-mensal.html?=&t=o-que-e

Electric Energy Statistical Yearbook (2019) [8]

They use another classification for consumers, where the Residential class is subdivided into:

- Low Income (social tariff);
- Conventional (except Low Income).

This same classification is adopted within the scope of the PEE ANEEL. Of a total of 330 projects implemented between 2009 and 2017, 252 fall into the Low-Income typology and 78 into the Residential typology.

Available at:

https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/anuario-estatistico-de-energia-eletrica

http://www.aneel.gov.br

BEN – National Energy Balance (2021) [9]

It presents a reasonable survey period with a consolidated systematization, in which the final energy consumption of the country is subdivided into seven sectors: industrial, residential, commercial, public, energy, agriculture and transport (these last two are the only ones with subdivisions). This classification reflects a time when consumption in “Buildings” (understood as a group of Residential, Commercial and Public classes) was neither so representative (notably in electricity) nor so diverse.

The final energy consumption of the Residential Sector is understood as the energy consumed in all social classes (according to income), but disaggregated data are not presented, according to TECHNICAL NOTE EPE DEA 005/2021 - BEN METHODOLOGICAL MANUAL 1st Edition.

Available at:

https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-ben

https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-578/NT.EPE.DEA.SEE.005.2021%20-%20BEN%20_%20Manual%202020_vf.pdf

[2] This definition of household is different from the billed residential consumer unit concept used by electricity distribution agents under ANEEL Resolution No 414 of September 9, 2010. One of the main differences is the possibility of generating more than one invoice per household depending on the electrical characteristics of the residences.

PDE 2030 – Ten-Year Energy Expansion Plan (2021) [10]

Same as BEN (without breaking down Final Consumptions) and in Box 2.1 refers to PPH/PROCEL [99] and to the MSR - Residential Sector Energy Demand Model, according to TECHNICAL NOTE EPE DEA SEE 011/2021.

It uses the same definition of household as the PNAD, without disaggregating by typologies, and describes the methodology developed for projections of residential energy demand (aggregate data / econometric model), in its final uses and by income classes, to be used in EPE studies, such as the Energy Efficiency Atlas, the Ten-Year Energy Expansion Plan (PDE), the National Energy Plan (PNE) and the National Energy Balance (BEN).

This approach by income brackets was initiated by electricity, having as a reference the PPH/Procel 2019 (bottom-up modeling of electrical equipment present in Brazilian homes). For the study for the other energy sources consumed in Brazilian households (LPG, LNG, firewood and charcoal), MSR uses a top-down modeling that is based on the projections of Specific Consumption and Number of Consumer Units, based on the analysis of microdata from POF (Family Budget Survey) and IBGE PNAD related to energy sources.

The adopted family income classes are as follows (Brazil's criteria): Class I: less than 2 minimum wages; Class II: from 2 to 3 minimum wages; Class III: from 3 to 5 minimum wages; Class IV: from 5 to 10 minimum wages; Class V: more than 10 minimum wages.

Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-490/PDE%202030_RevisaoPosCP_rv2.pdf

PDEf - Ten-Year Energy Efficiency Plan, Buildings Sector (2020) [11]

It details a set of actions to achieve the estimated energy efficiency gains for Brazil in the medium term, based on the macroeconomic and energy efficiency scenarios established in the Ten-Year Energy Expansion Plan (PDE).

It carries out a discussion on the foundations and dynamics of the group called "Buildings", since it is not characterized as a class of energy consumption, being one of the challenges for the elaboration of public policies of energy efficiency for this group, since there is no understanding of its elements which makes it difficult to analyze the database and, even more, to make them compatible.

It appears, without further statistical studies, that residential energy consumption is predominantly driven by occupation (per capita consumption), while in commercial and services the determining factor is the occupied area (specific consumption), which is not in itself a novelty (see Table 9 – Product 5).

The PDEf also brings the example of the Municipal Department of Urban Development of the City of São Paulo - SMDU. São Paulo City Hall is a pioneer in terms of presenting available historical data (even with some inconsistencies) in relation to Buildings. Through the Infocidade system (https://www.prefeitura.sp.gov.br/cidade/secretarias/licenciamento/desenvolvimento_urbano/dados_estatisticos/info_cidade/), makes available to the public an extensive compilation of indicators and information that make up the collection of its database. The sources are the municipal secretariats themselves, but also institutions such as the IBGE, Fundação Seade and the Ministries of Labor and Employment, Education and Health.

The classification of buildings for residential use in São Paulo is subdivided into:

- Horizontal Residence (Low Standard, Medium Standard and High Standard);
- Vertical Residence (Low Standard, Medium Standard and High Standard).

Available at: https://eletrobras.com/pt/Paginas/PlanoDecenalEficienciaEnergetica.aspx

SINDUSCON/SP - Guia interativo de eficiência energética em edificações (Interactive guide to energy efficiency in buildings) (2021) [12]

This guide covers five typologies of buildings that best represent the buildings built by members of SindusCon-SP. They are: Residential Buildings, Houses, Residential Condominiums, Office Buildings, Hotels, Shopping Malls, Retail and Logistics (Distribution Centers).

The Residential typology covers the following constructions:

- "House", which includes single-story houses and two-story houses;
- "Building" that corresponds to buildings with more than 2 floors;
- "Condominium", which are areas with a set of houses or residential buildings.

Available at: https://www.guiaenergiaedificacoes.com.br/tipologias/residencial/

International References

GIZ/AFD - Programme for Energy Efficiency in Buildings (PEEB) [13]

In its publication "Smart and Efficient – Digital Solutions To Save Energy In Buildings" (2019), it does not present a subdivision by types of buildings.

Available at: http://www.peeb.build

DENA – German Energy Agency [14]

In its publication "Rolle der Digitalisierung im Gebäudebereich" (2017), three types of buildings are considered:

- One- and two-family home (EFH / ZFH);
- Multi-story apartment building (GWB);
- Non-residential building (NWG).

Available at: https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/rolle-der-digitalisierung-im-gebaeudebereich.html

IEA – International Energy Agency [15]

On its platform, in the Home Energy Use section, residential final energy consumption is subdivided into four types:

- Single-family (detached or semi-detached);
- Apartments (2-4 units) and (more than 5 units);
- Mobile homes (trailers).

Available at: https://www.eia.gov/energyexplained/use-of-energy/homes.php

Directive 2010/31/EU on the energy performance of buildings (2018) [16]

It classifies buildings into the categories below, subdividing the residential sector into just two types:

- Single-family residences of various types;
- Apartment buildings;
- Office buildings;
- Educational establishments;
- Hospitals;
- Hotels and restaurants;
- Sports facilities;
- Buildings for wholesale and retail services;
- Other types of buildings that consume energy.

Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN

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Appendix 3 – Overview of digital solutions in the buildings sector

Digital technologies menu	Relationship with Industry 4.0	Commercial and Service	Public	Single-family Residences	Multifamily Residences	Social Interest Housing	Districts
Building Information Modeling (BIM)	Simulation Systems integration Cloud computing	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation
Building Energy Modeling (BEM) Urban Energy Modeling (UBEM)	Simulation Cloud computing	Design Operation Renovation	Design Operation Renovation	Design Renovation	Design Renovation	Design Renovation	Design Operation Renovation
Computational Fluid Dynamics (CFD)	Simulation	Design Renovation	Design Renovation	Design Renovation	Design Renovation	Design Renovation	Design Renovation
Simulation of natural and artificial lighting	Simulation	Design Renovation	Design Renovation	Design Renovation	Design Renovation	Design Renovation	Design Renovation
Energy Portfolio Management Systems	Simulation Systems integration Cloud computing	Design Construction Operation Renovation Demolition	Design Operation Renovation	Design Operation Renovation	Design Operation Renovation	Design Operation Renovation	Design Operation Renovation
Software for Life Cycle Assessment (LCA)	Simulation Systems integration Big Data and Analytics	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition
3D printing	Additive manufacturing Automation	Construction Operation Renovation	Construction Operation Renovation	Construction Operation Renovation	Construction Operation Renovation	Construction Operation Renovation	Construction Operation Renovation

Digital technologies menu	Relationship with Industry 4.0	Commercial and Service	Public	Single-family Residences	Multifamily Residences	Social Interest Housing	Districts
Augmented reality	Simulation Augmented reality	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation
Blockchain	Cloud computing Big Data and Analytics Cybersecurity Automation	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition	Design Construction Operation Renovation Demolition
Agile Management Software	Cloud computing Systems integration	Design Construction Renovation	Design Construction Renovation	Design Construction Renovation	Design Construction Renovation	Design Construction Renovation	Design Construction Renovation
Building Management Systems (BMS)	Systems integration Big Data and Analytics Automation	Construction Operation	Operation		Operation		
Smart sensors, actuators and switches	Systems integration Big Data and Analytics Automation	Construction Operation	Construction Operation	Operation	Construction Operation	Construction Operation	Operation
Digitally Addressable Lighting Interface (DALI)	Systems integration Big Data and Analytics Automation	Operation	Operation		Operation		
Smart facades and other systems	Automation Systems integration	Operation	Operation	Operation	Operation		
Virtual assistants	Internet of Things Big Data and Analytics Systems integration Automation	Operation	Operation	Operation	Operation	Operation	

Digital technologies menu	Relationship with Industry 4.0	Commercial and Service	Public	Single-family Residences	Multifamily Residences	Social Interest Housing	Districts
Smart apps and controls	Internet of Things Big Data and Analytics Systems integration Automation	Operation	Operation	Operation	Operation	Operation	Operation
Smart sockets and electric vehicle chargers	Internet of Things Systems integration Automation	Operation	Operation	Operation	Operation	Operation	Operation
Smart electrical and electronic equipment connected to the grid	Internet of Things Systems integration Automation	Operation	Operation	Operation	Operation	Operation	
Demand response, awareness and gamification apps	Big Data and Analytics Simulation	Operation	Operation	Operation	Operation	Operation	Operation
Cloud Computing	Big Data and Analytics Cloud computing	Design Construction Operation Renovation	Design Construction Operation Renovation	Design Construction Operation Renovation	Design Construction Operation Renovation	Design Construction Operation Renovation	Design Construction Operation Renovation

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