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CLIMATE-ACTIVE BUILDING ENCLOSURES: AN INTEGRATIVE LITERATURE REVIEW

ENVELOPES CONSTRUTIVOS ATIVOS: UMA REVISÃO INTEGRATIVA DA LITERATURA

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Abstract

The building energy demand and anthropogenic greenhouse gas emissions have risen since the preindustrial period, reaching the highest levels. Brazil is the eighth largest consumer of primary energy globally, with buildings accounting for 51.2% of the total electric energy consumption. In this sense, the building enclosure has substantial potential and the lowest cost for reducing energy expenditure. The dynamicity of environmental factors allows for many design approaches, and since the user comfort analysis evolved, time-varying building skin configurations emerged. When coupled with computational design, the building's skins no longer must compromise to one stationary condition that is never optimal to any particular condition. These climate-active envelopes need a seemingly conveyed characterization or a straightforward design process as a relatively new technique. We aimed to differentiate climate-active building typologies and gather the latest compositions and performance assessment metrics, rendering an integrative literature review, state-of-the-art, and bibliometric analysis. As the main results, we assembled tabular data on 100 research pieces considering various study methodologies, climate-active typologies, movement categories, actuation styles, simulation engines, and performance criteria, demonstrating that most studies evaluated facade typologies, concerned temperate climates and adopted simple, binary movement characterizations. Furthermore, the design process for active building enclosures needs to be clearer and well-structured, and the available computational tools still need improvement.

Keywords: climate-active. bibliometric analysis. state-of-the-art. building performance.

Resumo

A demanda energética de edifícios e emissões antropogênicas de gases estufa têm aumentado regularmente desde o período pré-industrial, atingindo seus níveis mais altos na atualidade. O Brasil é o oitavo maior consumidor de energia primária do mundo, com edifícios respondendo por 51,2% do gasto total de energia elétrica. Nesse contexto, envelopes construtivos têm grande potencial para redução do consumo energético. A dinamicidade dos fatores ambientais permite diversas técnicas de condicionamento e, com a evolução das métricas de análise de conforto do usuário, simultaneamente surgiram novos arranjos construtivos mutáveis. Quando atrelados a recursos computacionais, essas envoltórias não precisam se comprometer com uma condição estacionária e nunca ideal. Ademais, os envelopes ativos não possuem caracterização precisa ou metodologia padrão de projeto, principalmente devido à atualidade do tema. Objetivamos diferenciar tipologias ativas para envoltórias, compilando as mais recentes composições formais e metodologias de avaliação ambiental, realizando uma revisão integrativa de literatura, estado-da-arte e análise bibliométrica. Como principais resultados, tabulamos 100 pesquisas considerando metodologias de pesquisa diversas, diferentes tipologias ativas, classificação de movimento, estilo de atuação, programas de simulação computacional e métricas de desempenho, concluindo que os estudos compilados focam majoritariamente em avaliação de fachadas, ocorrem principalmente em climas temperados e normalmente adotam movimentações simples e binárias. Além disso, o processo de projeto, simulação, otimização e caracterização de movimento de envelopes ativos não é bem estabelecido ou padronizado e as ferramentas computacionais ainda são ineficazes.

Palavras-chave*: envoltórias ativas. análise bibliométrica. estado da arte. desempenho de edificações.*

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Introduction

Buildings are among the largest energy consumers worldwide, with up to 40% of the total energy requirement and 36% of carbon emissions (Zhou; Nazi; Wang; Roskilly, 2019). Despite the growth of emerging economies, developing countries are still responsible for an unbalanced energy consumption per capita (Clarke et al., 2018). Besides, the extensive implementation of building equipment for heating, ventilation, and air-conditioning facilitates reaching user comfort requirements indoors, overlooking building passive design strategies. As a result, buildings assume a conspicuous energy expense, and the conventional building enclosure does not function efficiently enough to handle the matter. Therefore, roofs, walls, and windows perform separately (Yang, 2020).

Postmodernist[1] climate-concerned architecture shifted the primary function of the building envelope into a many-criteria mediator that encompasses tangible (e.g., air temperature, radiation, etc.) or intangible (e.g., cultural and social) relationships. This connection with the outdoors plays a considerable role in indoor performance, presenting the building enclosure with significant potential and the lowest cost among building operations for reducing energy demand and carbon emissions (Delgarm; Sajardi; Kowsary; Delgarm, 2016).

Passive design approaches, such as solar shading, daylighting, natural ventilation admittance, and thermal mass, are essential enclosure-related tactics for boosting comfort. However, passive strategies alone are counterproductive to the latest concept of building enclosure: a tectonic, skin-like feature with environmental and aesthetical relationships (Oxman, 2006, 2017; Schumacher; Vogt; Krumme, 2020).

As the environmental performance metrics evolved, time-changing envelopes became a viable strategy for enhancing visual and thermal comfort (Hosseini *et al*., 2019a). Given seasonal and daily changes in solar positions and sky conditions, climate-active envelopes[2] are highly effective for managing daylight and solar radiation based on indoor requirements (Kirimtat; Koyunbaba; Chatzikonstantinoi; Sariyildiz, 2016). Coupled with computational design, they no longer have to compromise to one static state that performs acceptably under a wide range of situations but is never optimal.

Climate-active envelopes need a clear definition in the architectural research field (Attia *et al.*, 2018). Researchers address only a few geometric and motion explorations on the enclosure level because active systems' design and performance evaluation are complex, and existing performance assessment tools are insufficient (Kolarevic, 2015; Loonen, 2018). We aim to investigate literature-found climate-active enclosures, documenting the methodologies, study's location and weather classification, active typology and mechanical movement, modeling, simulation, optimization software, and simulation objectives and metrics to outline architectural responsiveness.

Systematic, narrative, and integrative reviews on the topic are scarce and only present a global perspective on responsiveness, failing to describe, organize, and scrutinize computational simulation, experiments, mathematical calculation, and case studies (Alkhati; Lemarchand Norton; O'Sullivan, 2021; Hosseini *et al.*, 2019a; Tabadkan;

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[1] Postmodern architecture emerged in the 1960s in response to the International Style, encompassing High-Tech, Contemporary, Sustainable, etc. architecture (Hopkins, 2014).

[2] We adopt climate-active envelopes as a broad combination of several other classifications (kinetic, intelligent, responsive, biomimetic, and smart typologies). We accept them as passive-active solutions considering they operate either statically (optimally fixed shading devices) or kinetically (moving devices).

Valinejad Shoubi; Soflaei; Banihashemi, 2021). They provide a base for future studies but do not clearly define methodological procedures, leading researchers to misinterpret motion categories due to background-lacking research pieces.

Hence, we strive to answer the following questions: How to distinguish climate-active building enclosures? What are the latest envelope configurations, environmental assessment methodologies, and performance metrics? What are the next steps in building performance simulations for enclosures? Consequently, this study assembles the most applied climate-active envelope terminologies and design strategies to distinguish climate-active skins. We also address the advances in climate-active building envelope research, tabulating literature-missing data for evaluating and improving building performance.

Theoretical frameworks

This section clarifies unfamiliar terms, presenting geometric, mechanical, and control approaches for various climate-active typologies, i.e., kinetic, intelligent, responsive, biomimetic, and smart. We focus on large-scale kinetic transformations (i.e., changing function, form, and size) and small-scale, material-related deformations that generate motion.

Building envelope overview

The physical environment operates upon multiple parameters (e.g., light admission and blockage, energy gain and loss, etc.) with a complex relationship that the human body absorbs or counteracts (Tabadkani; Roetzel; Xian; Tsangrassoulis, 2021). Humans seek a balance between energy investment and environmental adjusting. The comfort zone is the successful balance between both (Olgyay, 2015). A shelter helps meet these comfort requirements by adjusting the indoor space to optimal conditions by filtering environmental factors.

20th-century architecture was a product of the Industrial Revolution and ever-changing technology (Benevolo, 2001). The new engineering methods from the 19th century striped buildings from passive thermal comfort techniques and electromechanical ventilation improvement compelled architects to pay more attention to their role as a buffer of comfort and energy (Reki, 2018). Consequently, energy consumption increased, forcing 21st-century postmodernist architects to reimplement passive strategies and explore innovative design solutions for adequate human comfort, leading to a revival of kinetic motion.

Active envelope approaches

Theoretical interest in kinetic architecture arose with Futurism, Constructivism, and Expressionism in the first third of the 20th century. In the 1960s, Megastructure architecture planned to exclude static Functionalism, embracing change and motion through society's evolving needs (Schimidt III; Austin, 2016). In the 1970s, Zuk and Clarke (1970) classified kinetic structures by their application, separating them into static, kinetically controlled, self-erecting, reversible, incremental, deformable, mobile, and disposable. Later, Nicholas Negroponte coined the concept of a responsive environment utilizing computation (Negroponte, 1973).

Still, building components that could react to environmental conditions would only appear later in the 20th century. Information technology and data retrieval improved, and artificial intelligence facilitated spatial change without human resources. The developments in generative, parametric, and algorithmic thinking supported the surge of kinetic systems, helping to comprehend and conceive responsive systems (Schumacher, 2016).

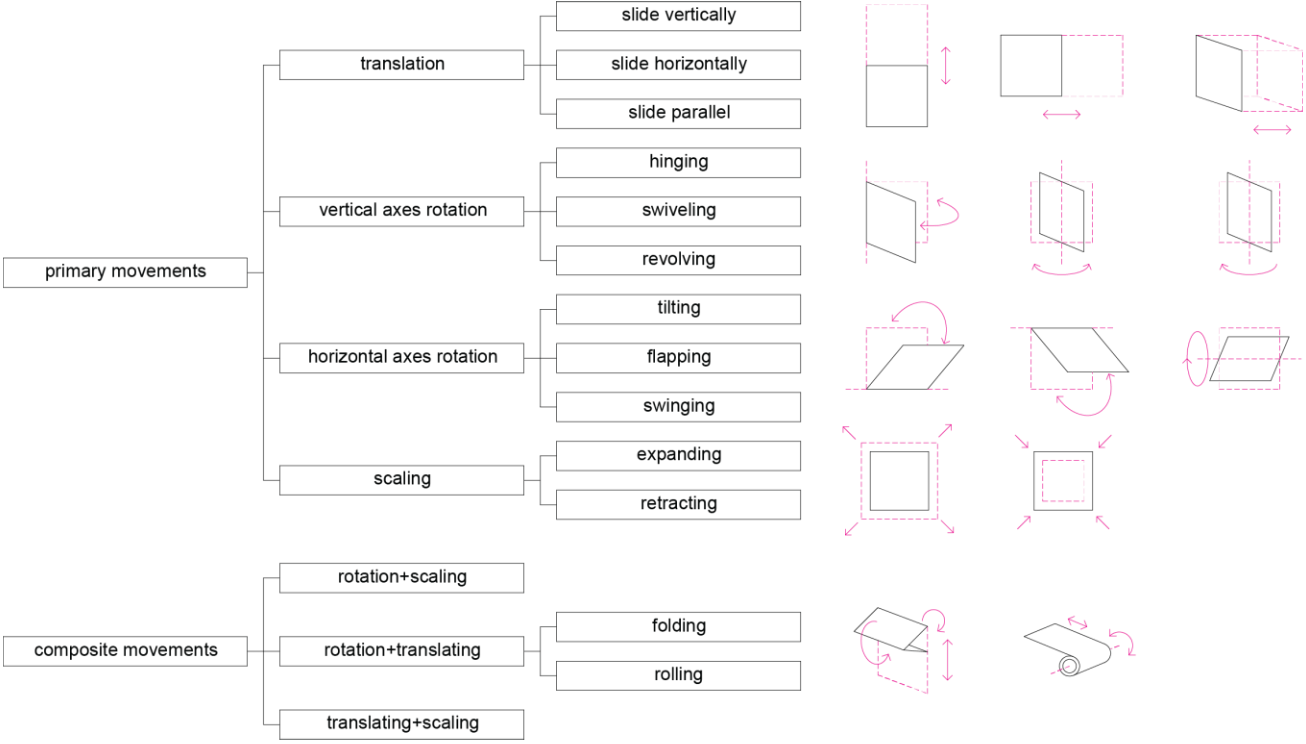
Nowadays, several interchangeable terms depict buildings with time-varying façade characteristics (Loonen, 2018). The most common variations include adaptive (Lo Verso *et al.*, 2019), kinetic (Shi; Tablada; Wang, 2020), responsive (Hosseini; Mohammadi; Guerra-Santin, 2019b; Yang, 2020), intelligent (Yi *et al.*, 2020), biomimetic (Augustin, 2018; Sheikh; Asghar, 2019), and smart (YOON, 2019).

We employ climate-active enclosures as a compilation, acknowledging all the classifications as smaller groups. We define climate-active envelopes as self-adjusting surfaces that contain systems with mechanical, moving, or advanced electronics or materials with varying intrinsic characteristics. These envelopes can change according to indoor and outdoor parameters, building performance criteria, weather sensing and prediction, environmental stimuli, user's needs and interactions, and etc.

Architectural components – geometry and motion

The first step of designing active envelopes is selecting their geometrical form and defining their primary movements (Ferschin; Di Angelo; Brunner, 2015). Moloney (2011) developed the basic kinetic patterns, which depict single movements and variations according to anchor points (Figure 1). The primary motion patterns were translation, rotation, and scaling. Other typologies could emerge from these simple patterns based on degrees of freedom, geometric restrictions, and coordinate axes. Also, combining primary patterns can generate composite configurations such as folding and rolling.

Figure 1 - Geometric motion classification - spatial movement vocabulary



Source: adapted from Moloney (2011).

Kinetic, responsive, intelligent, and biomimetic approaches (following sections) often deliver rigid or mechanic macro-level adaptation. Conversely, a microscale strategy considers material molecular structure and deformations. Smart and seldom biomimetic systems employ microscale transformation.

Kinetic typology

The kinetic architecture comprises technological systems in constant transformation driven by variable stimuli over a stipulated interval (Nguyen, 2019). These systems change building environmental performance according to outdoor conditions rather than indoor requirements. Other names for kinetic devices are deployable, retractable (Heinzelmann, 2018), dynamic (Schielke, 2019), convertible (Wang; Perez Morata, 2019), transformable (MATHEOU; COUVELAS; PHOCAS, 2020), and shape-shifting (Kolarevic, 2015).

Kinetic systems can be either conventional or complex. A conventional device displays one moveable element, a single motion pattern, or several identical components (such as Venetian blinds). Complex systems present more innovative forms with composite movement patterns.

Intelligent typology

The term ‘Intelligent’ gained widespread in the 1980s, accompanied by ‘smart architecture’ indiscriminately referring to capabilities of materials, structures, and buildings. Nowadays, intelligence conveys functionality for building structures that understand indoor and outdoor conditions and selects the most convenient operation for achieving a comfortable environment based on predictive models and minimal user intervention. Intelligent envelopes comprise perception, logic, and action, applying sensors and computational protocols to re-balance the indoor space without manual interference. Unlike kinetic models, a smart system can use future weather fluctuation to learn from occupants’ reactions (Knaack; Klein; Bilow; Auer, 2014).

For instance, Böke, Knaack, and Hemmerling (2020) developed a cyber-physical intelligent skin with various modules for selecting solar shading, natural and mechanical ventilation, and heating and cooling, creating a system that allows all processes to intercommunicate.

Responsive typology

Responsiveness indicates that building enclosures can adapt to weather oscillations instead of shutting the environment out. These envelopes benefit from the natural energy sinks and sources in their surroundings, improving functional building requirements (Loonen, 2018).

The first applications of contemporary responsiveness emerged in the early 21st century (Knaack; Klein; Bilow; Aue, 2014), complementing the broader and misleading intelligent definition from the 80s. For Bui *et al*. (2020) and Loonen (2018), responsiveness means changing properties over time to decrease energy consumption. Other terms are adaptive (Lee; Cho; Jo, 2021), interactive (Panya; Kim; Choo, 2020), and interchangeable.

We adopt the latest definition of responsiveness as a climate-active typology able to “deliver multi-objective comfort [...] under uncertain environmental conditions by changing its physical characteristics [to match people’s needs] within a short-timing scale” (Tabadkani; Roetzel; Xian; Tsangrassoulis, 2021, p.2).

Responsive envelopes are an evolution of kinetic and are not so different from intelligent systems. Like the former, they employ sensor networks, controllers, and actuators but respond to an action rather than moving according to programming. As the latter, responsive systems include real-time perception, building automation, and user-oriented operations. However, they can learn to self-adjust by progressively instructing the building and users, offering the manual override possibility, which is minimal in intelligent systems.

In responsive designs, the outdoors influence, reprogram and reconfigure the building envelope. "Rather than the designer predetermining appropriate responses to user inputs, the system measures reactions to its outputs and continually modifies its actions according to these responses" (Velikov; Thün, 2017, p.70).

Biomimetic typology

The biomimetic design incorporates biological compositions and processes into technological applications. A direct biomimetic approach copies the observed functionality for responding to changes in environmental situations. In contrast, the indirect technique abstracts the biological principle, loosely basing the result on the natural aesthetic (Pawlin, 2019; Romano; Aelenei; Aelenei; Mazzucchelli, 2018). Plant structure, growth, and development contemplate biomimetic envelopes as they perform similarly, responding to daylight (phototropism), radiation (heliotropism), and humidity.

Unlike the previous typologies, biomimetic systems can apply macro (mechanical movement) or microscale adaptation. They respond to environmental conditions within certain thresholds rather than complying with a parameter-based movement (Reichert; Menges; Correa, 2015).

Smart typology

Smart typologies correlate to kinetic, intelligent, and responsive classifications, as their main concept is adapting to external stimuli. The terms intelligent and smart were interchangeable in the 1980s. Their biggest difference is that intelligence relates to computation and automation, whereas smart features result from material intrinsic properties. Smart typologies can appear in any other active classification, enhancing mechanical actuation with material-imbued qualities.

For instance, an external force or energy supply can deform or modify their initial configuration; a subsequent exposure to an environmental agent will return the material to its primary shape. Their activity is typically binary and limited but is self-powering and self-actuating (Heinzelmann, 2018). Examples of smart materials include stimulus-responsive materials (SRMs), phase change materials (PCMs), color-changing paints, and building-integrated photovoltaics (BIPV).

Materials and methods

This section details the methodology for executing an Integrative Literature Review (ILR), electing the state-of-the-art, and presenting a bibliometric analysis. We cover multi-disciplinarily analyses of climate activity regarding study procedures, research locations, design solutions, active typology, movement characterization, and building performance simulation software and metrics.

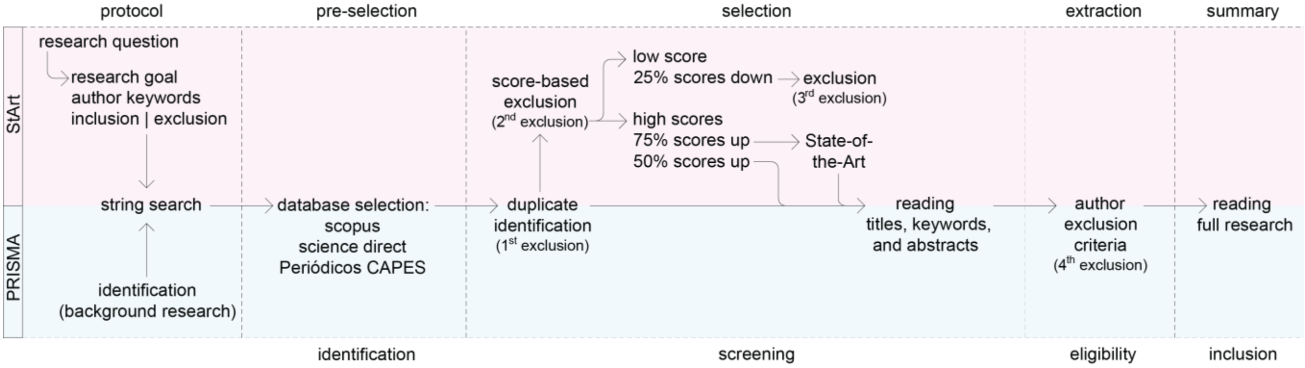
An ILR is an extensive investigation that contributes to deepening discussions on research methods and results, helping future studies on a distinct issue. It "reviews, critiques, and synthesizes representative literature on a topic [...] [to generate] new frameworks and perspectives [...]" (M*oher;* Liberati; Tetzlaff; Altman, 2009, p. 1). They normally apply to "dynamic topics that experience rapid growth in the literature" (Moher; Liberati; Tetzlaff; Altman, 2009, p. 1), especially because these are relatively unexplored and have not yet undergone an exhaustive examination.

ILRs incorporate different methodologies (i.e., literature review, mathematical calculations, physical experiment, etc.) into a single research object, allowing a combination of theoretical and empirical applications. Bibliometric analysis is a means for quantitatively interpreting a considerable volume of scientific information, graphically depicting the latest research breakthroughs and developments. Also, we portray state-of-the-art as the congregation of the most up-to-date research on a topic to uncover new research subjects, methods, and sub-topics.

Integrative literature review stages

For the ILR, we applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) workflow and the State-of-the-art through Systematic Review software (StArt v. 3.4) (Fabbri *et al*., 2016; Moher *et al*., 2009). The StArt Tool separates the research process similarly to the PRISMA methodology, making both approaches compatible (Figure 2).

Figure 2 - PRISMA and StArt methodological steps



Source: the authors.

StArt helps organize data, filter duplicate productions, score publications according to user-selected keywords (title, abstract, and keywords), and identify recurrent authors and topics. It also outputs BibTex and RIS files (research information and plain bibliography style), later utilized in the bibliometric analysis as input for VOSviewer 1.6.1.7's authors and co-authors network and keyword analysis.

Our review process comprises five stages (Figure 2): protocol (StArt exclusive), pre-selection or identification, selection or screening, extraction or eligibility, and summary or inclusion. In the first stage of the StArt/PRISMA workflow, we state our "research goal, research questions, [and] search and selection strategies [...]" (Moher *et al*., 2009, p.2). Our ILR questions are: What are the latest envelope configurations and environmental assessment methodologies and metrics? What are the next steps in building performance simulation for active enclosures?

This research aims to survey and discuss the characteristics, potentials, restrictions, approaches, and main results of state-of-the-art research on kinetic, intelligent, responsive, biomimetic, and smart applications. We considered papers, conference proceedings, dissertations, and thesis published in English and Portuguese from 2016 to 2022. We selected Scopus, Science Direct, and *Periódicos CAPES* as databases. We designated a set of synonyms, inclusions, and exclusions for searching criteria, using the most general terms in all string search attempts (Chart 1): buildings or enclosure typologies. Then, we added performance-related terms, such as simulation, parameterization, optimization, and manufacturing, or envelope-related terms, such as façade, canopy, roofing, and etc. Afterwards, we selected adjectives such as dynamic, active, kinetic, movable, responsive, interactive, and intelligent (TabadkanI; Roetzel; Xian; Tsangrassoulis, 2021). Database search compositions differ, and therefore, we adjusted the strings accordingly.

Chart 1 - Search strings and results for the protocol and pre-selection stages

Language	Database	Date	Search String	n° of pieces
en	Scopus	07/16/2022	(TITLE-ABS-KEY(“awning” OR “build* envelope” OR “build* enclosure” OR “canopy” OR “façade” OR “roof*” OR “shade*”) AND TITLE-ABS-KEY (“active” OR “adaptive” OR “automatic” OR “biomimetic” OR “dynamic” OR “interactive” OR “kinetic” OR “responsive”) AND TITLE-ABS-KEY (“daylight*” OR “light*” OR “energy” OR “glare” OR “illuminance” OR “radiation” OR “thermal comfort”) AND TITLE-ABS-KEY (“generative” OR “algorithm*” OR “optimize*” OR “parameter*” OR “simulation” OR “fabrication” OR “manufacture*”)) AND PUBYEAR>2015	709
en	Science Direct	07/16/2022	(“build* enclosure” OR “façade” OR “shade*”) AND (“kinetic” OR “responsive” OR “intelligent”) AND (“thermal comfort” OR “optimize*” OR “simulation”) AND PUBYEAR>2015	249
en	*Periódicos CAPES*	07/18/2022		152
pt	*Periódicos CAPES*	07/19/2022	*(“edifica*” OU “fachada” OU “sombra*) E (“cinético” OU “responsivo” OU “inteligente”) E (“conforto térmico” OU “otimiza*” OU “simulação”) E ANO>2015*	10
Total				1120

Source: the authors.

The string search incorporated terms within the same keyword category using the boolean operator OR. The operator AND appeared between different keyword categories (Chart 1). We applied the Portuguese version of all the keywords using the same boolean operators. Chart 1 also presents the number of research pieces found for each database.

The protocol stage in StArt has an embedded feature for scoring publications according to author-selected keywords. If the designated keyword appears on the collected publication title, StArt grants five points; if the word appears in the keyword section, three points; if they appear on the abstract, StArt assigns two points. All keywords appear in the search strings in Chart 1.

The next step is pre-selection (PRISMA identification) (item 1 in Table 1), in which the researcher loads the bibliographic information (publication title, authors, keywords, and abstract) into the StArt Tool. We collected 1120 research pieces based solely on the string search inclusion/exclusion criteria. Removing the duplicated files also occurred during the pre-selection stage. As seen in Table 1, item 2, we excluded 55 occurrences.

Table 1 - Pre-selection, selection, and extraction stages

language	database	(1)	(2)	(3)	(4)	(5)	(6)	(7)
		pre-selection stage	duplicated	selection stage	rejected researches	extraction stage	rejected researches	total research pieces
en	Scopus	709	12	697	601	96	53	40
en	Science Direct	229	25	204	171	33	18	15
en	*Periódicos CAPES*	172	18	154	25	129	85	44
pt	*Periódicos CAPES*	10	0	10	9	1	0	1
Total		1120	55	1065	706	259	126	100

Source: the authors.

The following stage is the selection (screening) (item 3 in Table 1), in which we rejected papers based on StArt scoring and author-defined criteria. We assessed all 1065 studies through titles, keywords, and abstracts, eliminating any irregular occurrence or duplicated pieces (not accounted for by StArt). For the selection, we adopted four exclusion criteria: (i) research has a low StArt score; (ii) the study is not available; (iii) the study is a peer-reviewed publication; (iv) the study covers only prescriptive design solutions (passive or analog strategies with no active motion).

Scoring in StArt grants five, three, or two points for each author-selected keyword appearance. The highest publication score in this research was 224. We consider any score below 25% (56 points) ineligible, as most did not cover climate adaptiveness. As seen in Table 1, we rejected 706 papers.

We read all 259 papers for the extraction (eligibility) stage (item 5 in Table 1) and removed further passive technologies that did not convey motion. We also rejected studies with no building performance evaluation and others not complying with the inclusion/exclusion criteria established in the screening phase. We separated our findings into two datasets (Lucarelli; Oliveira; Carlo, 2023). Dataset 1 (Lucarelli; Oliveira; Carlo, 2023) presents all 23 scores above 112 StArt points (50% of the highest score, 224), and within the last three years (2019, 2020, and 2021, since 2022 returned no papers) and composes the state-of-the-art. Among these 23 studies, we addressed and further scrutinized the most promising investigations.

Our qualitative selection concerns methodology complexity, combined research methods, novel approaches, distinct geometric compositions, and interesting results. Even though we did not discuss the remaining 77 studies, they are listed in the Dataset 2 (Lucarelli; Oliveira; Carlo, 2023). Therefore, both datasets present each study with its methodology, location, weather classification, active typology, movement classification, modeling suite, simulation software, optimization motor, and StArt score based on our keyword selection.

Results

With the highest StArt score (224) (Lucarelli; Oliveira; Carlo, 2023), Hosseini, Mohammadi, and Guerra-Santin (2019b) presented quali-quantitative research on daylight systems. Using Google Scholar and Scopus as academic research databases, the authors offered a brief literature review on light redirecting systems (from 1974 to 2017). As the highest-ranked research based on StArt scoring, their study is a complete composition that combines literature review and building performance simulation, addressing literature gaps, and adopting the most up-to-date software and performance metrics. However, the authors presented anidolic components, redirecting mirrors, diamond-shaped domes, perforated metal sheets, etc. as innovative static systems. Even though these strategies provide sunlight redirection, they only present technological innovation when coupled with computational methods for shape prediction, optimization, simulation, motion, and etc.

Furthermore, Hosseini, Mohammadi, and Guerra-Santin (2019b) referred to kinetic systems as dynamic, encompassing tracking systems, PCMs, and other dynamic configurations. Tracking systems would better describe intelligent or responsive architecture (depending on user-oriented operations), and PCMs would better fit the smart category. The authors also provided various geometric classifications (i.e., flapping, folding, translating, expanding, and extracting) but failed to clarify the primary motion types and composite arrangements. Regardless, they presented interesting tabular data on light redirecting configurations, rightly distinguishing the kinetic system typology and simulation objective. They also pointed out that daylight control strategies interact with sun radiation, interior space requirements, and occupant position and demands.

Hosseini, Mohammadi, and Guerra-Santin (2019b) developed a parametric algorithm for two and three-dimensional shape-changing façades to assess visual comfort and field of view in response to the sun's position. The authors discovered that although both configurations present significant potential for meeting visual comfort requirements, the three-dimensional façades deliver better useful daylight illuminance levels.

Although thermal metrics did not appear in their study, the authors affirmed that the façade could also prevent thermal discomfort, decreasing more than 98% solar heat gain compared to the base case. They concluded the study by declaring that the next step in the climate-active façade assessment would be applying the simulation logic to a real kinetic device. However, their three-dimensional façade presented scaling and transforming motion that did not translate to real-world materialization constraints. The authors might rework the selected geometry, utilizing rotating and translating motion for a similar geometric approach.

Yang (2020) applied a systematic approach to daylight evaluation using intelligent façades and skylight systems. Yang (2020) was the first study in this ILR that involved top-lighting strategies. We only found four other investigations, emphasizing the need for other active top-lighting applications. He simulated a cuboid (7mx7m) and shoebox model (6mx8m) using a parametric workflow for evaluating indoor illuminance through useful daylight illuminance, glare through daylight glare probability, and solar heat gain, similar to Hosseini, Mohammadi, and Guerra-Santin (2019b).

The simulations run for June 21st, September 21st, and December 21st, representing the northern hemisphere's hot, cool, and cold seasons. Adopting three or four representative days is typical in several other investigations in our ILR. The small representativity of simulation days is normally due to computational expense. An appropriate evaluation of indoor daylight and thermal performance should include complete annual indices, which is not feasible using the available simulation tools. Despite the few simulation days, we comprehend Yang's (2020) study as a noteworthy takeoff on building performance simulation and active approaches. Based on our ILR, the author could have proposed optimization states for various days, interpolating hour-specific simulation results with pre-determined geometric conditions. Besides, the control process only assessed environmental constraints, not involving the occupant's feedback.

Shi, Tablada, and Wang (2020) investigated the influence of two motion typologies on building performance simulation for active façades, evaluating energy expenditure and daylight. In this ILR, they are the first authors to address energy expenditure and human comfort parameters. Their research comprised modeling, simulation, and analysis within a single procedure. The authors applied the Rhino3D+Grasshopper suite creating a fan-like skin. We consider the object an innovative approach to geometrical characterization since it encompasses various motion axes, creating other classifications such as scaling, expanding, and retracting within material constraints.

They adopted a theoretical office space with a typical open floorplan instead of a cuboid or shoebox model. They applied daylight autonomy and useful daylight illuminance as visual comfort calculation indexes. They evaluated three simulation models (base case, dynamic folding motion, and dynamic rotating motion) for four days (March, June, September, and December 22nd) and three hours (9 am, noon, and 3 pm). They employed the hourly energy consumption in Wh/m^2 using Honeybee for energy examination.

Daylight autonomy and useful daylight illuminance were typical visual metrics improved with active applications, rendering static envelopes inefficient in all investigations with stationary base cases. However, Shi, Tablada, and Wang's (2020) simulation results showed that not all façade configurations positively affect daylight performance due to the various parametric combinations.

Heretofore, all studies covered some environmental analysis tools (experiment, simulation, case study, and etc.). However, we selected Hosseini *et al.'s* (2019a) research as an example of a literature review on various approaches to active design processes. Likewise, we also point to Tabadkani, Roetzel, Xian, and Tsangrassoulis (2021) paper as a state-of-the-art example of building performance classification for various active systems, even though their study ranked 23rd.

Hosseini *et al.'s* (2019a) study covered six complementary subjects: kinetic systems, biomimicry, building geometry, energy efficiency, comfort conditions, and parametric design thinking. After the systematic research, the authors concluded that, until 2019, studies for proposing kinetic façades were relatively rare, principally when coupled with visual requirements. However, we found 72 research pieces analyzing, simulating, or proposing active shading systems; among those, 43 are kinetic (Heinzelmann, 2018; Nguyen, 2019; Tabadkani; Banihashemi; Hosseini, 2018), and 60 concern visual analysis (Elkhatieb, 2016; Yi; Sharston; Barakat, 2019). Hosseini *et al*. (2019a) also stated that generative and parametric studies could help respond to climate fluctuations with high adaptability and create a framework for designing active façades. Nonetheless, they did not consider façade categories, only addressing biomimicry and kinetics, later revised in Tabadkani, Roetzel, Xian, and Tsangrassoulis (2021) and Alkhatib, Lemarchand, Norton, and O'Sullivan (2021) research. Likewise, the authors did not acknowledge dynamic daylight measures (e.g., daylight autonomy, spatial daylight autonomy, useful daylight illuminance, and etc.) or adaptive comfort strategies.

Yi, Sharston, and Barakat (2019) investigated the effects of auxetic shading systems with varying shapes for daylight and glare. In this ILR, we consider their approximation very innovative, applying an interpretation of Iranian patterns to a kinetic structure. Even though pattern inspiration is a common approach for design, they developed an interesting geometry that applies rotation and translation, causing scaling transformation. We only consider translational, rotational, and scaling movement as the base geometry modifications because the transformation is mechanical, not intrinsic; their study is the first to apply all three basic movements. The authors also developed an equation to find the number of vertices according to the façade angulation, facilitating the simulation process. Yi, Sharston, and Barakat (2019) stated that the geometry responds to varying outdoor and sky conditions. We consider the structure kinetic since it did not involve any sensors and only relied on simulation data.

Tabadkani, Valinejad Shoubi, SoflaeI, and Banihashemi (2019) developed a comprehensive literature review to create an origami-based active system using three numerical timing patterns. As we commended Yi, Sharston, and Barakat (2019) research, we also acknowledge Tabadkani, Valinejad Shoubi, Soflael, and Banihashemi (2019) for their approach to digital modeling.

The authors used 'adaptive' to signify a "potential to react or benefit from external climatic conditions to meet occupant comfort and well-being requirements" (Tabadkani; Roetzel; Xian; Tsangrassoulis, 2021, p. 3). Our study classifies their approach as responsive since the design reacted to real-time weather conditions and assessed user needs. We also note that the authors would later rectify the proposed adaptive category, establishing a theoretical background for each active typology (Tabadkani; Roetzel; Xian; Tsangrassoulis, 2021). They aimed to design a modular hexagonal responsive origami-inspired shading design, highly integrated with the dynamic building system. Since origami is a folding-based technique, the geometry showed a composite movement (rotation + translation). The authors created 1800 design examples in the modeling stage based on several variables, including rotation, indoor view, and transmittance properties.

To evaluate daylight and glare, Tabadkani, Valinejad Shoubi, Soflaei, and Banihashemi (2019) ran useful daylight illuminance, daylight glare index, and daylight glare probability simulations for each building skin configuration on March, June, September, and December 21st. They considered four days instead of three (which all authors have done until now). For daylight metrics, both equinoctial days would present comparable results. Unlike the other studies, they applied other simulation parameters such as glazing ratio, task area height, space width, length and height, wall, ceiling, and floor reflectance, and etc. The authors selected proper daylight illuminance maximization as optimization criteria, maintaining daylight glare probability below the perceptive range. Compared to Yang (2020), they did not prioritize glare over illuminance values.

Yi and Kim (2021) used smart materials to study a self-shaping building skin. Even though they presented their study as a first approximation to kinetic motion using these materials, other studies have already experimented with smart actuation and even employed digital manufacturing techniques (Yoon, 2019, 2021; Yoon; Bae, 2020). However, as the previous authors did, they evaluated shape-memory alloy applications instead of shape-memory polymers. They investigated the controllability of shape memory alloys in building performance applications, reverting the scope of Yoon’s (2019) research that evaluated the benefits of shape memory polymers instead of managing indoor conditions through controlled transformations.

Yi and Kim (2021) are the first authors to couple simulation, materialization, and environmental survey techniques in our state-of-the-art. Although Yoon (2019) applied prototyping techniques and assessed materialization parameters, Yi and Kim (2021) assembled physical thermal and daylight data to validate their simulation. They created two 1:20 building models: one with a motor-controlled shading and the other with an actuated shading as a test case, demonstrating that thermo-mechanical shape memory alloy applications could achieve comparable results to kinetically-actuated devices.

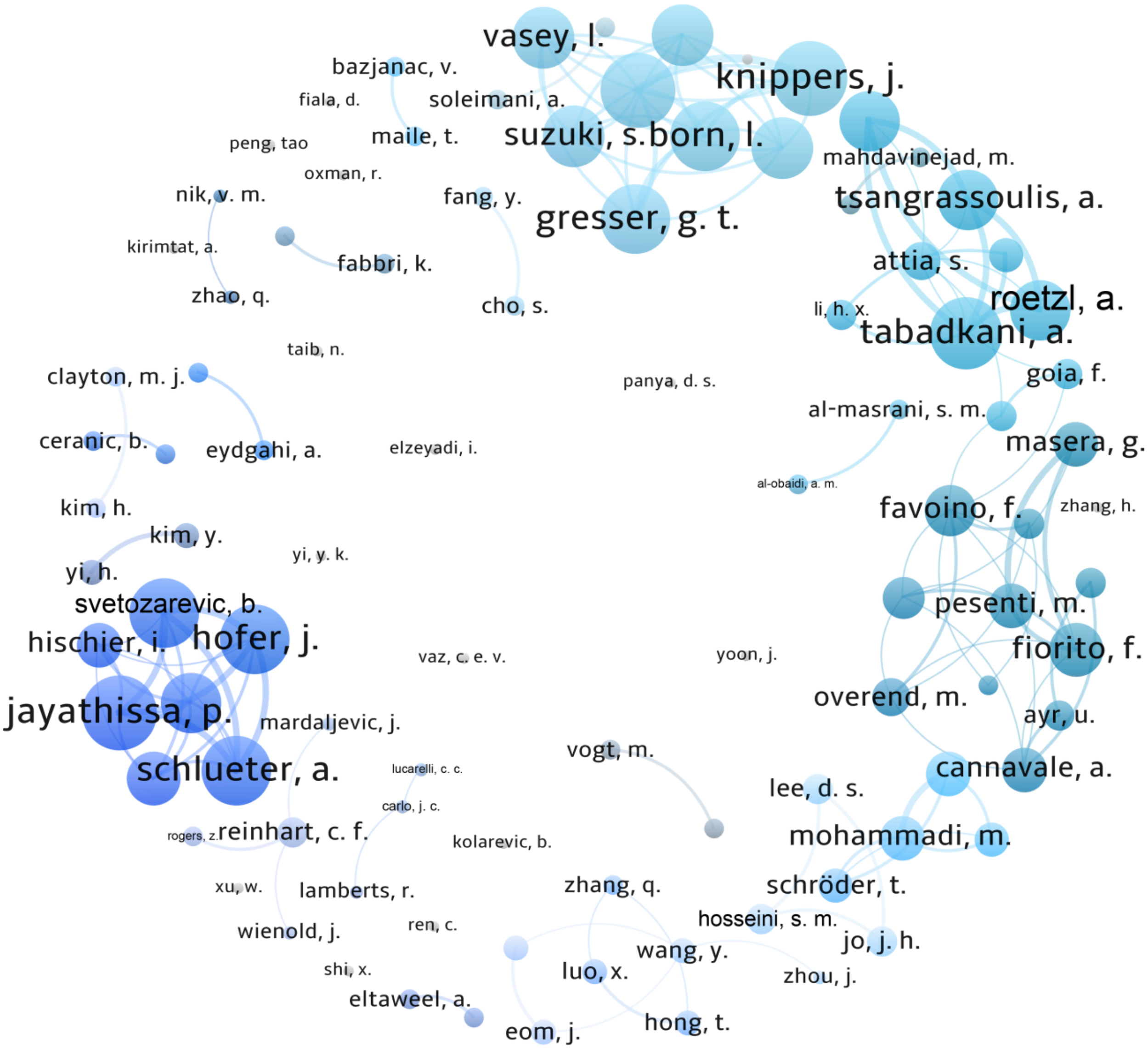
Further research pieces on active envelopes

All 100 research pieces in this ILR are essential for developing up-to-date research on active building envelopes (Lucarelli; Oliveira; Carlo, 2023). The studies that did not comply with our state-of-the-art criteria (scores above 112 points and within the last three years) are still very representative and fulfilled all inclusion criteria. We followed a specific methodology for creating the state-of-the-art, which upholds the remaining studies. As we see in Dataset 1 (Lucarelli; Oliveira; Carlo, 2023), all studies scored at least 56 points, present one or more building performance criteria, depict a specific movement and actuation (macro or micro), and are within the time limit set in the search strings.

Bibliometric analysis

We used VOSviewer 1.6.1.7 to create a co-authorship cluster analysis (first authors and co-authors) considering all studies (Figure 3). We adopted ten maximum authors per document and a minimum of 3 papers per author.

Figure 3 – Co-authorship analysis

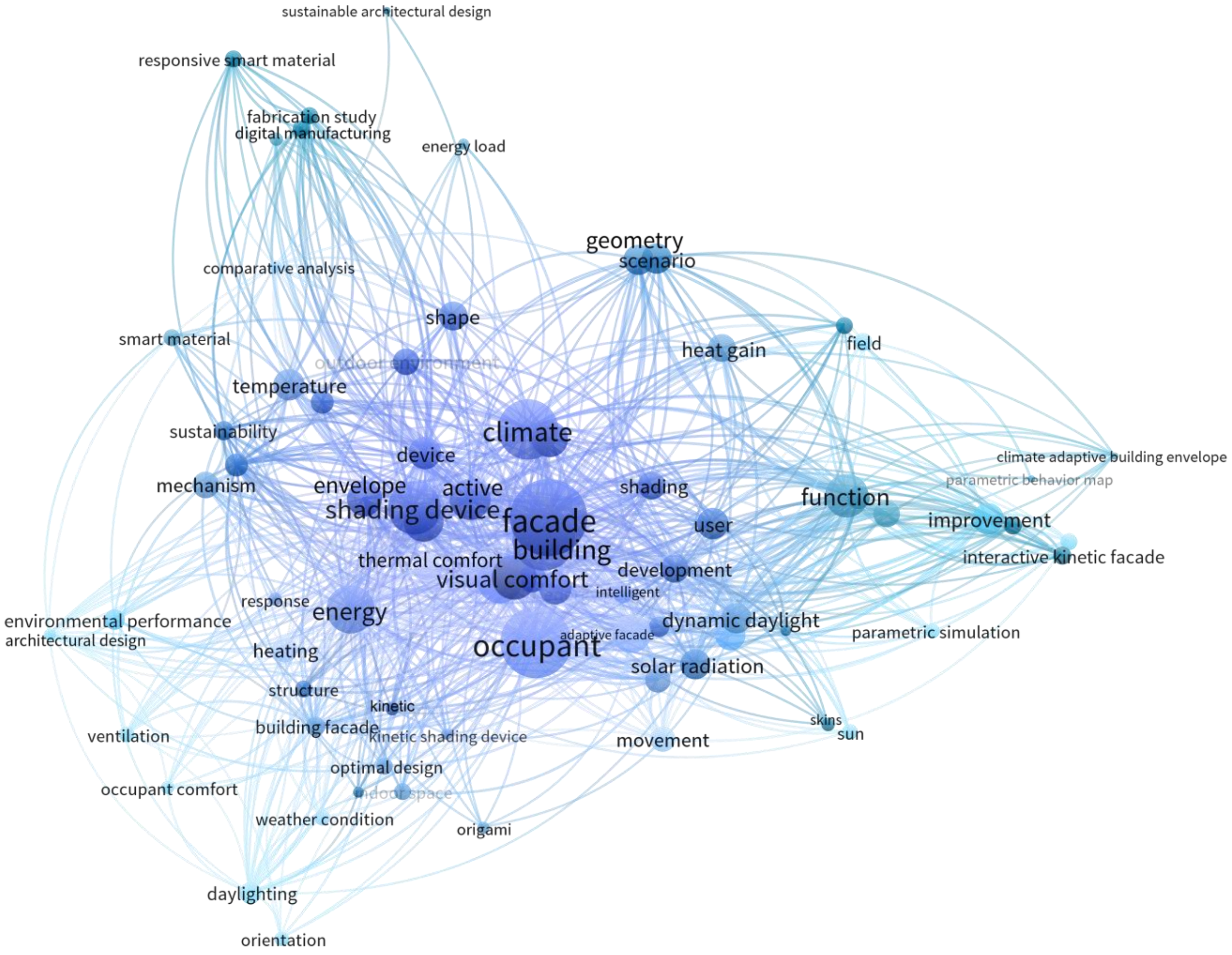


Source: the authors.

Wider circles and larger names represent higher name occurrences; the lines indicate the author networks and co-authorships; different colors represent research groups. Some authors have no connections, representing no coincident research. Although important for this ILR, some authors have limited or no co-authorship connections (De Dear; Brager, 1998; Kirimtat; Koyunbaba, Chatzikonstantinou; Sariyildiz, 2016; Kolarevic, 2015; Oxman, 2017). Most wider circles adequately represent our state-of-the-art and ILR and describe the higher-scored research pieces (Fiorito *et al.*, 2016; Loonen, 2018; Nagy *et al.*, 2016; Svetozarevic *et al.*, 2019; Tabadkani; Roetzel, Xian; Tsangrassoulis, 2020).

Furthermore, Figure 4 displays the most usual terms on selected research titles, abstracts, and keywords. The analysis criteria are similar for both cluster analyses. The most recurrent words are 'façade, building, envelope, thermal comfort, visual comfort, occupant, and energy.' They are also part of our string search. Some of our classifications do not appear among the wider circles or in the cluster, indicating that active, kinetic, intelligent, and smart typologies are the most employed in building performance simulation studies.

Figure 4 – Keyword clustering



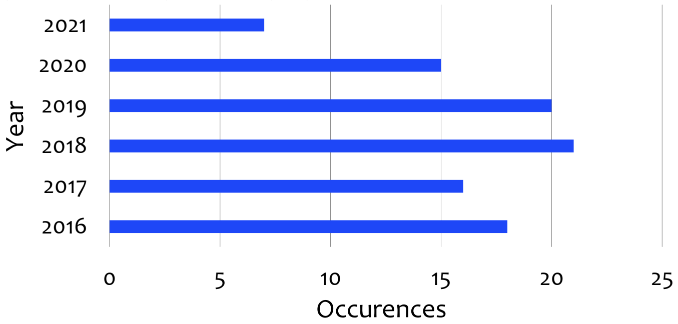
Source: the authors.

Based on these analyses, some keywords can be new additions to the search string since they show a good representativity in the clustering, i.e., heat, mechanism, occupant, temperature, and etc.

We also gathered study methodologies and location, active typologies, type of movement, modeling suite, simulation motor, and simulation metrics and presented a bibliometric analysis below. Although we only considered studies from 2016, the literature suggests that active façade systems are an uprising research topic. Even in a limited period, we observe an increasing publication pattern in building simulation modeling for climate-active envelopes per year (Alkhatib; Lemarchand; Norton; O'Sullivan, 2021; Tabadkani; Roetzl; Xian; Tsangrassoulis, 2020) (Figure 5). We understand that 2020 and 2021 were pandemic-ravaged (COVID-19), diminishing scientific publications in some academic fields, and, therefore, 2018 and 2019 appeared as the peak production years among the collected research pieces.

Even though our investigation encompassed all envelope typologies, façades appear to be the most common research approach with 89% of the studies. We only found five studies concerning top-light strategies and three stand-alone physical prototypes. For instance, all physical prototypes are part of experimental studies. Experiments appeared in 25% of the research pieces, and software simulation is the most common research approach, appearing in 80% of all investigations.

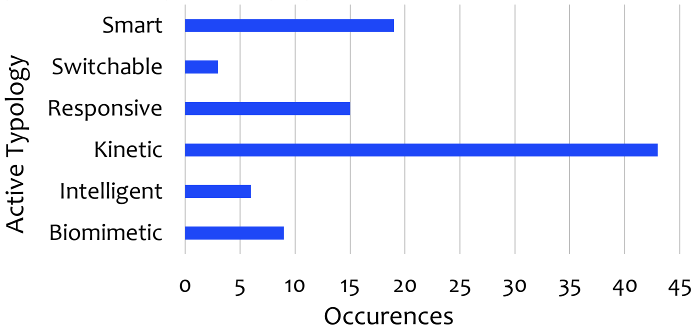
Figure 5 – Research publication per year



Source: The authors.

According to Figure 6, kinetic envelopes are the most common research subject in this ILR. Since building performance simulation and building modeling suites for active envelopes are still being developed, most studies simplify all possible input parameters (motion patterns, deformation, simulation days, performance metrics, etc.). We understand that kinetic designs are simpler than the other typologies, requiring only outdoor sensing and no user inputs. Furthermore, mechanical biomimetic, intelligent, responsive, and kinetic typologies better fit the building simulation framework since they generate motion according to predictable weather/user parameters. Smart or smart-actuated systems are usually binary and unpredictable, limiting building simulation applications.

Figure 6 – Research publication per year



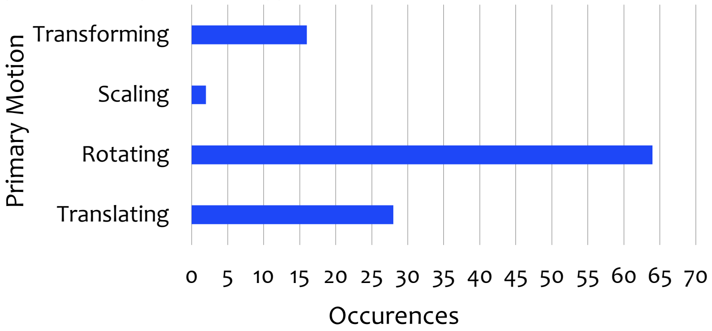
Source: the authors.

Also, most kinetic investigations employed further simplifications such as primary movement selection or single-objective simulation criteria They commonly presented thermal or energy simulations since they do not necessarily provide comfort. More comprehensive studies (intelligent, smart, and biomimetic typologies) considered visual objectives but rarely offered user override options (responsiveness). Figure 6 also indicates that smart approaches are the second-largest publication group. Smart applications are usually experimental and function as binary kinetic actuators. Most studies on smart typologies presented shape-memory polymers, followed by shape-memory alloys. For polymers, there are various studies in additive manufacturing and self-assembled structures. Most alloy research pieces use spring alloys with a simple mechanical motion as base-case. Biomimetic approaches applying alloys were also recurrent.

Even though more advanced than intelligent systems, responsive applications appeared third, with approximately 70% of publications after 2018. Responsive research also involved one simulation objective in most studies. Visual (daylight and glare) simulations were the most frequent as they considered the user directly.

We do not present a graphical representation for mechanical and non-mechanical actuation since non-mechanical approaches only appeared in 18% of studies. The shape memory systems are mainly responsible for non-mechanical procedures. The primary motion typologies in Figure 7 are more recurrent than composite movement patterns, appearing in 54% of the publications. We point out that folding mechanisms (rotating + translating) occur in 25% of the research pieces and normally appear as origami designs.

Figure 7 – Primary movement appearances



Source: the authors.

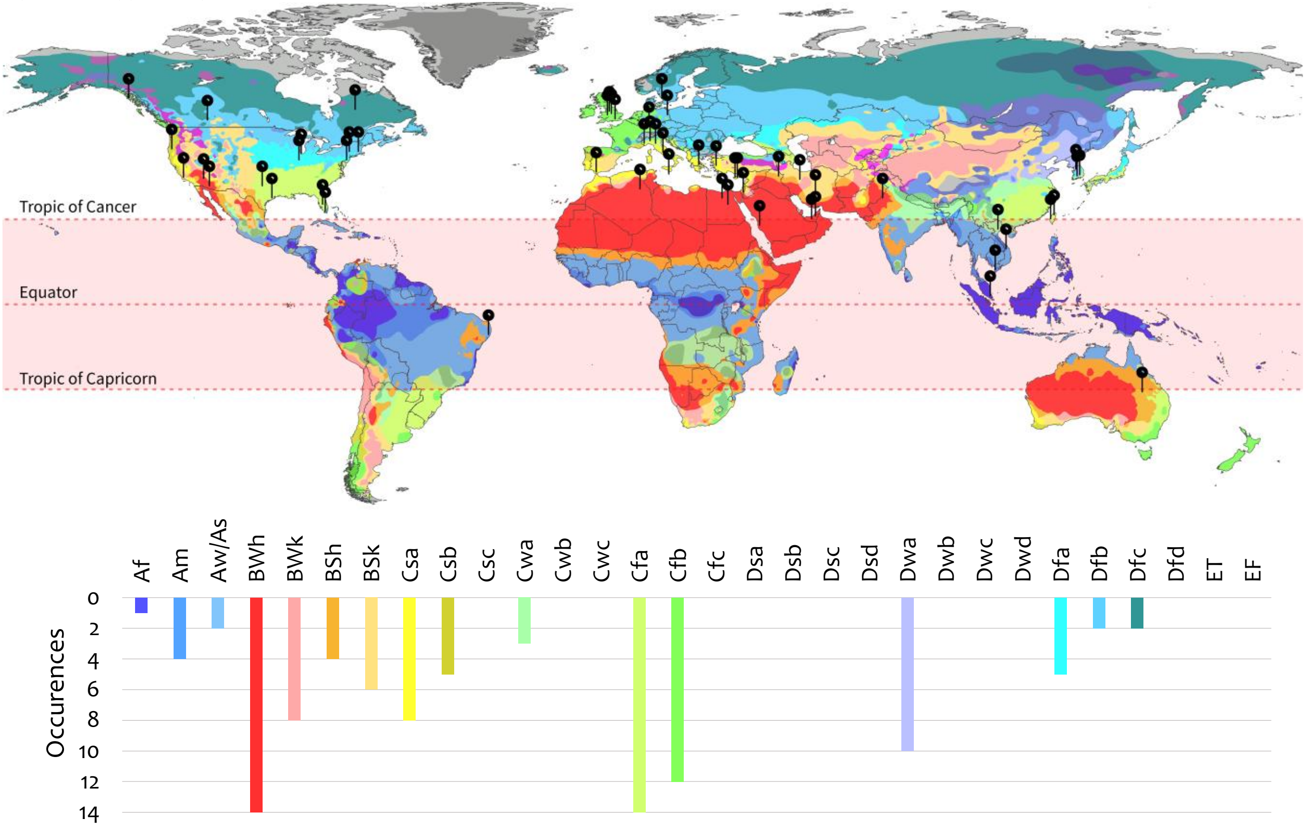
Adaptability through rotation is the most used among active envelopes, followed by translational motion. Passive strategies are well established and normally apply simple geometries (fins, louvers, and egg crates); therefore, the transposition of passive geometries into active strategies preserves the shape simplicity, offering one-axis motion, demonstrating that normal shapes perform similarly to non-conventional geometries. Transformational patterns appear in software simulation studies that are not concerned with physical/material properties and only regard building performance optimization to the detriment of materialization. They also occur for tensile modules (which can present elastic action) and some shape memory materials.

Most reviews do not characterize studies' location and climate classification. However, it is essential to comprehend the climatic conditions from several viewpoints. For instance, heat gains during the winter could be desirable in locations with large seasonal outdoor temperature fluctuation, while shading is imperative in tropical climates throughout the year. Another issue is the prevalent atmospheric conditions, i.e., regions with high precipitation rather than arid climates have more cloudy sky conditions; thus, less illuminance and more diffuse natural light are available.

We use the Köppen-Geiger weather classification to categorize the studies; we pin all studies' locations on the Köppen map (Figure 8). Most investigations found in our ILR occur in temperate regions (42%) and dry weather (36%). Furthermore, 36 studies are in regions with no dry season (subclassification f); 22 studies appear in desertic climates (subclassification W); and 15 research pieces are in dry winter locations (subclassification w). Most studies are also in hot or hot summer areas. So, we confirm that most research pieces consider mild temperatures, humid regions, and warm summer months. Tropical climates are the least representative, with seven investigations (disregarding the polar group - classification E).

Among the 86 pins, only six are between the tropics, and only one is below the Tropic of Capricorn. Most research appears in the northern hemisphere, mainly in Asia, with 36 studies; North America is second with 24 locations, only in the United States; Europe (mainly in the Mediterranean) has 14 studies; the African continent appears 11 times (mainly northern portion). As mentioned above, Latin America only has one study in South America.

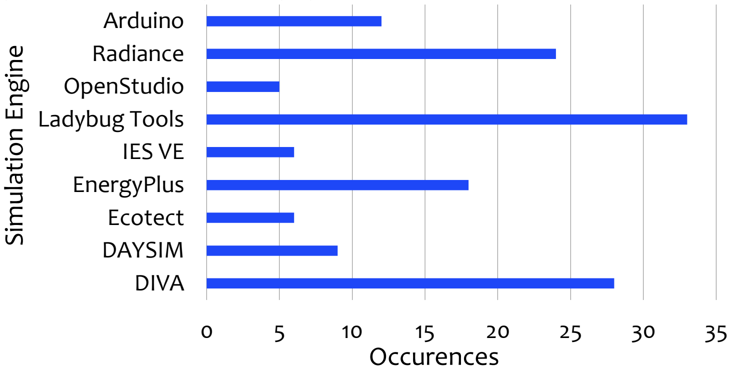
Figure 8 – Köppen-Geiger classification and studies' location



Source: the authors.

We found five distinct modeling software: DesignBuilder, Revit, Rhinoceros3D, Sketchup, and SolidWorks. Among those, two are parametrically-coupled modeling suites: Rhino3D+Grasshopper and Revit+Dynamo. The Rhino3D+Grasshopper appears in 78% of our literature pieces, followed by Revit with 8%. Also, Revit+Dynamo only appeared in building information modeling research. The high adhesion of Grasshopper is due to the coupled plug-ins for environmental, mechanical, structural, fabrication, and etc. investigation. We only included environmental analysis and performance criteria in our search strings.

Figure 9 – Simulation engines employment

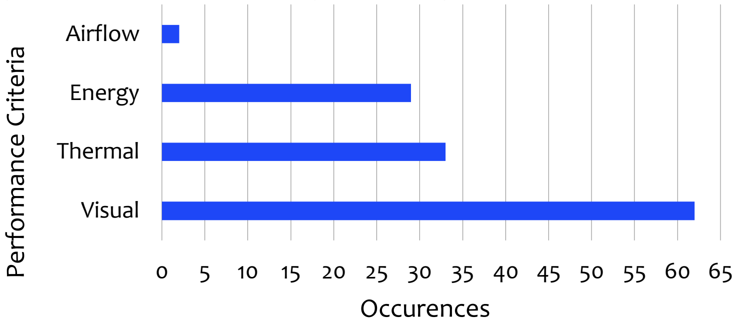


Source: the authors.

We consider all simulation software (Figure 9) autonomously, i.e., research pieces can apply DIVA unaided or through Ladybug Tools. The Ladybug Tools, including Honeybee, is the most employed simulation software. Other engines include DIVA (20% of research pieces), Radiance (17%), and EnergyPlus (13%). We recognize that Arduino is not software; however, since some investigations did not apply computational simulation, we accepted the Arduino peripherals and sensors as environmental data collectors.

Concerning simulation objectives (Figure 10), we observe that visual metrics are the most common. They appear in 49% of all research, and in 23%, they are the only simulation objective. Thermal and energy analysis are also very representative, with 26% and 23% appearances. The most common association is visual and thermal, appearing in 11% of the studies.

Figure 10 – Performance Criteria adoption according to the ILR



Source: the authors.

Some daylight studies focused exclusively on glare, especially in simplified, single-occupancy office units. The authors adopted static daylight metrics in these investigations to estimate illuminance levels. They require only one point-in-time and unchangeable sky conditions, consuming less computational time. However, they do not represent the dynamism of active building shading and only appear in approximately 12% of the investigations. Regarding daylight evaluation, daylight levels (25%), useful daylight illuminances (20%), spatial daylight autonomy (17%), annual sunlight exposure (9%), and daylight autonomy (8%) are the most frequent. The daylight glare probability (DGP) also appears in 19% of studies. We also found modified daylight glare probability, daylight glare index, predicted mean vote, and percentage of people dissatisfied.

Energy appraisal mostly considered heat and cooling loads (7%) and photovoltaic generation (3%). Generally, most evaluations relied on specific days and hours, representing different seasons with the same time step.

Even though we show simulation motors and objectives, we acknowledge other research typologies apart from computational simulation. Although fast and economically effective, we also note that they require no field measurements and are prone to low accuracy due to design simplifications. Experiments were the most accurate among the reviewed studies, although relatively high-cost and time-consuming. We found examples of full-scale objects, large-scale mockups, physical measurements, and surveys appearing right before simulation approaches with 27 occurrences. They allow accurate weather characterization, physical materialization, design revision, microcontroller applications, and etc. We also found experiment research coupled with numerical calculations (3 studies) or software simulations (22 studies). The latter presented the best results and thorough research pieces.

Conclusion

This study developed a comprehensive theoretical background on climate-active skins, creating a preamble for future building enclosure classifications. We also conducted an Integrative Literature Review with a state-of-the-art selection on active building envelopes, compiling study methodologies, geographical location, weather classification, design solution, active typologies, movement characterization, software application, and simulation metrics and objectives.

We applied a novel methodology coupling StArt v. 3.4 and the Preferred Reporting Items for Systematic Literature Reviews and Meta-Analysis's (PRISMA) selection criteria. The methodology description also supports future studies, guiding and suggesting new keyword insertions. As a drawback, we point out that a permissive string search offers many results, leading to time-consuming analysis.

Even though Scopus conveyed 40% of the selected studies, we indicate Periódicos CAPES as the best scholarly search engine since it represented 30% of research outcomes, with 61% of research pieces as state-of-the-art studies. Furthermore, the superposition of Scopus and Science Direct returned several duplicated research pieces and deviant studies.

We found no nomenclature standardization, so we adopted the most used classifications according to building envelope theoreticians and systematic literature reviews. Since some groups have similar characteristics, we only presented the most occurrent. We also conclude that active strategies mainly concern passive reinterpretations as kinetic systems, explaining the abundance of kinetic research. There is no clear correlation between geometry and active control strategy. Studies mostly applied top-down approaches for selecting envelope shapes. Typically, geometric choices are related to case studies or cultural aspects. Further geometric analysis showed that most researchers apply one-axis rotation or simple motion techniques. Only a few studies considered complex motion typologies that did not comply with mechanical actuation. Also, there is no typical room typology for conducting simulation-based methodologies.

Among our findings, one of the most important factors is the occupant's daylighting preference (illuminance levels and glare). Other representative simulation objectives were thermal and energy assessment. Only two studies did not adopt one of these objectives. We found several studies confirming that users can endure short periods of glare discomfort if adequate lighting is available. We recommend correlating daylight levels with glare analysis. However, glare evaluation research only considered one or two reference points due to simulation limitations (which corresponds to most of our findings).

We consider the simulation workflow as a significant limitation. Active systems lack simulation-based control strategies and cannot predict long-term energy performance or comfort levels in early design stages, limiting their applicability. As a solution, associating simulation with physical experimentation rectifies some drawbacks. For instance, various experimental research with digital manufacturing or prototyping techniques appeared in our state-of-the-art. We consider empirical validation under real climate conditions imperative for simulation approaches.

Experimentation also allowed digital controlling techniques, such as Arduino-based prototypes, to provide a good indication of the system's performance, allowing controlling adjustments and materialization discussions. Another solution for automatizing simulations is the optimization approach. However, we only found 13 research pieces that applied optimization motors.

Following, we pinpoint some major conclusions of this research:

- Building envelope research primarily focuses on façades to the detriment of other envelope geometries and stand-alone projects, mainly due to the predominancy of evaluations on high latitudes. Most investigations occur above the Tropic of Cancer, with 8% below/between the tropics. Furthermore, only a few studies considered more than one location with different weather classifications, presenting no comparable results.

- Overall, climate-active enclosures are more effective than optimized static geometries. Building retrofitting and simulation studies demonstrated that even seasonally actuated envelopes perform better than a point-in-time geometry.
- Recent research offers more intricate adaptation parameters, shifting from kinetic motion (very representative until 2018) into responsive or intelligent systems. Some authors focus on smart actuation without mechanical components or further energy expenditure. However, smart applications require market-ready products or specific fabrication technologies.
- Simulation motors do not offer a straightforward methodology for assessing active approaches, explaining the lack of standardization. Research pieces also adopt diverse simulation motors and different input parameters and optimization objectives. Therefore, we can analyze the studies independently, but comparing all approaches is difficult. Besides, a successful simulation procedure involves multiple or many criteria parameters such as indoor activity, climatic zoning, and user requirements. So, current simulation software needs substantial efforts from developers to offer a real-time evaluation of active elements under variable weather conditions, considering potential scenarios in controlling and automation.
- The primary XY or ZY-axis rotation is the most frequent mechanical motion. Most studies considered hinging and swiveling motion. The second recurring motion pattern is the translation (especially horizontal sliding). The folding motion is also very present. We assume primary movements have a low initial cost, are more mechanically feasible, and rely on market-ready pieces.
- Daylight simulations with illuminance-based objectives are the most common and frequent combinations comprise visual+thermal and thermal+energy analysis.

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