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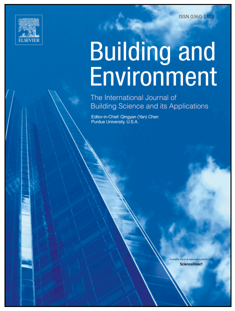

The state of the art of living walls: Lessons learned

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Living Wallessons learned

Title:

The State of the Art of Living Walls: Lessons Learned

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Abstract

Marching toward legitimacy, living walls are slowly being vetted. Establishing living walls as a viable constructive system will require filling gaps in our knowledge by taking advantage of the lessons learned from recently built projects. Growing plants on a vertical surface gives the appearance of natural simplicity. However, achieving a successful living wall is a complex problem with many factors, including ensuring an appropriate support structure, maintaining the proper amount of water, oxygen, nutrients and pH levels, choosing plants which can survive seasonal climatic changes, and establishing the appropriate lighting conditions; not to mention affordability, sustainability and longevity. Satisfying these complex needs - mastering all of these factors – will be essential for living wall systems to mature beyond their use as vanity projects and gain acceptance by the construction industry. This article aims to aid those considering living walls and dispel some of the mystery surrounding them by studying precedents and addressing their commonly cited criticisms: living walls are too expensive and unsustainable, too complicated and prone to failure, and too decorative and superficial to the buildings they serve.

Keywords

Living wall technologies; Green wall integrated systems; Urban vegetation; Sustainable built environments; Architectural case studies; High performance design

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1. Introduction

1.1. Background

Architects, designers, builders, and owners interested in living walls can find themselves sifting through an abundance of conflicting information. Case studies often transmit technical data without tackling the most instructive formal design strategies. Ignoring the evolution of a system's form risks the blind copying of construction details, i.e., inappropriate appropriation. This is a danger even more exaggerated with living walls than with other constructive systems due to the singularity of supporting life on architectural projects; projects whose environmental factors are rarely, if ever, replicated. These environmental factors can have as much importance as technical design details in determining the success of a living wall.

For example, environmental factors vary across a wall's surface [1]. Microclimatic differences can mean fluctuating conditions of heat and humidity or variance in wind stresses at the ends, corners, and tops of living walls. It can also mean degressive daylight. An exaggerated example of this is on the "Chikusa-za" living wall in Nagoya, Japan [Fig. 1]. Notice the zone – outlined in red and highlighted with arrows – exhibiting stress on the left-side of the façade; stress visible by the exposed metal structure. Then note how this zone corresponds to the shadow cast by the building across the street. These are the sort of precarious risks living walls confront. Microclimatic differences can affect plant species growing successfully in one area to have difficulty thriving elsewhere on the same wall or building, thus one can imagine the challenge of appropriating solutions across projects.

Fig. 1. Chikusa-za" living wall in Nagoya, Japan: The zone outlined in red and highlighted with arrows exhibits stress presumptively from the shadow cast by the facing building. Photo by author c.2015. *[2-column fitting image]*

1.2. Aim of the study

Despite pitfalls in misappropriating solutions, there are a number of recently built living walls which provide insights into how to construct successful systems. In addition to case studies, new scientific research is contributing to making living wall systems less enigmatic. Research into technical aspects of living walls has begun to provide answers to questions about their advantages and challenges. Some conjecture about living wall performance has been reduced as results are published, e.g., about their cost-benefit analyses and their ability to clean the air, reduce the urban heat island effect, and manage storm water.

If one accepts the proposition that living walls will become a viable constructive system to augment vegetation in urban areas, then architects, builders, suppliers, and installers must come to terms with and answer these frequently cited criticisms: living walls are too expensive and unsustainable [2], too complicated and prone to failure [3], and too decorative and superficial to the buildings they serve [4]. The following lessons respond to these criticisms with an eye toward optimizing existing systems, employing them to the greatest architectural advantage, and even altogether rethinking living walls.

1.3. Living Wall Definition

Green walls are divided into two main categories: green facades and – the focus of this paper - living walls. Green facades typically use climbing plants, e.g., ivy, to grow vertically on a building’s façade; growing either directly on the building’s surface or by climbing upon a secondary support system. Plants for green facades are typically planted in the ground or in strategically placed planters. Conversely, living walls have plants planted throughout the surface of the wall. The two main types of living walls are hydroponic and soil-cell systems.

Hydroponic systems often use a dense mat or felt-like material as a growing medium for plants. The growing medium is doubled and continuously wetted with nutrient-enriched water. Plant roots grow on and in-between the two layers of felted substrate. Soil-cell systems grow plants in soil that is compartmentalized into individual cells, which are grouped together in panels that attach to a frame (however, there are some hydroponic systems which use a modular, cell-based typology, typically replacing soil with an inorganic material such as rock wool). Essentially a collection of “potted” plants, the individual soil-cells are subject to the same challenges that face most potted plants: soil compaction, climatic stress, and soil nutrient replenishment. But, exterior soil-cell walls also face the problem of soil loss due to wind and water-driven erosion. Both systems face the possibility of plant stress, not least because the plants’ growing surface is vertical (although some cell-based systems have a canted growing surface which is less unorthodox for most plant species). This paper discusses both hydroponic and soil-cell living wall systems; both systems require expert design and on-going maintenance, and both systems are prone to failure if all of the factors of their design and operation are not successfully synthesized.

2. Methodology

Two years of observation, discussion, and examination were used to create this review. Built examples of living walls were observed in England, France and Japan and visits were typically accompanied by the living wall's owner, designer or installer. Discussions with experts in the field of living walls were part of the observational experience, focusing on empirical knowledge and jobsite challenges. Experts were also questioned at international conferences devoted to presentations on living walls, green roofs and green infrastructure. Archives of recently published work were examined with an emphasis on scientific articles which can substantiate the empirical claims of experts. The following partial review does not claim to be exhaustive and recognizes that for a living wall to be fully vetted it requires repeated visits to record seasonal and annual evolution. The following sections respond to the most commonly cited criticisms encountered while this research was conducted.

Sections 3 – 5: Addressing living walls criticisms

3. Addressing criticisms part 1: too expensive and unsustainable

Cost is the biggest factor hindering living wall proliferation. Locating published costs is challenging, partly because there is not a one-size-fits-all solution, so costs are adapted to each project and thus vary widely [5]. Prudence to not invoke "sticker shock" restrains living wall providers from posting cost estimates (see section 3.2. for a UK cost estimate). Yet an often hidden shock occurs once the ongoing maintenance cost is discovered.

3.1. Long-term maintenance

The initial capital investment of exterior living wall systems is high when compared to other exterior cladding systems [6], but long-term maintenance costs are also problematic. The conundrum for manufacturers and installers is even a well-designed system with suitably selected plants relies heavily on maintenance for success. This challenges traditional preconceptions of a building envelope’s operating costs. For example, per year, maintenance can be 8.5% [7], or even 15%, of a living wall’s installed cost [8]. One conservative study estimated annual maintenance to be approximately a third of the living walls’ installed cost [9].

Maintenance is often contracted separately; meaning the installer may not have to be responsible for the success of the wall beyond the warranty period [10], and the warranty may only cover the support system [11]. Clients are often surprised by the service costs associated with maintaining a living wall, even for the comparably simple tasks of pruning and weeding.

One solution is to move the industry toward tethering the installer to maintenance by encouraging purchasing living walls with a service contract. This avoids putting short-term gain ahead of long-term viability by constructing systems which emphasize longevity. Thus, the focus returns to optimizing initial capital investments to lessen long-term costs.

3.2. Short-term investment vs. CBA (cost-benefit analysis)

Reevaluating what is an acceptable short-term investment must be part of an optimization strategy. Optimization requires rethinking systems entirely, especially where a system’s life-expectancy is less than its superstructure [12]. This is done to keep initial costs down, i.e., living walls are often constructed of lightweight, economical materials of sometimes dubious longevity. For example, there have been reports of plastic living wall modules falling-off buildings due to differential thermal expansion [13]. A cost-benefit analysis (CBA), which assumes total living wall replacement factored into long-term maintenance, encourages living walls to become as durable as the superstructure supporting them [6].

Paradoxically, to be affordable, many experts agree the living wall "ignition point" is approximately half their current cost [14] (in the United Kingdom estimates currently range from 350 to 500£/m², whereas 200£/m² is considered the affordability tipping point) [14]. As discussed, living wall maintenance costs can become many times more expensive than the installed cost [9]. It is a catch-22: reducing maintenance may require more investment in system quality, i.e., increasing short-term investment. To reduce both short-term and long-term costs the most-likely avenues are innovation, tax incentives, and government subsidies, towards the goal of attaining economies of scale. To start, the issue obliges an evolution of a living wall's CBA.

Recent research into the CBA of living walls epitomizes the impending challenge [15]. One study of a living wall system found it unable to produce enough economic benefit to cover its installation and maintenance costs until after 50 years [7]. An example of embedded high maintenance costs is plant replacement. Some living wall systems assume 5% plant population replacement per year, others assume 10% [6]. Because living wall costs cannot compare to standard wall systems because their life-cycles are drastically different, it is logical to compare their installation and maintenance to the aggregate costs of combining a high-performance exterior wall enclosure with traditional landscaping.

3.3. Monetizing health and well-being

Emphasizing living walls' ability to increase wellness and consequently their return on investment (ROI) is one strategy to make their cost more attractive [16] [17]. Quantifying the economic benefits of a living wall's intangible qualities, i.e., their biophilic design potential, is one way to amortize a living wall's capital costs [18]. Evidenced-based design research into the cost benefits of linking planted surfaces to reduced hospital stays is one template for measuring the economic benefits of contact with nature [19]. Until these are better understood, research into the more tangible economic benefits of living walls, e.g., lowering a building's cooling load or garnering media impact [20], will be used to justify their added expense.

3.4. Energy savings

Potential energy cost savings associated with incorporating vegetation on buildings is illustrated in several recent studies [21]. Research in England confirms plant choice affects wall cooling [22]; green walls help at the extreme ends of the cooling and heating times, e.g., the hotter or warmer the weather the greater the benefits of green walls [23]; vegetation can cool the air around a green wall by 3-5°C in the UK, while wall surfaces can be up to 10° cooler and wall cavities 5° cooler; and during winter (green façade) vegetation can convey a mean winter energy cost reduction of 38% because of warmer temperatures between the plants and the wall surface [22].

Other discoveries of interest include: the importance of avoiding the monoculture problem by combining species good for "cooling" with those better for "heating"; the importance of plant architecture, e.g., how the fan effect of stems and branches affect cooling; and how plant design is as important as plant selection [24]. Complimentary studies also found vertical greening systems capable of providing energy savings in buildings, especially with the shade effect of plants [18] [25]. A study in the United Kingdom observed stabilized indoor wall temperatures of 2°C cooler in summer and 2° warmer in winter when comparing potential thermal benefits of four exterior green walls installed side by side on the southwest façade of a second-story classroom [26] [27].

Another way to fulfill energy goals is to borrow from historical approaches. For example, living walls in Northern climates having deciduous plants rather than evergreens permit the sun, after abscission in winter, to warm-up the façade [28] (depending upon the system-to-building interface).

3.5. Unsustainable irrigation

Unsustainable use of water is a criticism aimed at living walls from within the design profession [29]. There is very little information published on this topic, but some off-the-record figures were shocking. Occasionally the topic is addressed [30], but more transparency is needed if living walls are to become a sustainable construction system. Some researchers are responding to this need. There is a growing list of published research on sustainable living walls and their irrigation, noteworthily from Spain [31]. For example, in Seville's hot arid climate an interior living wall specimen consumed 3 - 5 liters of water per m²/day [32]. On today's market the most efficient living wall exterior systems consume 1 liter of water per m²/day [33] [34].

Systems can be developed to reduce the overconsumption of potable water by harvesting rainwater and/or recycling water [35] [28], which can be simultaneously advantageous for storm water management [36]. Surprisingly, most living wall systems do not recover their wastewater because it is expensive to collect and filter recycled irrigation water in a reservoir and also, according to many system providers, because using recycled water means plants living in their own waste and exposure to non-nutrient salts [37].

Two recent living wall projects have apparently solved the conundrum of both supplying enough water and using water sustainably. One project, The Rubens at the Palace in London [Fig. 2], is said to have achieved rainwater-only irrigation through harvesting rainwater in rooftop storage tanks [38]. The 350m² soil-based modular system completed in

2013 was envisioned by its designer, Gary Grant, to be a demonstration of how green infrastructure can be used to collect, store, and evaporate storm water, lessening urban run-off [39] [40].

Fig. 2. The Rubens at the Palace in London, England, is said to have achieved rainwater-only irrigation through harvesting rainwater in rooftop storage tanks. A. Project elevation, B. Living wall portion, C. Detail of 20cm wide vegetated vertical louvers. Photos by author c.2015. *[2-column fitting image]*

Another example, the One Central Park project in Sydney, Australia, completed in 2014 and designed by Jean Nouvel with PTW Architects and Patrick Blanc, uses harvested rainwater and recycled black water to irrigate its hydroponic living walls thanks to a water recycling plant in the building's basement [41] [Fig. 3]. The City of Sydney's influential role in fostering a culture of water conservation cannot be underestimated [42]. Governmental incentives and regulations strengthened by discounts and fines is one of the most effective stimuli to promote – and help pay for – sustainable living wall water consumption [43].

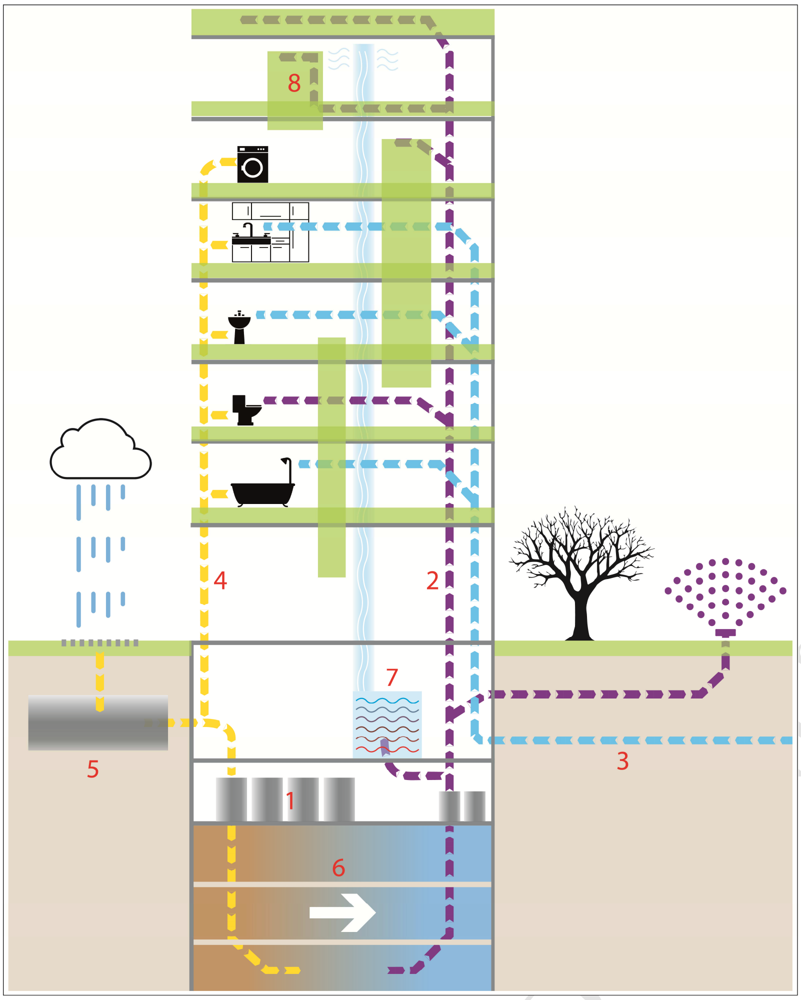

Fig. 3. Water recycling plant in the One Central Park project in Sydney, Australia: 1. Membrane bioreactor for water purification, 2. Recycled water, 3. Potable water, 4. Wastewater, 5. Rainwater collection, 6. Eight-step purification including reverse osmosis and ultraviolet germicidal irradiation. 7. Air cooling towers, 8. Green wall irrigation. Diagram by author and inspired by Flow System's interactive graphic. *[1-column fitting image]*

3.6. Irrigation: over-watering

Overwatering will have harmful effects on living wall plants. Brown, dying, or dead plants which appear to have perished due to lack of water are often killed by too much water and poor drainage. A few telltale signs of overwatering are: algae growing on the substrate [Fig. 4B] ('growing media' is referred to as 'substrate' in industry jargon - see the photo with the four red arrows that the buff-colored stone wool substrate appears green from algae which can attract plant-attacking pests [44]); plants which are yellowish with a "washed-out" appearance (typically indicative of system-wide stress primarily due to root rot because the overall system is too wet, a potential problem for all living walls and especially with certain types of systems where the plants do not have sufficient air in the substrate); and when one can see excess irrigation evidenced by water collecting under the bottom of the wall (note the image with the wet pavement outlined in red) [Fig. 4C]. Fig. 4A is a photo of the plants just above the door lintel which appear brown and dry (highlighted by the red arrow). In fact, the hydroponic growing media (a type of stone wool) is too wet; potentially as a result of the system not being "intense" enough, i.e., its depth is insufficient.

Fig. 4. Telltale signs of overwatering on a living wall adjacent to Westminster Chapel, London: A. Dying plants above lintel, B. Algae growing on substrate, C. Water collected at wall bottom. Photos by author c.2015. *[2-column fitting image]*

A second example illustrative of watering excess is on the project pictured in Fig. 5 showing a modular living wall system with a compost substrate. After two years, vertical bands of brown dead/dying plants have appeared which alternate with green bands of living plants. The brown strips are the result of an irrigation issue wherein the substrate has become supersaturated. This phenomenon can be a drawback with some types of cellular systems which allow continuously sitting water.

Fig. 5. Paradox of excess watering on a living wall by Windsor House, London: A. Bands exhibiting plants with supersaturated substrate (brown zones highlighted with blue arrows representing axis of overwatering), B. Detail of alternating bands of substrate with excess watering (blue arrow) and without (blue arrow with interdictory circle), C. Detail of overwatered zone (outlined in red) at glass canopy. Photos by author c.2015 (taken prior to system repair). *[2-column fitting image]*

A formal architectural issue with this project is the colored glass canopy above the living wall which may be sheltering the wall from the wind, thus lessening evaporation, and potentially limiting daylight [Fig. 5C]. Clear single-pane glass reduces available light by 14% and when dirty by more than 20% [45] (note: indoor plants tend to prefer light which arrives through a diffuse material rather than through a visibly-clear material [46], lessening the disadvantage of the colored panels). But, it is important to keep in mind that little useable light exists for plants after it has passed through glass more than 4.5 meters [47].

3.7. Response to part 1 criticisms: Summary of analysis

In summary, the costs of living walls can be reduced if both short-term investment and long-term maintenance are tethered, optimized, and subsidized. ROI will increase once living wall tangible benefits such as energy savings are quantified [48]. And ROI will increase further once the intangible benefits of living walls are quantified, e.g., when the health and wellness impacts of Biophilic design become more easily assessable. This is an exciting time for proponents of living walls because the industry is ripe with new ideas and budding experts. Unfortunately, these experts are often entrepreneurs understandably reluctant to openly share knowledge earned by trial and error through developing proprietary systems. This effort to conceal positive and negative attributes is slowing advancement and normalization. Sharing solutions to problems such as heterogeneous substrate irrigation and over-watering will help living walls become more sustainable. But living walls will only become sustainable when they are conceived as entire systems integral to the building's functioning while using little to no potable water.

4. Addressing criticisms part 2: too complicated and prone to failure

Conceptually living walls are not complex. In fact, they are uncomplicated and often technically simplistic. The do-it-yourself (DIY) modular soil-based systems which parcel-out topsoil into wall-mounted plastic pockets are examples of primitivity over sophistication. Yet, conceding complexity begins with the notion of growing plants on a vertical surface, it is the variability of the aforementioned environmental factors and our superimposed performance requirements which create complexity.

We ask living walls to be sustainable, clean the air, reduce noise pollution, absorb storm water, reduce the urban heat island, provide the psychological and physiological benefits of nature, and simultaneously remain unfailingly visually pleasing. This performance criterion creates convolution, and the following insights aim to make some of the complexities more comprehensible.

4.1. Local design factors: climatic design impacts

There are three climatic factors to consider when designing living walls: temperature plus humidity; wind; and orientation [49]. The influences of these factors during the design process will play a decisive role in determining success. Local temperature and humidity data is to be collected and analyzed based upon monthly and, if available, daily data readings to reveal the extreme range of climate data, rather than using mean data averaged over a long period of time; this ensures data will be useful to the designer [49]. The same holds true for average rainfall data. Taken as monthly data, average rainfall data can falsely indicate that rainwater collected in a reserve and distributed when needed is sufficient. Whereas daily rainfall data may show instances within the month of a long dry period(s) suggesting supplemental water is needed. Consequently, designers can not focus exclusively on average temperature and rainfall data when making design decisions.

As living organisms, plants must be chosen to survive the extreme climatic conditions they will inhabit. Unable to survive the cold, there are examples of living walls in which all of the plants died during the first winter [50]. Conversely, plants often will not “drink” water when it is too hot [51] or if the pH is incorrect [52] (note also the variability of potable water quality willaffect mineral balance). A full range of climatic data will reveal the plant and substrate characteristics necessary for survival.

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Wind is one environmental factor which cannot be overlooked. Wind speed and direction will influence living wall humidity and therefore plant survival [49]. Wind can also directly affect plant foliage, as is often seen on living wall plants in their prematurely brown leaves caused by wind stress. Turbulent air flow can stress plants as well, which often occurs at wall corners and ends. These areas, along with the upper portions of tall living walls, require selecting plants with wind-tolerant characteristics.

With enough access to light virtually any wall orientation can support a living wall. The flourishing northwest-facing living wall on the Quai Branly museum is proof of this [Fig. 6]. This project's living wall was made with a felt-based hydroponic system invented by the French botanist and artist Patrick Blanc [53]. Whether oriented cardinally or directed secondary-intercardinally, a living wall's success will be determined by the appropriate choice and distribution of plants for the orientation and the system's ability to create a supportive site-specific environment. For example, plants in the lower portions of a wall may need to be more shade-tolerant than plants selected for the upper portions; these same plants selected for the upper region of a living wall may need to also be more drought-tolerant since their substrate can be drier due to wind-driven evaporation and irrigation heterogeneity [53].

Orientation and sun exposure will also play a role in determining the cooling benefits a living wall will provide. Benefits correlate with the amount of direct sun exposure [25]. For example, in the Italian cities of Lonigo, Pisa and Venice, researchers tested a different living wall design in each of the three cities, yet southwesterly oriented each wall. They found that the walls were between 12°C and 20°C cooler on sunny days and between 1°C and 2°C cooler on cloudy days than non-vegetated walls of the same orientation [25].

Fig. 6. Its northwest orientation did not hamper this living wall from flourishing (designed by Patrick Blanc for architect Jean Nouvel's Quai Branly museum, Paris, France). Photo courtesy of Bernadette Forest. *[1-column fitting image]*

4.2. Measuring light for plants

Expected light conditions for living walls must be calculated before plant selection is made. Light for plants is measured in terms of its quality, quantity, and duration: light quality for plants is described by its color, i.e., its wavelength; light quantity is measured for its photosynthetic irradiance; and light duration is counted by the length of plant exposure to light per day [54].

Light quality: plants reflect the majority of green light, hence their color, so the most photosynthetically efficient light is in the blue and red ranges of the spectrum [55]. Daylight carries the entire spectral range, so light quality readings are often more critical for artificially lit living walls. Nevertheless, photosynthetically important light can be measured with a spectrometer or a spectroradiometer [56], which measures spectral power distribution (energy by wavelength), though spectroradiometer cost may prove a limiting factor.

Light quantity: an insufficient quantity of light is one of the pitfalls of living wall maintenance [57], but it is necessary to measure the quantity of available light useful for plant growth with the appropriate units. Measuring light with a lux meter (lux is a ratio of illumination, i.e., lumens, over a distance: 1 lux = 1 lumen/m^2) is useful for the human visible wavelength range of about 375 to 750 nanometers [58]. Conversely, plants benefit from UV-A and UV-B light, and light at the far-red spectral range [54] beyond human perception.

Nevertheless, the quantity of available light for plants is typically measured in the spectral range most useful to plants for photosynthesis of about 400 to 700nm. Photobiologists prefer to measure the number of photons incident on a surface, i.e., photosynthetic irradiance, measured in terms of: photon flux density (PFD); photosynthetically active radiation (PAR); or photosynthetic photon flux density (PPFD) [59]. The unit used for PFD, PAR, and PPFD is $mol\ m^{-2}s^{-1}$, but also the micromol (μmol). For light quantity the PAR meter may currently be the most economical device. One drawback, as with the lux meter, is the PAR meter misreads LED (light-emitting diode) and HID (high-intensity discharge) artificial light: red and blue LED light is undervalued and HID yellow-green light is overvalued [60] [61].

Light duration: is defined by the available light and periods of darkness. The process by which plants respond to the daily duration of light and dark is called photoperiodism; the photoperiod controls many plants’ reproductive cycles (although some known as day-neutral plants aren’t affected) [54]. Photoperiodism is also a way for plants to monitor the time of year and predict changing seasons [56]. Besides minimum light requirements, it is also instructive to consider access to dark - which can be more complicated in dense urban areas with light pollution or constantly lit communal spaces - because certain plants rely on specific photoperiods to flower (known as short-day and long-day plants) [55].

4.3. Metrics: quantifying living walls

Standardizing the metrics used to quantify living wall performance to compare data between systems will influence living wall optimization. The following list begun by Prof.

Manfred Köehler [62], including appropriate units/methodology, begins to establish the criteria: Species richness (in number of species) [63]; Habitat richness (using a gradient or line-transect technique) [64]; Retention capacity (in liters per square meter per year, or in percentage); Dust reduction (in grams or micrograms per square meter, or by concentration) [65] [66] [67]; CO_2 fixation (airborne concentration, in units of micromol mol^{-1}) [68] [69]; Insulation (U-value) [70]; and Cooling load (evaporation load in kilojoules) [62].

4.4. *Response to part 2 criticisms: Summary of analysis*

In summary, living walls' reputation for being complicated and prone to failure is understandable. The industry is emerging and requires acclimatizing to new design factors; hence the learning curve is steep. Also, these new design factors require new criterion to judge living building systems which evolve over time. The criteria which guide living wall design and implementation need to provide designers with metric targets to help analyze their designs and specify appropriate materials and plant species.

These design requirements will have both local and regional factors. The regional factors have mainly to do with plant and material selection based on climate and specific regional criteria. Local design factors can be studied in terms of climatic impacts on a building and tectonic design factors, i.e., the practical constructive principles of living wall design. Identifying and satisfying metric targets can not only help to increase a living walls' ROI but also lead to optimized systems less prone to failure.

5. Addressing criticisms part 3: too decorative and superficial to the buildings they serve

Following are three built examples which challenge the criticisms that living walls are decorative and superficial. These criticisms emerged from a backlash to green-washing and the limiting paradigm of living walls in new construction: their relegation to an element tacked onto an otherwise “blank” wall as if a façade treatment independent of the building’s function. Consequently the living wall is not “experienced” from inside the building; all visual benefits favor neighbors and passersby. The limit to this approach is the lost opportunity for the living wall to play a participative role in the architectural concept’s formal arrangement.

5.1. Beyond decoration: The Anne Demeulemeester Shop

The Anne Demeulemeester Shop in Seoul, South Korea completed in 2007 by the architecture firm Mass Studies is instructive for its unorthodox use of a living wall. The living wall is presented as just one of many material finishes in an architect’s arsenal, albeit a peculiarly dominant one. In this project there are three main materials and each unifies the design, yet the dynamism of the planted material being alive (and intensely green-colored) raises its significance beyond decoration as it becomes the building’s main thematic element [see Fig. 7].

5.1.1. Living wall description

The living wall is made of small modules, called “geo-textiles”, of flexible mesh boxes containing a coconut fiber hydroponic growing medium [71]. The box-like modules are hung from the exterior concrete walls and inclined surfaces. The living walls are located on the SSE exterior wall and S, E, and W exterior courtyard walls and on the exterior walls and sloped surfaces of the subterranean level. Besides the moss-planted walls on the underground level meant to evoke the feeling of a cavernous descent, the living walls are monocultural. The plant species used is Pachysandra Terminalis – a perennial in the boxwood family native to Korea, Japan, and China [72]. Experts warn against creating a monoculture for living walls because of their susceptibility to failure from pathogenic attack and cultivation problems [73], but so far the plants have survived.

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5.1.2. Analysis and conclusions: The Anne Demeulemeester Shop

This project challenges the architectural interpretation of the role of vegetation in construction. Here vegetation is an architectural material abstractly representing nature. This abstraction sets it apart from projects using living walls purportedly for ecological purposes. This may seem antithetical, but it is actually a typology which can contribute to living wall proliferation. The architect accomplished this abstraction by avoiding variegated plantings, instead choosing a single species typically employed as ground-cover. One species of plant can result in an immutable [74] uniform coloration (at least theoretically, because differences in nourishment and stress between plants can result in color variations). These possibilities appear to have been avoided, and the result is a relatively homogenous architectural surface which hints at expressing a living wall simply as one of many possible building materials.

Fig. 7. The Anne Demeulemeester Shop in Seoul, S. Korea: A. View from east, B. Streetview of front (south-southeast) facade, C. Detail of storefront. Images captured: Nov 2009. © 2016 Google. *[2-column fitting image]*

There is a striking contrast between the planted surfaces, exposed concrete and white-painted elements. The uniformity of species does not change the fact that plants by their nature are typically more three-dimensional than standard building materials, hence they create highly textured planes in sharp contrast to the smooth concrete and white-painted surfaces. Also, in reaction to wind plants create dynamic surfaces. This project can be credited with helping to expand the profession's material palette. Analogically, this is similar to developing a new "skin" for rendering an element in a 3D digital architectural model, which is exactly the sort of digital tool architects employ during the conceptual design phase. One could imagine this project's conceptual design being a case of a visualization tool influencing construction typology.

This project differentiates itself and establishes its didactic value by challenging our pre-conception of living walls as strictly vertical and flat, or either exterior or interior, which differentiates this project. Some living walls begin vertical and flat but morph into sloped and curved surfaces. Some of the living wall planes overlap the glazed envelop, blurring the line between interior and exterior.

In conclusion, the Anne Demeulemeester Shop living walls are technically successful in spite of – if not due to – the simplicity of their construction. The aesthetic has played an important role in proving the feasibility of using vegetation as a dominant building material. Here vegetation is not simply tacked onto the exterior as a surface treatment, but is used as a material which highlights the building's formal organization.

5.1.3. Further discussion: the architectural language of living walls

As a side note, the 2013 "Kibo no Kabe", or "Wall of Hope" [Fig. 8], monument in Osaka, Japan, exhibits an evolution of the Anne Demeulemeester Shop's aesthetic approach. Designed by Tadao Ando, it is built of stacked alternating horizontal bands of living wall and green façade, noted as “LW” and “GW” in Fig. 8C. The effect is dramatic and aesthetically reminiscent of a planted version of Henry Hobson’s massive rusticated stone blocks (see his Marshall Field’s warehouse or J. J. Glessner House in Chicago, IL) [75], or the decorative black and white patterning of Siena’s cathedral [76]; in all of these examples we have mechanistic man controlling nature, exploiting its natural qualities, and manipulating its variability for purely aesthetic or symbolic intentions.

Apparently, the stripes indicating two different green wall systems may have been unintentional, an accidental outcome of the monument’s construction typology (if the true intention is represented in the photo of the architect presenting his rendering) [77]. Incidentally, it is an interesting twist on the idea of authorship and beauty as a self-justifying aesthetic [78], since it is engineering necessity determining the aesthetic effect. The original intention, according to the project’s conceptual rendering [77], suggests an aesthetic vision of a pattern independent of the alternating support systems; an abstract patterning akin to the work of Patrick Blanc which uses three-dimensionality and color to create painterly graphic patterns or symbolic gestures. Despite being neologistic, Mr. Ando’s monument expresses the three-dimensionality of materials in a traditional architectural language.

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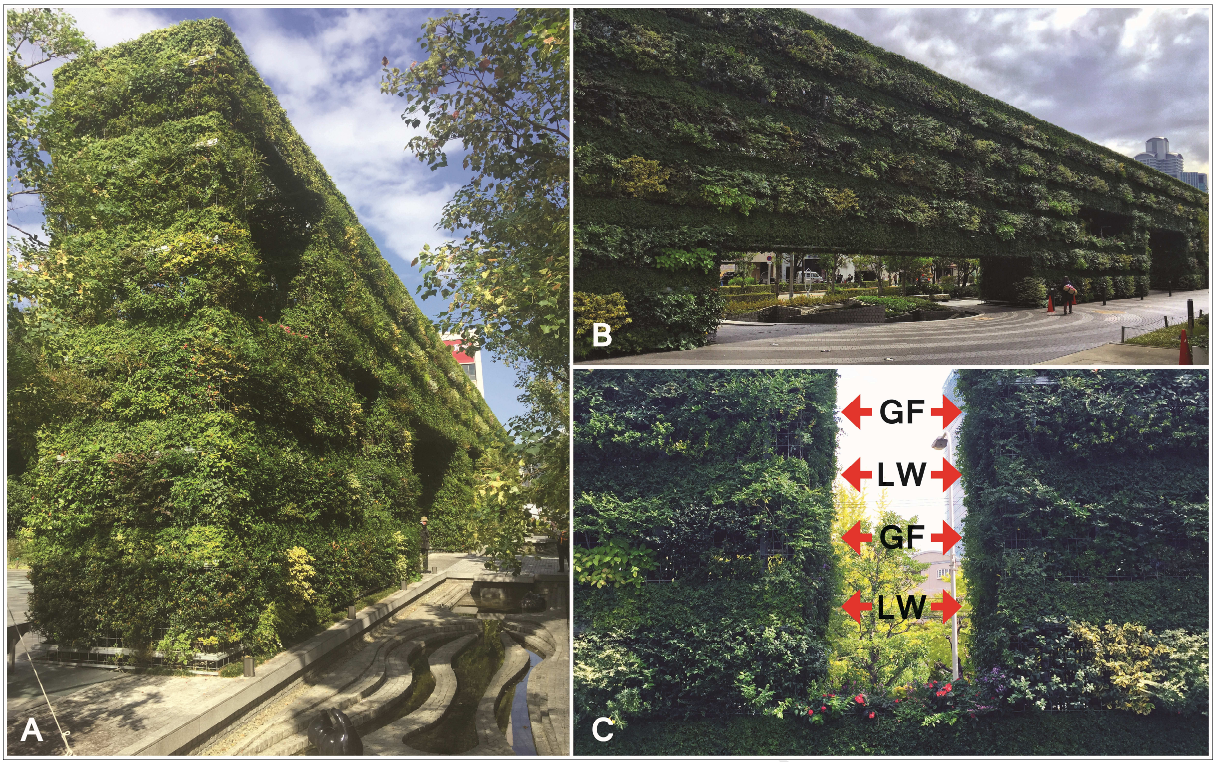

Fig. 8. The striated patterning of the Kibo no Kabe (Wall of Hope) monument in Osaka, Japan, by architect Tadao Ando, are aesthetically reminiscent of modular stone construction: A. View of south end, B. Oblique view of west facade, C. Detail of an opening with red arrows indicating “GF”, denoting the green façade bands, and “LW”, denoting the living wall bands. Photos by author c.2015. *[2-column fitting image]*

5.2. Defining form: the living wall of Casa CorManca

The Casa CorManca in Mexico City, Mexico by Paul Cremoux Studio is more instructive in terms of how a living wall can help define the architectural form of a building. This residence uses a living wall as one of its main organizational elements (the other being a courtyard home typology) [see Fig. 9].

Fig. 9. In the Casa CorManca in Mexico City, Mexico by Paul Cremoux Studio, the house has been designed around the advantages of the living wall, an example of an architectural system defining a building's form. Photos courtesy of Héctor Armando Herrera c.2013. *[2-column fitting image]*

5.2.1. Living wall description

The architect, Paul Cremoux, designed the living wall of the Casa CorManca to improve the air quality and humidity of the home and moderate its internal temperature [83]. The three-story living wall is attached to a contiguous north-facing wall and made from a modular-type system with a soil-based substrate [86]. Over 4000 "environmentally-friendly" individual plants were installed [83]. According to the architectural staff: "The vertical garden is mounted to a metal frame structure and it has an automatic (drop by drop) watering system which pulls out water from an underground storm water tank located at a service patio adjacent to the home's kitchen." [87]

Mexico City's infamous air pollution was one of the main drivers of this project; vegetation in a building can act as a filter for localized air [79]. In the early 1990's the United

Nations declared Mexico City as having the most polluted air in the world [80]. Since then, the government has made a considerable effort to improve the city's air quality, yet pollution remains well above the acceptable levels suggested by the World Health Organization [81]. The architects were interested in exploiting how plant leaves have the ability to collect fine particles on their surfaces (some varieties more than others). One recent study suggests urban air quality can be improved by 40% to 60%, if one accounts for the spatial formation of the urban environment and, specifically, if the space created by the buildings and infrastructure results in an urban canyon [82]. This possible improvement is higher than previously estimated (before these findings a 5% improvement by plant leaf particulate matter deposition was estimated) [82].

In addition to its role as a "practical temperature-humidity comfort control device, or as a beautiful energetic view", the architect wanted to make the living wall behave like a "light curtain" [84]. Apparently, this meant orienting the wall so the plants' leaves capture the oblique rays of the sun making the vegetated surfaces appear to "glow" [85].

5.2.2. Analysis and conclusions: Casa CorManca

The architect placed the living wall at the south-end of the site with a courtyard in front of the wall, thus all of the interior and exterior spaces are in a U-shape around the courtyard [see Fig. 9]. This strategy provided a number of advantages. First, it makes the planted wall a focal point of the design. This means the living wall is visible from most spaces, guaranteeing biophilic impact, i.e., it ensures nature is a part of the inhabitants daily experience, at least visually. Second, the wall becomes a unifying element in the design, tying together the disparate spaces surrounding it. This formal strategy (a strategy wherein the living wall influences the building's form) can be a didactic example to architects and planners of how to incorporate living walls for new construction as an integral, rather than superficial, factor determining the conceptual design.

Vitruvius wrote a building must have commodity, firmness, and delight to be considered architecture [88]. The Casa CorManca project is instructive because, despite being an exterior element, the living wall helps organize the building plan, improve local air quality, and aesthetically alter the interior living spaces. This results in a living wall which is an essential component of the building and begins to satisfy the Roman architect's three principles; moving the living wall beyond the potential criticism of being decorative or superficial.

5.3. Redefining superficiality: The Cusset wall

The Cusset wall [see Fig. 10], inaugurated in 2010 near Lyon in Villeurbanne, France, offers an example of how to invert the criticism of superficiality, i.e., retroactively add a living wall to an existing building while remaining completely independent. It is self-supported and freestanding which is in contrast to the vast majority of systems which are designed to be hung from, or braced by, the wall they are intended to cover. The Cusset wall has implications which may prove interesting to the preservation community and urban planners wishing to construct a living wall independent of existing construction. Also, this type of living wall can play a role in influencing the formal valor and spatial attributes of the adjacent cityscape [89].

Fig. 10. The freestanding Cusset wall in Villeurbanne, France, conceived by Eric-Pierre Ménard: A. View of its east-southeast façade, B. Detail looking up showing small trees and large plants, C. Views looking up at north and south "bookends" (framed steel grills acting as "bookends" to the wall, giving the false impression the living wall is attached to the building - note the thin continuous strips of sky visible between the building and living wall structure). Photos by author c.2016. *[2-column fitting image]*

5.3.1 Project history

The Cusset living wall is a modular, self-supporting system using soil-based growing media built adjacent to the east-southeast-facing wall of an approximately 1,400m² mixed-use five-story retail and residential building [Fig. 10A]. The vertical planted surface area is 238m². The project's design strategy was to erect the tallest self-supporting living wall in France, add to the biodiversity of the city's fauna and flora, mark the entrance to the east-side of the city, and build the living wall next to, but not touch, an existing building [90] [91].

The City of Villeurbanne claims over 22,000 cars/day pass through the intersection this project faces, creating an opportunity to both display the city's ecological initiatives and help diminish air pollution [90]. The project was conceived by a landscape specialist named

Eric-Pierre Ménard who proposed a living wall which changes with the rhythm of the seasons [90]. According to their press release, the project was conceived as a continuation of the city's effort to create natural spaces in each of the city's neighborhoods [90]. The project was designed and engineered by a company called Canevaflor, now defunct [90] [92]. Canevaflor designed an intensive system of large cages lined with a strong fabric which was filled with earth and then planted. Touted as both the tallest living wall in France (at the time of construction, it is still the tallest self-supported living wall in France) [93].

11,000 plants and more than 30 different species were installed, including ivy, geraniums and crocuses [94]. Four small trees were planted at the top of each of the four main tower structures [Fig. 10B]. Changing with the rhythm of the seasons is achieved by using varying species of flowering plants.

5.3.2. Analysis and conclusions: The Cusset wall

The Cusset wall presents a strategy for retroactively adding living walls to existing buildings which are otherwise unsuitable candidates due to structural or other concerns. The living wall system is self-supporting in spite of its appearance as being attached to the adjacent building's façade. The Cusset wall's entirely independent structure has its own foundation and steel-framed superstructure. Weighing 30 tons, the superstructure weighs the same as the soil it supports [95]. This is rather innovative: one of the disadvantages of using soil on a living wall is the additional weight superimposed on the building's structure. Soil, especially when wet, is relatively heavy. The designers made a structure which can take advantage of the added soil weight to have a supplemental 30 ton mass to stabilize its five-story and 30 ton structure, amounting to 60 tons of stabilization.

A second innovation is how the designers' maintained the separation of the living wall from the adjacent building while simultaneously giving the illusion that the living wall is attached to the building. This is achieved in two ways. First, the designers cantilevered "bookends" off both ends of the steel superstructure using the same steel-framed grills used for the planter-cages. These "bookends" fill the gap between the living wall and the existing building [Fig. 10C]. Second, the large size of the caged plant-containers also allows the plants within them to grow to a considerable size, and they are beginning to hide the gap (see right-side of Fig. 10C).

These formal and structural innovations are unheralded. Instead the Cusset wall is hailed for its symbolic rather than typological value. Yet it is its typological innovation which holds the lion's share of its didactic value for those looking to restore nature to the city. If it were to become a template for future retroactive vegetative installations, then the municipality's strategy of using the Cusset wall to ameliorate the problems of air and noise pollution can move beyond a symbolic effort and have a sizeable impact.

5.4. Response to part 3 criticisms: Summary of analysis

In summary, the criticism that living walls are decorative and too superficial to the buildings they serve is not experientially applicable to all projects. There are ways to avoid these pitfalls, as shown by the Anne Demeulemeester Shop and Casa CorManca projects. However, the criticism is only applicable to the Cusset wall in one respect: the adjacent building's residents can only enjoy its vegetation when outside. Unless designed intentionally as a factor of their experience, building occupants will have no interaction with the exterior living wall while inside the building. This is often the case for retrofitted and retro-designed exterior green walls: they are enjoyed more by pedestrians and residents of facing buildings than their own inhabitants. This is why the first two examples are so instructive: the Anne Demeulemeester Shop and Casa CorManca projects prove that living walls can play a role in defining the architectural concept, and in doing so allow their living walls to be seen and appreciated from both inside and outside the building.

The most common criticism of living walls, in terms of their superficiality, has to do with their environmental sustainability. For example, the Cusset wall uses potable water for its irrigation; we can assume with the intense automobile traffic surrounding it that it will not be able to change the immediate air quality to a significant degree, and in terms of embodied energy its deficit is unrecoverable. Therefore, it can be considered superficial for symbolizing sustainability more than for its actual sustainability. But its symbolism and the symbolism of living walls in other urban environments can have practical value in spite of this criticism.

There is an interesting parallel between the criticism that living walls are merely decorative and the contemporary criticisms of the utopic *Garden City* and *City-Beautiful* movements. Some criticized these movements as being less about social improvement than aesthetics, or at least being overly focused on aesthetics [96], an oft-cited criticism of living wall systems. But there are many advocates of living walls who, at least partially, lend their support because of the transformative aesthetic power of green walls and their ability to lend a new identity to the public realm [97], stating that they give urban areas a sense of place [98]. These supporters argue that aesthetics is more than just decoration. Aesthetics allows for communication of potent social and cultural ideas because buildings can be used as a language to communicate messages; messages instilling a sense of place. The aesthetics of green walls can send a new and convincing message of what “sustainability” is in a dynamic way through the changing and evolving nature of plants, i.e., urban canyons can serve as more than just corridors of transportation [49]. To quote Tadao Ando referring to his two recent green wall projects, “...in terms of the influence to the townscape and the contribution to public space of the city, … [living walls] may have more significance than closed architecture within a given site.” [97]

6. Conclusions

Learning from the above lessons can make living walls more reliable and affordable. Some of the latest research is less positive than living wall proponents may wish. Rather than hide or ignore unfavorable results, the new data provides an opportunity for the nascent living wall industry to openly come to terms with the real costs and implications of creating a living, breathing, reproducing, and, as is a fact of all life, dying wall systems.

And, of course, the keyword here is system. To become truly sustainable it is becoming clear that the industry must shift paradigms and evolve from selling the simple idea of 'wall' into marketing the idea of an entire system, rainwater storage tanks and all.

The promise of this new data is the opportunity to fully understand all the complexities of living wall systems. Once vetted, a mature living wall industry can become normalized; likely resulting in the proliferation of living walls. Despite this promise of standardization, and until then, it is prudent to remember that the existence of living walls, in their modern incarnation, is relatively new. Consequently, the longevity of nearly all of the competing systems is unknown. As a result the world of living walls is open to change and redefinition. This largely undefined world will continue to evolve until we learn how to optimize living wall systems and limit the effect of their associated variables. Some policy experts predict the implementation of standards and norms for living walls are still at least 10 years away. Until then, the world of living walls will remain a testing ground rampant with innovation; it is the Wild West of an architectural system in its infancy.

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Highlights

of

The State of the Art of Living Walls: Lessons Learned

by Benjamin Riley

Highlights of this review article

- Recent research and case studies could make living walls reliable and economical.
- Accepting the disadvantages of living walls can lead to optimized systems.
- Living walls can be sustainable if conceived as an entire system.
- The living wall industry must tether installation to maintenance.
- Beyond façades: examples of architects using living walls to define building form.