ACTIVATING CIRCULAR ECONOMY THROUGH INDUSTRIAL SYMBIOSIS:

A CASE STUDY OF A NOVEL MODULAR LIVING WALL SYSTEM

A Dissertation

by

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ABSTRACT

This research investigates the potentials of designing for sustainability, specifically “design for reuse” using a systematic by-product of industrial production processes, in a mutual exchange known as industrial symbiosis (IS) for a more circular economy (CE). CE seeks to change traditional methods of take, make, waste to eliminate the concept of waste after consumers use goods. This study focuses on fostering CE through IS between the automotive and the building and construction industries through creative architectural reuse. Previous attempts at IS between both industries have involved reusing materials such as end-of-life metal, tires and plastics but none have explored the reuse of prompt sheet metal cutouts (Offal) from automotive assembly processes.

A workflow of three parts is presented in this manuscript-style dissertation. The first manuscript presents “design for reuse” modules made from Offal. Experimental studies were conducted for four unique geometries to determine their cooling effect in two seasons and resource efficiency. The second manuscript presents a novel modular living wall system (MLWS) made with a module from Manuscript 1. Experimental data from measurement campaigns during four seasons (winter, spring, summer and fall) was used to calibrate 24-hour simulations of thermal performance in ENVI-met. Life cycle analyses (LCA) were also used to determine economic and environmental impacts. The third manuscript presented a techno-economic analysis comparing the novel MLWS to traditional living wall systems (LWS). Analysis of the novel MLWS was carried out through LCA and available data for parameters such as fuel consumption, electricity, net primary energy, and product costs.

This dissertation investigates the potentials of creatively reusing industrial by-products as feedstock in building and construction products through a case study. The case study was approached by studying module units, then a system which provided data for simulation at a bigger scale. Findings include a new method to test the performance of LWS; a new methodology to initiate reuse for solid non-hazardous industrial waste streams and opportunities to investigate frameworks for other industrial waste streams. Activating CE through IS could provide economic, environmental and technical benefits. Findings contribute to operational data required by decision and policy makers to promote circularity.

DEDICATION

To my parents, James and Gloria Okoye for your care, support and unrelenting love. To my second parents, Peace and Agbani Batubo for kindly teaching and guiding me. To my dear husband Adaiyibo, this achievement will not be possible without your vision and guidance. To my lovely daughters, Agbani and Ibim, you make me better and give me reasons to be strong. To Charles, Theresa, my relations, and to all who care about our planet.

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The design, fabrication and installation of the modules used for the case study were carried out by master of architecture and master of landscape students at the Texas A&M University's College of Architecture. The experimental study was carried out with the assistance of Mr. Bruce Dvorak and his team from the Department of Landscape Architecture and Urban Planning.

All other work conducted for the dissertation was completed by the author independently.

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GLOSSARY

Industrial Symbiosis (IS)	“engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products.”[1]
Circular Economy (CE)	“A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.”[2]

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[1] Chertow, M. R. (2000). Industrial symbiosis: literature and taxonomy. *Annual review of energy and the environment*, *25*(1), 313-337.

[2] Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, conservation and recycling*, *127*, 221-232.

Architectural reuse	“The process of designing for future reuse in which existing materials are reused or which aims to enable future reuse of building elements.”[3]
Microclimate	“Thermal condition of an outdoor space due to the effect of design on the sun, wind, humidity and air temperature.”[4]
Living wall	“Self-sufficient vertical gardens that are attached to the exterior or interior of a building.”[5]
Galvanized metal	“Metal with protective coating made from zinc to halt the formation of rust. Galvanization is important because it provides long-lasting protection for steel and iron products.”[6]
Revit	“Multidisciplinary building information modelling software for quality and coordinated designs.”[7]
Tally	“A Revit plugin that quantifies a building or material’s embodied environmental impacts to land, air, and water systems.”[8]

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[3] Kozminska, U. (2019). Circular design: reused materials and the future reuse of building elements in architecture. Process, challenges and case studies. In *IOP Conference Series: Earth and Environmental Science* (Vol. 225, No. 1, p. 012033). IOP Publishing.

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[5] Giordano, R., Montacchini, E., Tedesco, S., & Perone, A. (2017). Living wall systems: a technical standard proposal. *Energy Procedia*, *111*, 298-307.

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1. INTRODUCTION

Walter Stahel, a Swiss architect and environmentalist, known as one of the fathers of modern circular economy, described circular economy (CE) as a concept engaged in closing loops, changing economic logic, and replacing production sufficiency (Stahel, 2016). Strategies for CE include the following R-frameworks: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover (Kirchherr, Reike, & Hekkert, 2017; Potting, Hekkert, Worrell, & Hanemaaijer, 2017). CE strategies could preserve products, their parts, materials and energy embodied in resources that cannot be preserved by other strategies.

Creative architectural reuse of by-products and waste flows from consistent industrial waste streams could improve resource efficiency, reduce costs of traditional products; and reduce energy and greenhouse gas emissions caused by conventional recycling practices. CE has different implementation scales, *micro*, *meso* and *macro*. The *micro* scale usually focuses on a single product, service, or organization. *Meso* scale incorporates eco-industrial parks and industrial symbiosis and *macro* scale is implemented as a city, province, region or nation (Ghisellini, Cialani, & Ulgiati, 2016; Kirchherr et al., 2017). These scales are neither consistently used nor clearly defined by authors (Moraga, Huysveld, Mathieux, Blengini, Alaerts, Van Acker et al., 2019).

The current linear economy is steering the world towards a 3- to 6- degree temperature increase and CE is the big shift that could stall this change. Circularity gap reports show that the global economy moved from being 9.1% circular in 2018 to 8.6%

in 2020 (PACE, 2021; Wit, Verstraeten-Jochemsen, Hoogzaad, & Kubbinga, 2019). There need for more circularity and architectural reuse could accelerate the transition to more CE by reduced material consumption, shrinking global greenhouse gases (GHG), and cutting virgin resource use.

Industrial symbiosis (IS) enables mutual exchange of waste or byproducts among firms, companies and industries (Chertow, 2000; Domenech, Bleischwitz, Doranova, Panayotopoulos, & Roman, 2019; Tseng, Wu, Lim, & Wong, 2019). Industrial Symbiosis is a growing key driver which supports the transition towards a circular economy (Baldassarre et al., 2019; Commission, 2015; Domenech et al., 2019; Ludeke-Freund, Gold, & Bocken, 2019). Three key drivers for IS are: decrease in company costs in the area of resources, reduction of generated company waste and creation of new areas of revenue. Examples of waste materials exchanged during IS include chemicals, construction materials, energy, heat, metals, mining, paper, pulp, steam, water and wood (Chertow & Lombardi, 2005; Domenech et al., 2019; Jacobsen, 2008). Attempted IS initiatives between the automotive and construction industries include reusing tires in asphalt (Landi, Gigli, Germani, & Marconi, 2018); modifying electric vehicle batteries for battery energy storage systems in buildings (Cusenza, Guarino, Longo, Mistretta, & Cellura, 2019); and reusing sheet metal scrap for new metal façade systems for building exteriors (Ali, Kio, Alvarado, & Wang, 2020; Ali, Wang, & Alvarado, 2019). However, there exists the need for more detailed CE initiatives and IS approaches between cross sector industries (Neves, Godina, G. Azevedo, Pimentel, & C.O. Matias, 2019). In addition, previous attempts have not reused prompt sheet metal (Offal) from the automotive industry as plant containers/modules in modular living wall systems (MLWS). MLWS are efficient in mitigating urban heat island effect but viewed as luxury installations (Kharrufa & Adil, 2012; Riley, de Larrard, Malecot, Dubois-Brugger, Lequay, & Lecomte, 2019). No specific material has been decided for living wall systems and their benefits are rarely quantified (Ottele, Perini, Fraaij, Haas, & Raiteri, 2011; Radić, Brković Dodig, & Auer, 2019). In the light of this, it is important to investigate the viability of Offal as modules in MLWS.

In this research, the architectural reuse of Offal as modules in MLWS is presented. The experimental study of modules and a MLWS provided data for larger scale building simulation carried out in four seasons. Additionally, a techno-economic analysis comparing the circular product to traditional products provided the potential impacts of replacing virgin and recycled materials in traditional products determining its feasibility.

1.1. Research Problem and Questions

CE focuses at the point of sale and actions of the owner-consumer towards the disposal of their goods and materials while IS focuses on production processes and seeks to eliminate waste through mutual exchange of byproducts (Stahel & MacArthur, 2019).. However, producers and manufacturers could act as owners/consumers as well as manufacturers who procure and use resources. The utility and value of waste during production are the responsibility of the owners.

There is need for harmonized frameworks of assessments to quantitatively assess the impact of IS in the transition towards CE (Domenech, Bleischwitz, Doranova, Panayotopoulos, & Roman, 2019); and CE initiatives (Ellen Macarthur Foundation, 2012) In addition, more industrial symbiosis is encouraged between cross sector industries, using circular materials and reporting more quantified synergies (Neves, Godina, Azevedo, & Matias, 2019).

The Sixth Assessment Report by Intergovernmental Panel on Climate Change (IPCC) states that human influence has warmed the atmosphere, ocean and land. human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Deep reductions in carbon dioxide and other greenhouse gas emissions could slow down global surface temperature and in turn global warming

The American Institute of Architects' 2030 Challenge seeks to eliminate annual global emissions from the urban built environment. In 2006, Ed Mazria an architect, established Architecture 2030 as an initiative for the construction industry to bring awareness to the impact that they could have in reducing carbon dioxide emissions. Architecture 2030's mission is to rapidly transform the built environment from the major contributor of greenhouse gas (GHG) emissions to a central part of the solution to the climate and energy crisis. One of the targets required that fossil fuel reduction standard for all new buildings and major renovations to 80% in 2020, 90% in 2025 and carbon-neutral in 2030. These targets may be met by implementing innovative sustainable design strategies and applying low/no passive design strategies to achieve maximum energy efficiency.

Three issues were identified in this research: product innovation level approach in designing for sustainability focused on developing life-long new products in place of traditional products. The use of circular principles for unconventional materials by designing with modularity for reuse after dismantling.

Environmental impacts were investigated through life cycle analysis (LCA) and building information modelling (BIM), employing multi-objective optimization methodologies and development of country-specific data for the implementation of LCA studies is encouraged (Kylili & Fokaides, 2017). Applying a case study for green infrastructure design provides a win-win scenario for designers to reuse materials and for industry to reduce their carbon emissions.

In addition, the materials of MLWS and surrounding microclimate parameters determine their cooling effect. Several approaches to assessing the cooling effect of MLWS have been utilized in existing literature. However, methods to determine cooling effect of MLWS vary due to the wide range of materials used in MLWS.

Also, the feasibility of CE initiatives is determined by the technique of techno-economic analysis (Bakshi, Ziv, & Lepech, 2015; Wijeyekoon, Suckling, Fahmy, Hall, & Bennett, 2021). Information on the novel MLWS could add to current research on living wall systems (LWS) bridging the research gap on MLWS and provide a support tool for researchers and manufacturers in sustainable design (Ingrao, Scrucca, Tricase, & Asdrubali, 2016).

This dissertation addressed the above-mentioned issues through a case study approach providing groundwork for future research. This research proposes to address the following questions:

- How can creative reuse influence the performance and efficiency of an industrial waste stream?
- What method determines the performance of a novel product- (modular living wall system) made from an industrial waste stream (scrap metal)?
- What process could determine the potential economic and environment impacts of reusing an industrial waste stream (automotive prompt scrap metal) in a novel product?

1.2. Background

1.2.1. Industrial Symbiosis

Industrial activities generate waste and byproducts as raw materials are transformed into products; these waste and byproducts are potentially harmful to the environment (Giusti, 2009). Reusing waste avoids contaminants and reduces the need for industrial companies to consume virgin raw materials (Pajunen, Watkins, Wierink, & Heiskanen, 2012). IS, a branch of industrial ecology (IE) achieves benefits by exchanging waste between companies as waste and by-products from one company become raw material for another (Bocken, de Pauw, Bakker, & van der Grinten, 2016; Morales & Diemer, 2019).

Industrial symbiosis (IS) is a growing key which supports the transition towards a more CE (Baldassarre, Schepers, Bocken, Cuppen, Korevaar, & Calabretta, 2019; Commission, 2015; Domenech et al., 2019; Ludeke-Freund, Gold, & Bocken, 2019). IS initially manifested as eco-industrial park developments, occurring for the first time in the 1960's in Kalundborg, Denmark (Jacobsen, 2008). Currently, eco-industrial parks are located around the world in India, Australia, Korea, Japan, Canada, the U. S, and Europe; they build upon existing and potential linkages within a region (Desrochers, 2002; Gibbs & Deutz, 2007). Most eco-industrial parks are inspired and supported by policy (Winans, Kendall, & Deng, 2017).

IS has been officially recognized as a practical approach to promote CE and is embedded in the European Union (EU) law through the final ratification of the EU CE package in July 2018 (Domenech et al., 2019). The package explicitly refers to IS as a core strategy for promoting circularity. Industrial symbiosis is a concept that involves cascades of reusing waste from production processes within the linear industrial economy (Saikku, Antikainen, Droste, Pitkänen, Loiseau, Hansjürgens et al., 2015), the IS concept is vulnerable to structural change in production processes and materials change.

Subsequently, cross-industry networks have evolved in the CE model since the early 2000s and many industries have applied industrial and urban symbiosis approaches (Domenech et al., 2019; Tseng, Tan, Chiu, Chien, & Kuo, 2018; Wen & Meng, 2015). However, there is need for proper indicators and measures to communicate the potential benefits of an IS to stakeholders, citizens, customers, companies and policy makers. This study proffers a method of initiating and quantifying the potential impacts of an IS by using a case study between two companies in different sectors – the automobile and building construction sectors.

1.2.2. Circular Economy

Circular economy (CE) seeks to change traditional linear methods of take-make-dispose to closed-loop systems. CE root's go as far back as the late 18th century, (Figure 1.1). CE optimizes the use of objects; preserves the value and utility of objects and materials; and recovers molecules at their highest utility levels, after point of sale of goods and materials (Stahel & MacArthur, 2019).

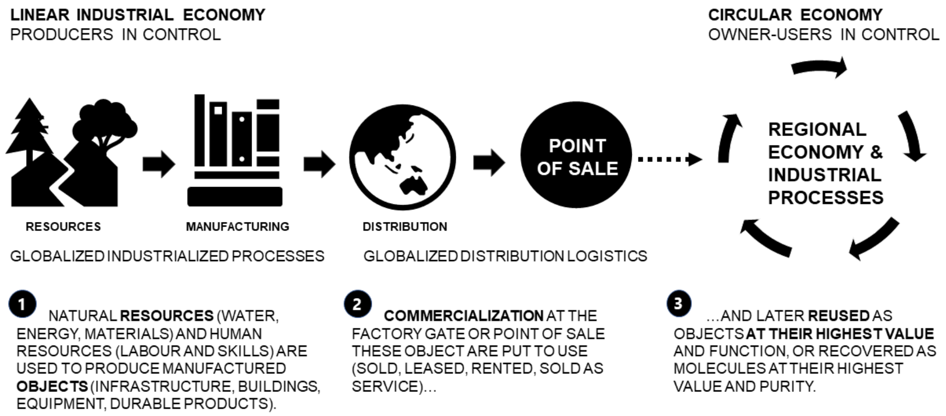


Figure 1.1: Situating the linear economy, the circular economy and the actors in control. Recreated from (Stahel & MacArthur, 2019).

Contributors to the CE concept include United States (US) professor John Lyle; his student William McDonough; the German chemist, Michael Braungart; and architect and economist, Walter Stahel (Winans et al., 2017). The CE concept became popular in Germany in the early 1990's to address issues associated with raw material and natural resource use for sustained economic growth (Geng & Doberstein, 2008); and in China the late 1990's (Naustdalslid, 2014; Wang, Hashimoto, Yue, Moriguchi, & Lu, 2013; Zhijun & Nailing, 2007).

CE approaches to circular building and building elements optimize their useful lifetime, integrating the end-of -life phase during initial design and using new ownership models for temporary storage of building materials (Lacy & Rutqvist, 2016). (Geldermans, 2016), states that circularity-values emerge at the intersections of unique intrinsic properties (material and product characteristics) and relational properties (design and use characteristics).

Applying CE through IS means widening the range of CE processes. Before end-of-life CE, a CE at production stages could have significant impacts towards waste reduction and carbon emissions. Production waste in the automotive industry, such as prompt metal could be converted to primary materials in other sectors such as the building construction sector, (Figure 1.2).

Significant opportunities for greater material efficiency especially for steel are yet to be widely implemented as steel is one of the most ‘circular’ manufactured materials (Walker, Coleman, Hodgson, Collins, & Brimacombe, 2018); and the producing steel accounts for nearly 25% of industrial carbon emissions, uses a high amount of energy and pollutes the environment (Hasanbeigi, Khanna, & Price, 2017; Pauliuk, Milford, Müller, & Allwood, 2013). In this study, CE is applied for reuse towards material efficiency and towards lifelong vertical greening product.

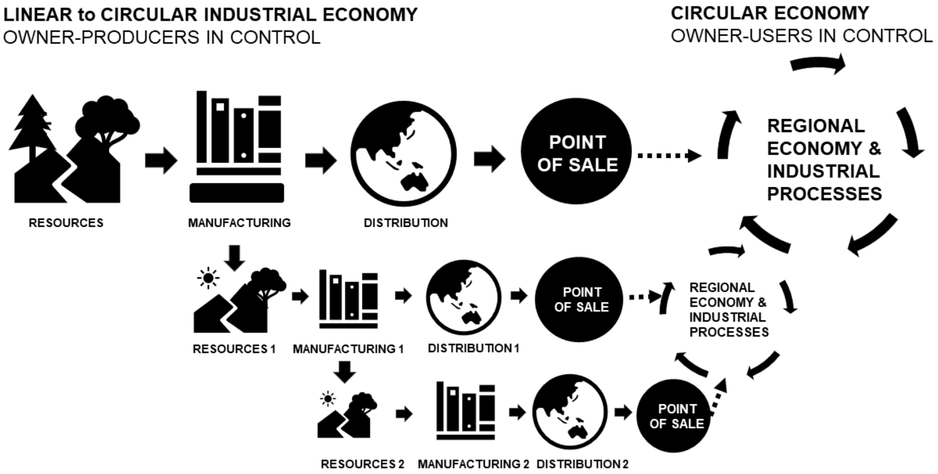


Figure 1.2: Proposing circularity at manufacturing stage in the linear economy. Recreated from (Stahel & MacArthur, 2019)

1.2.3. Vertical greening systems

Vertical gardens were cultivated in the Mediterranean region about 2,000 years ago (Köhler, 2008); the Hanging Gardens of Babylon dating back to 500BC and 600BC is one of the earliest examples of greenery systems (Vijayaraghavan, 2016). From studies, some terms used to describe greening systems include: “vertical garden” (Bass & Baskaran, 2003; Peck, Callaghan, Kuhn, & Bass, 1999a); “vertical greening systems” (Perini, Ottele, Fraaij, Haas, & Raiteri, 2011); “green vertical systems” (Pérez, Rincón, Vila, González, & Cabeza, 2011); or “vertical greenery systems (VGSs)” (Wong, Tan, Chen, Sekar, Tan, Chan et al., 2010).

Vertical greening systems (VGS) are found in temperate and tropical climate regions and they provide environmental and ecological benefits (Perini, Magliocco, & Giulini, 2017). VGS aims to reduce building operational energy consumption by shading and cooling the building envelopes while adding aesthetic value to them (Bianco, Serra, Larcher, & Perino, 2017; Perini, Magliocco, et al., 2017). The four key considerations in the contributions of VGS on passive energy savings in buildings are (1) the construction system used to place plants on the building façade; (2) the climate influences on the thermal behavior of the VGS and the choice of plants and how this climate influences their growth; (3) the type of plant species used, if they are deciduous or evergreen, shrub or climbing plants; and (4) mechanisms influencing the operation of the green system (Pérez, Coma, Martorell, & Cabeza, 2014).

The first VGS was invented by Stanley Hart White, (Hart, 1938). Later, Patrick Blanc who became a leading figure on VGS made them from materials such as metal frames, polyvinyl chloride (PVC) layer polyamide felt, automated fertilizer and watering system and an assemblage of indigenous and exported plants (Gandy, 2010). (Manso & Castro-Gomes, 2015b) reviewed many types of VGS to identify and systematize their main characteristics and technologies. This exercise involved emphasizing the importance of understanding their composition and construction methods. Typical items found in VGS include: supporting elements, growing media, vegetation, drainage and irrigation. VGS are subdivided in two main types: green facades and living walls (Manso & Castro-Gomes, 2015a). Green facades grow on the wall covering it directly while living wall systems (LWS) make use of plant modules/containers on supporting frames which are in turn supported by the wall of a building.

1.2.4. Living wall systems

The development of LWS has been rapid, contributing immensely to the environment (Ottele, Perini, & Haas, 2013). They improve building thermal performance, mitigate urban heat island effect, improve biodiversity and air quality when applied in the retrofitting of existing buildings (Cameron, Taylor, & Emmett, 2014). LWS provide greenery without using up valuable land in urban areas; they are also applied to blank exterior walls which are without windows or ornamentation to make these exterior surfaces aesthetically pleasing, and more attractive. An example of LWS can be found at the Vancouver International Airport made from a collaboration between Canadian and Japanese companies (G-Sky and Sugiko). A second example of a LWS can be found at the entrance to Awaji Island Akashi Kaikyo National Government Park, Japan. LWS have been aesthetically and functionally sufficient, however, LWS have not been fully approved as structures for energy saving due to the lack of availability of data on their efficiency and financial benefits (Ottele & Perini, 2017; Zhao, Zuo, Wu, & Huang, 2019).

The average temperature difference between living and bare walls is approximately 1-31.9 º C (Anđelković, Gvozdenac-Urošević, Kljajić, & Ignjatović, 2015). LWS in China were also shown to reduce exterior wall temperatures by a maximum of 20.8 º C and interior wall by 7.7 º C. The value of LWS to cool buildings has recently been cited for climatic zones with warm or hot summers (Francis & Lorimer, 2011). The range of the heat flux reduction is reported to be 30-70 W/m^2 during daytime and 1.5 W/m^2 during night (Besir & Cuce, 2018). Further investigation on the performance of LWS could show the factors that contribute to their effectiveness.

LWS require growing substrate, irrigation systems, pre-vegetated plants and supporting elements. There are two main types of LWS; continuous and modular (Vox, Blanco, & Schettini, 2018). Modular systems are designed with either planters, pocket-shape planters or panels (Charoenkit & Yiemwattana, 2016), while continuous systems have lightweight and permeable screens for plants to be inserted individually (Bribach & Rossomano, 2012; Corradi, 2010) Many studies overlook the contribution of the supporting materials of the planters to the success of the living green walls (Alberto, Ramos, & Almeida, 2017; Anđelković et al., 2015).

1.3. Research Objectives and Significance

From the preceding discussion, the following research objectives were defined:

A case study approach of architectural reuse for Offal as modules in a novel MLWS. This study was carried out in three parts. Firstly, to address the issues arising from the novelty of material reuse, experimental studies were carried out. The effect of design geometry on the modules, economic and environmental impacts due to reuse were investigated. It was expected that there would be significant difference in the thermal performance of the modules; environmental impacts from reusing Offal as primary materials for the modules; and economic impacts from replacing virgin materials. Secondly, experimental studies to determine the cooling effect of a prototype MLWS made from a module design in the first part, was conducted for four seasons. Data from the field studies were used to calibrate 24-hour simulations on a building scale. It was expected that its cooling effect should fall within the range as those for traditional MLWS. Thirdly, a techno-economic analysis was carried out to determine the feasibility of the new MLWS. The technical and economic impacts were calculated using available data from literature reviews and industry data. It was expected that the novel MLWS would be more affordable than traditional MLWS.

The research objectives were addressed through field observations, simulation, life cycle analyses, and data analysis as presented in Figure 1.3.

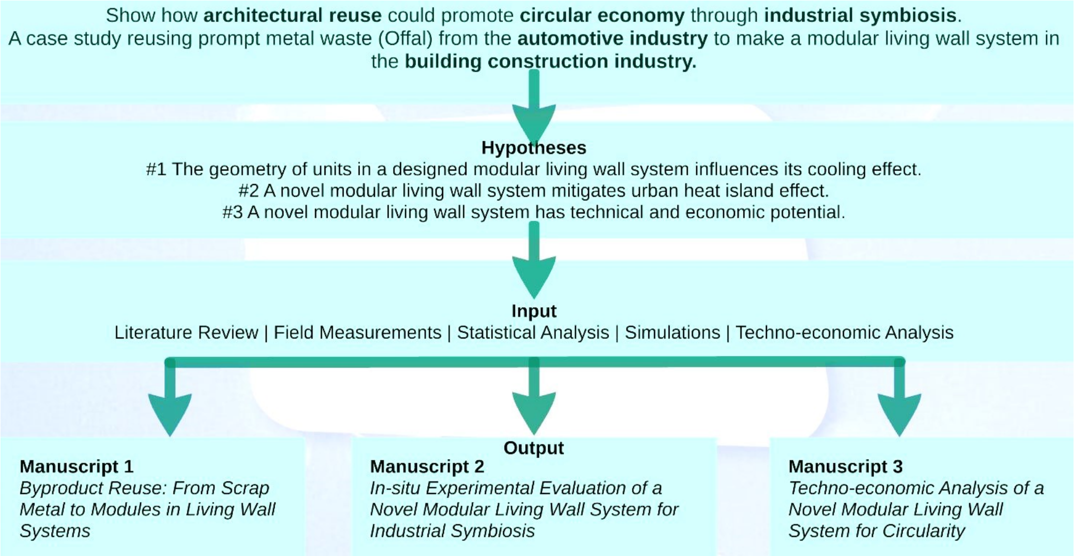


Figure 1.3 Research design

1.4. Research Methodology

Research strategies given by Linda Groat and David Wang in *Architectural Research Methods* are experimental, quasi-experimental, correlational, qualitative, historical, simulation, logical argumentation, case studies and combined strategies. These methods enable discovery through measurable controls and empirical research that attribute causality, observations and measurement in a natural setting, social and cultural interaction, archival materials and philosophical framing. (Kerlinger & Lee, 1999) define four general ways of knowing: the method of tenacity, the method of authority, the a priori method or the method of intuition, and the method of science. They offer a stricter definition of scientific research as: “systematic, controlled, empirical, amoral, public and critical investigation of natural phenomena. A significant advantage of a case study research is its capacity to investigate a setting or phenomenon embedded in its real-life context (Groat & Wang, 2013).

The types of research combined in this dissertation include: case study, field experiments comprising in situ measurement methods; and simulation using output of experiments to test performance on a bigger scale. In case studies and combined strategies type of research; data sources include- archival research to ascertain pre-existing conditions, formal analyses of the case study and records of examples or user experiences. A three-stage research design- field experiment, simulation and literature reviews was used to investigate the impacts of reusing an industrial waste stream as primary material in a novel MLWS.

The field experiment of designed modules occurred in winter and spring 2019. Four unique student designs were selected for in situ microclimate measurements. The variables measured were surface temperatures, ambient air temperatures and relative humidity. Resource efficiency was calculated by matching geometry of modules to Offal. Then, environmental and economic impacts were evaluated using Tally a Revit plug-in and United States Environmental Protection Agency, Waste Reduction Model (WARM).

In the second phase of this study, on-site measurements were carried out for specific days in the four seasons –winter, spring, summer, and fall. Data from these field measurements were used to calibrate 24-hour simulations in ENVI-met software. In addition, a life cycle analysis (LCA) was also carried out with Tally the plug-in for Revit building information modeling software and United States Environmental Protection Agency's WARM, for environmental and economic impacts. Variables measured include ambient air temperature (AAT), air layer temperature (ALT), soil temperature (ST), leaf temperature (LT), relative humidity (RH), and solar radiation (SR).

The experimental setup in Figure 1.2, included- FLIR E6 thermal imaging camera (accuracy: ±2% between -20°C to +250°C (-4 to +482°F) was used to collect surface temperature data. Each image was converted to comma separated value file in excel and analyzed in R Studio for average temperatures. A Kestrel 5400 WBGT Heat Stress Tracker (HST) and Weather Meter (Kestrel Instruments, accuracy: wind speed | air: larger of 3% of reading, least significant digit or 20ft/min speed: ambient temperature: accuracy: 0.9°F or 0.5°C; relative humidity: 2%RH) was used to monitor outdoor air condition at bare brick wall, in front of and behind MLWS. A TES 132 datalogging solar power meter (accuracy: ±0.7dB, ref 94dB@1KHz) was used to measure solar radiation on concrete, brick wall in front of and behind the MLWS. Thermal images, wind speed, air temperature and relative humidity were recorded between 700hrs and 2200hrs for daily measurements. In August 2019, daily measurements were recorded at 1600hrs at maximum air temperatures, while in 2020, surface measurements were recorded at 1400hrs at maximum surface temperatures. A Davis leaf and soil (VantagePRO2) weather station was introduced at MLWS by July and August 2020 to monitor leaf and soil temperatures, leaf wetness, and soil moisture.

Figure 1.4 Equipment for measurement campaign for 2019 and 2020. 1-FLIR E6 thermal imaging camera, 2- Kestrel 2400 Heat Stress Tracker, 3 – Solar Meter, 4- Canon EOS fisheye camera, 5- Davis weather station, 6- Davis Vantage Pro 2, 7 – soil moisture and temperature probes, 8 – leaf temperature and wetness sensor.

The mixed-methods research tasks include:

1. Conduct an experimental monitoring of modules and the case study living green wall.
2. Characterize the cooling effect in four seasons of winter, spring, summer and fall.
3. Simulate for a building facade in an urban area using ENVI-met for extent of mitigation.
4. Conduct a “cradle-to-gate” life-cycle analysis.

The research intends to explain how and why architectural reuse can be impactful in the IS scale for more CE. A case study research incorporates multiple sources of evidence, data for this study were obtained from reports, literature and field measurements. Although case study research is criticized for its difficulty in generalization, the case study's strength is its capacity to generalize to theory, which can be tested through other experiments.

The next three chapters are dedicated to three manuscripts that were developed between 2019 and 2021. Chapter 2 presents a literature review, design outputs to add value to Offal and experimental study of four modules. Chapter 3 focuses on a prototype MLWS which is the basis for experimental study in four seasons. Data from the experimental study, is used to calibrate 24-hour simulations in ENVI-met. Chapter 4 presents a techno-economic analysis comparing the novel MLWS to traditional LWS to determine if it was feasible. Lastly, Chapter 5 states the theoretical and practical implications, novel procedure for testing the thermal performance of novel MLWS and component, novel framework for creative reuse, the significance of this study, and future work.

1.5. Limitations of the research

The limitations of this study are as follows. Student designs chosen for field observations in Chapter 2 were arbitrary and the MLWS supporting frame could not carry the four modules. The thermal performance investigation in Chapter 2 and Chapter 3 were based on the study site climate, a humid sub- tropical climate, hence experimental results could only claim performance based on the locality.

In addition, the MLWS composition and fabrication methods were ultimately different from other market-based LWS. Due to commercial sensitivity in obtaining data from companies, assumptions were made concerning data for automotive industries. Available data for annual passenger car production was used to calculate the volume of

Offal. Also, it was also assumed that the Offal came in fixed, predictable sizes and quantity.

2. BYPRODUCT REUSE: FROM PROMPT SCRAP METAL TO MODULES IN LIVING WALL SYSTEMS (MANUSCRIPT 1)

2.1. Overview

A limited number of case studies have addressed the feasibility of transforming industrial waste streams into building construction materials. Prompt metal scraps in the automotive industry, referred to as Offal represent a significant yet consistent waste stream; primarily in the metal industry and many other industries that use sheet metal for their products especially the automotive industry. Offal are usually sent to conventional recycling for producing new sheet metal but circular economy handling through creative reuse could reduce energy consumption, pollution from zinc and greenhouse gas emissions. This study presents alternate approaches of reusing Offal applying the ‘Design for Reuse’ strategy. Approaches including students’ architectural reuse designs and an experimental study of four selected module units are presented. Offal was transformed into modules for a living wall system (LWS). What are the impacts, opportunities, risks and challenges of reusing Offal as modules in LWS? In this pilot study, four modules with distinct geometries from the students’ designs, were observed in situ during winter and spring 2019 for the influence of their design geometry on their cooling effect. Furthermore, their cooling effect was determined by comparing their surface temperatures to the brick wall surface in similar surrounding environment. Environmental and economic impacts were evaluated comparing reuse to recycling and landfilling. This proposed process presents lessons that open up broader implications and challenges such as its applicability, generalization and scaling-up of feasible practices from one industrial sector to another to achieve more circular economy towards industrial waste streams.

2.2. Introduction

The automotive industry uses sheet metal for producing car bodies. Alloys of steel and aluminum are used in different ratios to achieve light weight cars with reduced fuel consumption; base alloys for external body paneling are the 6016 alloy in Europe and higher-strength 6111 and 6061 alloys in North America (Fridlyander, Sister, Grushko, Berstenev, Sheveleva, & Ivanova, 2002). Studies of Offal have generally overlooked the additional energy and processes required due to recycling –steel involves the additional process of de-galvanizing prior to recycling (Ali et al., 2019). Offal (Figure 2.1) is a by-product of vehicle production processes and their quantity is expected to increase with increasing world population. Exponential growth world's population has increased the demand for cars and it is expected that there will be an increase in the world's population up to 10.1 billion in 2050 (Bos, Vu, Levin, & Bulatao, 1992). This expected increase puts additional need for efforts to provide alternatives to current conventional recycling handling of this waste-flow to reduce net energy consumed during production processes; and to reduce carbon emissions during conventional recycling and virgin material production.

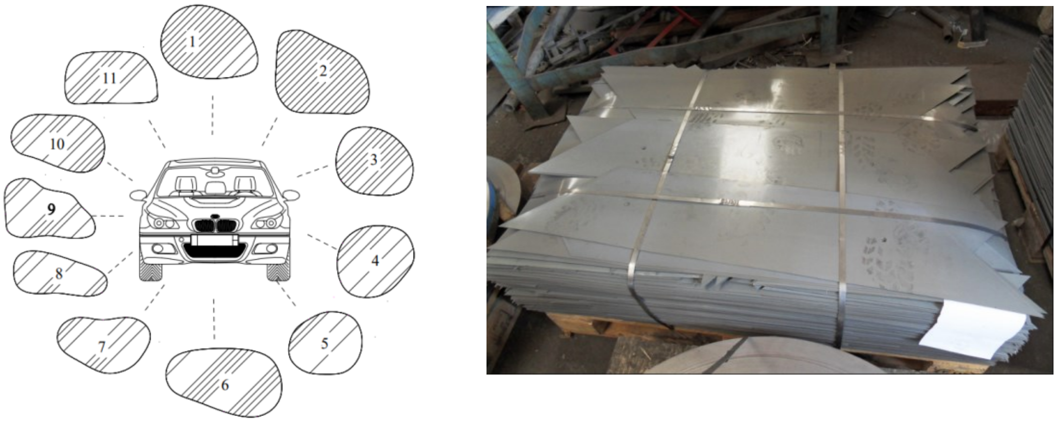


Figure 2.1: Automotive prompt metal scrap (Offal)

The primary focus of this study is galvanized sheet metal Offal for the automotive industry produced during stamping and blanking operations on sheet metal (Cooper, Rossie, & Gutowski, 2017; Hauw, Dubar, & Oudin, 1999). The steel sheet is among the highest quality steels produced due to its chemical “purity” (Koros, Hellickson, & Dudek, 1995). Prompt scrap referred to as Offal are cutouts from sheet metal for openings in car bodies and engine parts. Hot dipped galvanized steel sheets are used in the automotive industry (Katundi, Tosun-Bayraktar, Bayraktar, & Toueix, 2010). Although the quality and strength of sheet metal material are not affected during stamping, Offal are viewed as scrap and sent to plants for recycling.

The inclusion of galvanized scrap in steelmaking charges introduces zinc and small amounts of lead below the surface of the liquid steel in the steelmaking vessel. Zinc affects the environmental performance of steelmaking shops, ladle metallurgy facilities and foundries. Penalties include the loss of recyclability of Basic Oxygen Furnace (BOF) dust/sludge to sinter plants, to injury to product quality through release of residual zinc during solidification of cast sections. Penetration of zinc brings on severe operating and refracting penalties (Koros et al., 1995). BOF furnace uses iron ore as its base raw material and electric arc furnace (EAF) uses scrap as its base (Brown, Cortes-Lobos, & Cox, 2011; Pvt, 2021). EAF dusts could not be landfilled if they contained an excess of 15% Zn and processes used to treat EAF dusts that could contain up to 40% Zn in flat rolled producing shops did not allow for economic treatment of BOF dusts because processing costs and low zinc credits were unfavorable. EAF dust is listed as hazardous waste by the regulations of most countries (Salihoglu & Pinarli, 2008). Currently, more than half of EAF dust produced worldwide is still sent to landfill and the other half is processed pyrometallurgically or hydrometallurgically to recover Zn (Lanzerstorfer, 2018). This dust sent to landfill contains approximately 7.0% of the world Zn production. In the USA, for 22 years between 1988 to 2010, virtually every new process to recover EAF dust and avoid landfilling failed (Southwick, 2010).

These issues are increasing the importance of Circular Economy (CE) efforts. CE advocates extracting value from waste towards reaching sustainability goals and leads to competitive advantage (Sharma, Govindan, Lai, Chen, & Kumar, 2020). The strategy of sustainable reuse for industrial waste has been applied to waste glass and incinerated sewage sludge ash for insulating building products (Lu, Zhou, He, Wang, Shen, & Poon, 2019); waste tire textile fibers as reinforcement materials for landfill liners/covers (Narani, Abbaspour, Mir Mohammad Hosseini, Aflaki, & Moghadas Nejad, 2020);automotive prompt sheet metal as building envelopes (Ali et al., 2020; Ali et al., 2019); automotive matrix trays as autonomous shading device (Ali, Layton, Kio, &

Williams, 2021); and EAF dust in concrete or asphalt (Al-Zaid, Al-Sugair, & Al-Negheimish, 1997; Sayadi & Hesami, 2017). More methods are required to increase global circularity. Strategies which identify value in industrial waste streams and circular approaches are essential at early decision stages for efficient and exhaustive product exploration and choice.

Many novel materials are rapidly brought to the market by manufacturers and their development is seen as a radical shift in society's use of chemistry. Design strategies towards CE include 'design for x' tactics (Bakker, Wang, Huisman, & Den Hollander, 2014; Haines-Gadd, Charnley, & Encinas-Oropesa, 2021). Design for sustainability is a combination of eco-design strategies including: Design for Environment, Design for Assembly, Design for Disassembly, Design for Modularity, Design for Maintainability, Design for Reliability, Design for Remanufacture, and Design for Upgrade (Go, Wahab, & Hishamuddin, 2015; Haines-Gadd et al., 2021; Moreno, De los Rios, Rowe, & Charnley, 2016). This study proposes the 'Design for Reuse" concept for materials which are byproducts from consistent industrial waste streams.

The work presented here investigates creative reuse opportunities to add value to Offal in order to preventing their recycling. The aim was to explore how product design can proactively address the choice of waste treatment and extend the life of an existing by-product by providing a life-long alternate utility. This study presents a methodology for reusing Offal instead of recycling them in line with goals to reduce energy consumed, EAF dust landfilled and greenhouse gases. A two-stage ideation process involved 1) product design by architecture students that further developed modules for modular living wall systems using the Offal without extensive modifications 2) experimental studies in two seasons (winter and spring). Both efforts center on creative reuse of Offal for a novel product.

2.3. Background

2.3.1. Global production of Offal

Locations and facilities for automotive assemblies can estimate the flow of Offal. This study focuses on passenger cars which are motor vehicles used for transporting passengers. These cars usually have a maximum of eight seats for passengers and the driver. Results from a study in Colombia indicated that passenger car stock would be increased by 6.6 times between 2010 and 2050, and the energy consumption and CO_2 emissions would be increased by 5.5 and 4.9 times respectively (González Palencia, Furubayashi, & Nakata, 2012). USA is one of the top ten producers of passenger cars. Figure 2.2 shows the number of passenger cars produced globally from 2010 to 2020 (OICA, 2021). Table 2.1 highlights the global reach and magnitude, respectively, of Offal as a potential raw material if reuse is enabled. A symbiosis between the automotive and construction industry could provide a profitable secondary use of Offal.

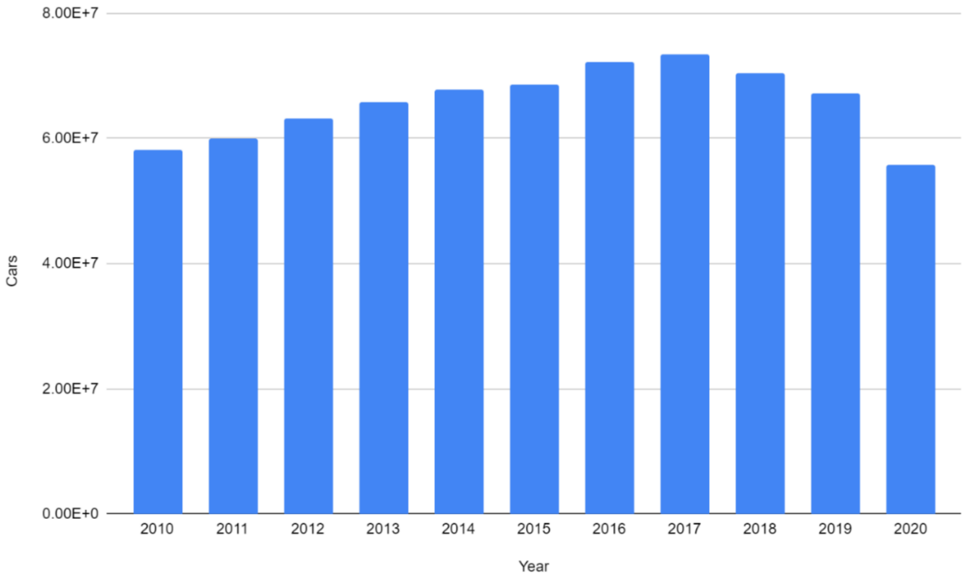


Figure 2.2: Global production of passenger cars from 2010 to 2020

Table 2.1: Top cars producing countries 2010 to 2020, in millions of units (OICA, 2021)

	2020	**2019**	**2018**	**2017**	**2016**	**2015**	**2014**	**2013**	**2012**	**2011**	**2010**
China	20.00	21.40	23.50	24.80	24.40	21.10	19.90	18.10	15.50	14.50	13.90
Japan	6.96	8.33	8.36	8.35	7.87	7.83	8.28	8.19	8.55	7.16	8.31
Germany	3.52	4.66	5.12	5.65	5.75	5.71	5.60	5.44	5.39	5.87	5.55
South Korea	3.21	3.61	3.66	3.74	3.86	4.14	4.12	4.12	4.17	4.22	3.87
India	2.85	3.62	4.06	3.95	3.68	3.38	3.16	3.16	3.30	3.04	2.83
USA	1.93	2.51	2.80	3.03	3.93	4.16	4.25	4.37	4.11	2.98	2.73
Spain	1.80	2.25	2.27	2.29	2.35	2.22	1.90	1.75	1.54	1.84	1.91
Brazil	1.61	2.45	2.39	2.27	1.78	2.02	2.50	2.72	2.59	2.52	2.58
Russia	1.26	1.52	1.56	1.35	1.12	1.21	1.68	1.93	1.97	1.74	1.21
Czech Republic	1.15	1.43	1.35	1.41	1.34	1.30	1.25	1.13	1.17	1.19	1.07

Table 2.1 continued: Top cars producing countries 2010 to 2020, in millions of units (OICA, 2021)

	2020	**2019**	**2018**	**2017**	**2016**	**2015**	**2014**	**2013**	**2012**	**2011**	**2010**
France	0.93	1.68	1.76	1.75	1.63	1.55	1.50	1.46	1.68	1.93	1.92
Mexico	0.97	1.38	1.58	1.90	1.99	1.97	1.92	1.77	1.81	1.66	1.39
Canada	0.33	0.46	0.66	0.75	0.80	0.89	0.91	0.97	1.04	0.99	0.97

2.3.2. Offal in the automotive industry

An automotive company provided eleven samples of their annual Offal waste. Available data included the monthly volume range, their physical properties, and thicknesses (Table 2.2).

Table 2.2: Annual weight of Offal from an automotive assembly plant.

Offal	Monthly Volume Range	Annual Volume Range (Numbers of pieces)	Surface Area per Offal (m^2)	Thickness (mm)	Mass per m^2 for gauge (kg)	Mass per Offal (kg)	Annual mass (kg)
1	5,000	60,000	0.28	0.70	5.40	1.51	90,600.0
2		100,000	0.31	0.75	5.75	1.78	178,250.0
3	5,000	60,000	0.21	0.70	5.40	1.13	68,040.0
4	3,000	36,000	0.22	0.70	5.40	1.19	42,768.0
5	6,000	72,000	0.16	0.70	5.40	0.86	62,208.0
6		1,000	0.31	0.75	5.75	1.78	1,782.5
7	1,000	12,000	0.20	0.70	5.4	1.08	12,960.0
8	1,500	18,000	0.16	0.70	5.4	0.86	15,552.0
9	1,000	12,000	0.20	0.70	5.4	1.08	12,960.0
10	1,000	12,000	0.21	0.70	5.4	1.13	13,608.0
11	5,000	60,000	0.22	0.70	5.4	1.16	69,660.0
Total	28,500	443,000					568,508.5

2.3.3. Conventional recycling programs

Production optimization includes in-house loops of reuse and recycling to minimize costs. Secondary steel mills produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an EAF. This study focuses on EAF production processes as its process is mainly one of melting scrap (Yellishetty, Ranjith, & Tharumarajah, 2010) and foundries are excluded.

2.4. Reuse Ideation: Module Designs

An interdisciplinary collaboration between academia and the automotive industry led to a 3-year design exploration with Offal as the primary raw material (with minimal transformation). Master of Architecture students were challenged to experiment with the different sizes of the Offal in the design of building skins/envelopes. They were challenged to use Offal in as original of a state as possible. Subsequently, digital fabrication and computer numerical control (CNC) processes to cut/modify/fold/form the Offal. Students were encouraged to minimize cutting and waste by design; they were encouraged to undergo training before using the CNC mill.

Students produced module designs in design studios for two semesters in 2018 and 2019. Four modules (Design #1 - #4) were selected for field observation, Figure 2.3. Design #1 had a rectangular shape at the back and a diamond shape at the front for the substrate and plant. It was finished with white spray paint. Design #2 was the widest module, it was V-shaped at the side with two perforations at its rectangular shaped back. It had an interesting curve from its left to right side. Design #3 was a slanted cuboid, it had the most volume for substrate and Design #4 was also diamond shaped like Design #1, it had more room for substrate and a diamond shaped back; the room for substrate began halfway and slanted towards the base.

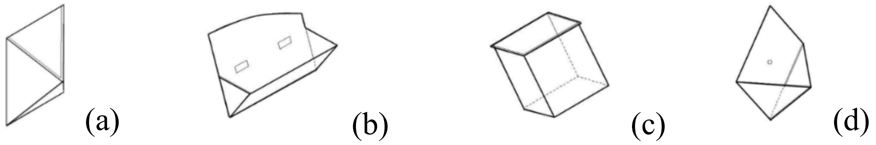


Figure 2.3: Modules used for experimental in situ observations. (a)- Design #1, (b) Design #2, (c) Design #3, and (d) Design #4

2.5. Experimental Study

2.5.1. Literature review

A search for “living walls in tropical regions” in Compendex a comprehensive bibliographic database of scientific and technical research resulted in 18 studies. A second search in Compendex with “vertical greening systems in tropical regions yielded 11 studies. Thirdly in google scholar both searches yielded 20 more tropically inclined studies. The 49 studies were screened and 24 studies were selected for further investigation. Research methods applied in studies, location and duration of study, soil type, number of plant species and physical properties of modules declared were identified.

2.5.1.1. Research methods

From 16 studies, three methods of investigating living walls were observed – experimental, simulation and survey, (Figure 2.4). Experimental studies comprised field studies on buildings and measurements of microclimatic parameters such as air temperature, surface temperatures, relative humidity and wind speed (Basher, Sheikh Ahmad, Abdul Rahman, & Qamaruz Zaman, 2016; Galagoda, Jayasinghe, Halwatura, & Rupasinghe, 2018; Jaafar, Said, Reba, & Rasidi, 2013; Liang, Dong, Yuan, & Wang, 2014; Othman & Sahidin, 2016a; Rupasinghe & Halwatura, 2020a). Some studies focused on plant performance, plant height, leaf area index, and plant temperatures (Perera, Jayasinghe, Halwatura, & Rupasinghe, 2021a).

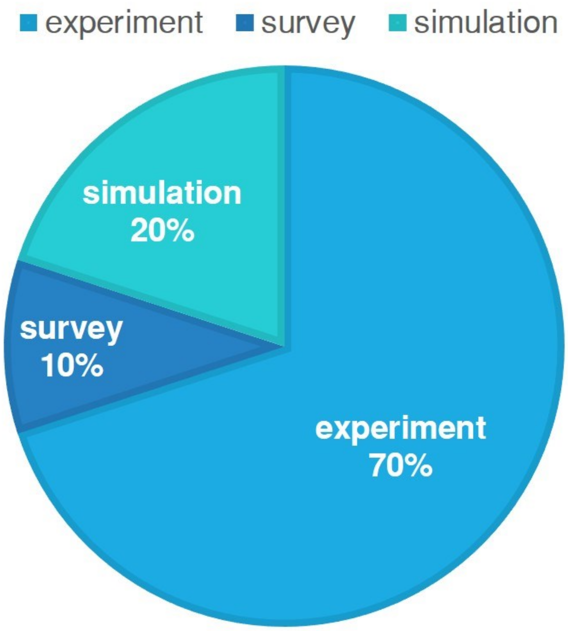


Figure 2.4: Research methods of living wall investigations.

2.5.1.2. Duration of study

The range of duration of studies was high with a minimum of 9 hours (Othman & Sahidin, 2016b) and maximum of 300 days (Perini & Bazzocchi, 2017). Studies that applied simulation used Design Builder (Galagoda et al., 2018; Rupasinghe & Halwatura, 2020a) and ENVI-met (Acero, Koh, Li, Ruefenacht, Pignatta, & Norford, 2019; Perera et al., 2021a). (Figure 2.5) shows the duration of studies for some living walls.

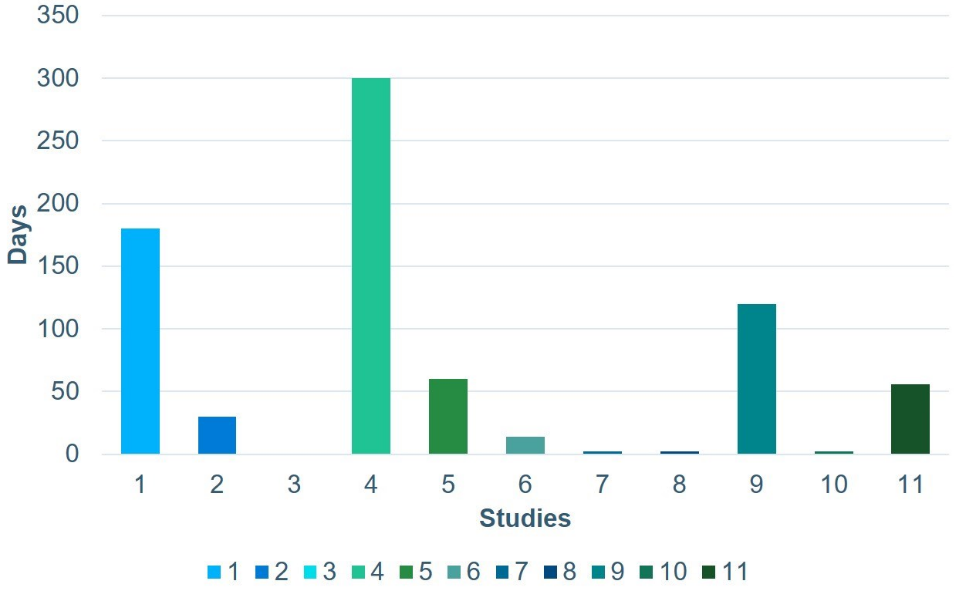


Figure 2.5: Duration of living wall studies; minimum of 9 hours and maximum of 300 days.

2.5.1.3. Soil type

A variety of soil types were utilized. Some were coconut peat (Perera, Jayasinghe, Halwatura, & Rupasinghe, 2021b), composted plant residues, husk, coconut fiber and cow dung (Charoenkit & Yiemwattana, 2017); others used a mix of vegetative soils and moss.

2.5.1.4. Number of plant species

Low income community had 100% support for VGS which provided a maximum of 16 crops for food and medicinal plants annually (Akinwolemiwa, Bleil de Souza, De Luca, & Gwilliam, 2018). The number of plant species cultivated ranged from 1 (Galagoda et al., 2018) to 20 (Perini, Bazzocchi, Croci, Magliocco, & Cattaneo, 2017). (Figure 2.6) shows the number of plant species stated in seven studies. These differences in duration of experimental methods and choice of type and number of plant species support the claim of a lack of standardized protocols for growing and building LWS (Bartesaghi Koc, Osmond, & Peters, 2018).

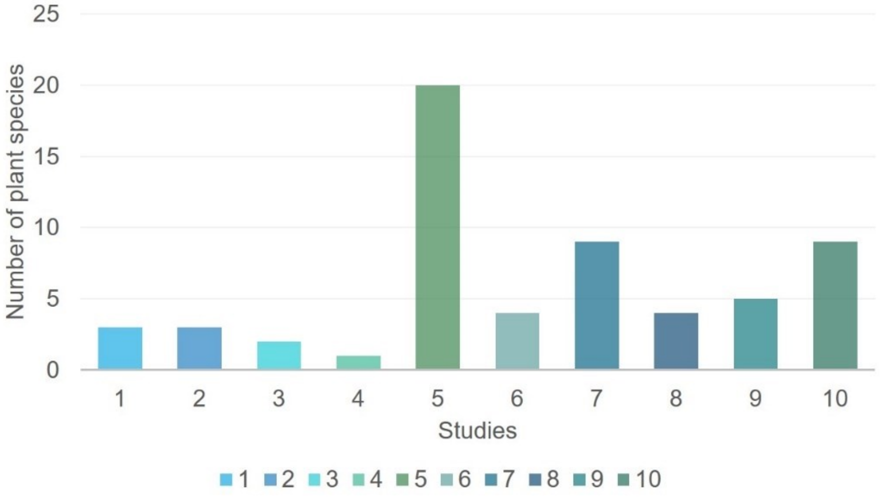


Figure 2.6: Number of plant species

2.5.1.5. Physical properties of modules

Modules were made from plastics (polypropylene, HDPE, PVC, felt and recycled) (Akinwolemiwa et al., 2018; Charoenkit & Yiemwattana, 2017; Galagoda et al., 2018). Wood was used for supporting material and modules (Basher et al., 2016); and as modules (Akinwolemiwa et al., 2018; Perera et al., 2021a). Metal modules were made utilizing aluminum (Akinwolemiwa et al., 2018), stainless steel (Oluwafeyikemi & Julie, 2015), and galvanized steel (Fernández-Cañero, Urrestarazu, & Perini, 2018). Materials used for modules are shown in (Figure 2.7).

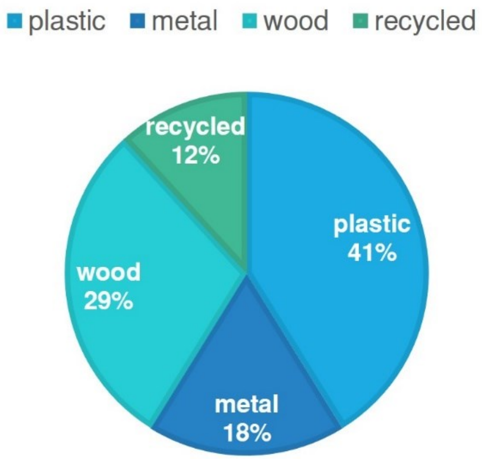


Figure 2.7: Material for living wall modules - plastic, wood, metal and recycled plastic.

Three studies gave dimensions of their modules as 500 x 500 x 100 (Charoenkit & Yiemwattana, 2016), 787 x 260 (Jaafar et al., 2013), and 600 x 400 x 50 (Perera et al., 2021a), Figure 2.8.

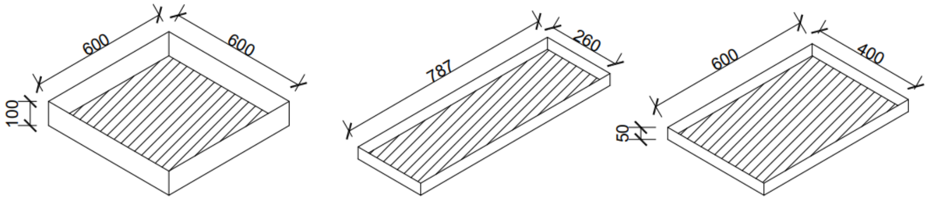
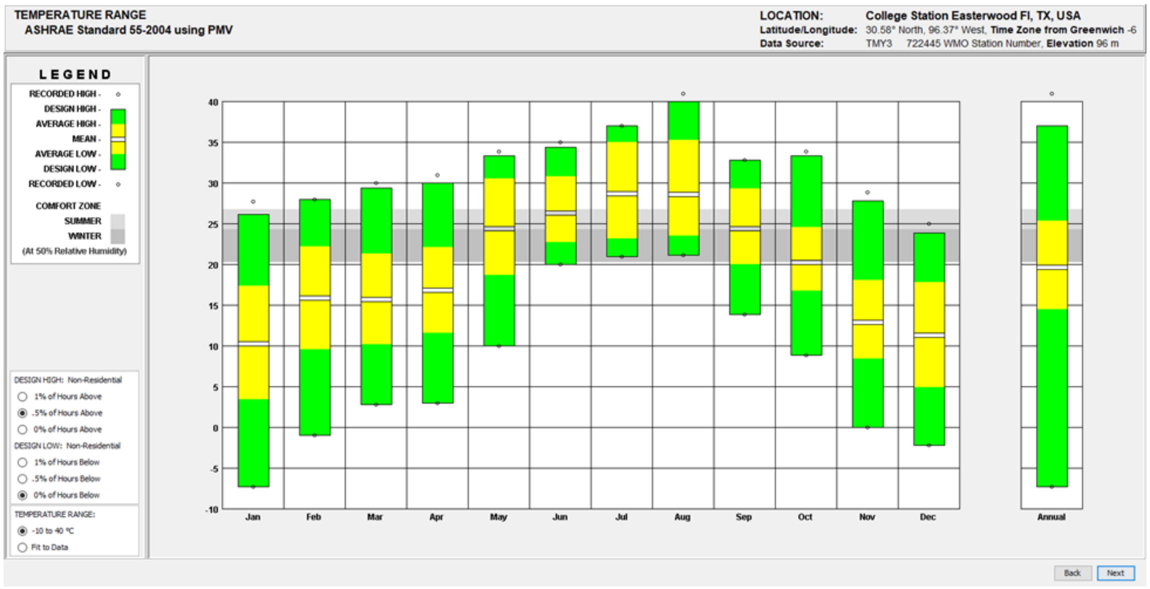


Figure 2.8: Examples of modules from studies.

2.5.2. Site study area

The site study area, College Station is classified as humid sub-tropical climate (Cfa); it is mild with no dry season and hot summers (Service, 2021). The average temperature of warmest months is over 22 º C and average temperature of the coldest month is under 18 º C; year around rainfall is highly variable. Temperature in the warm months from May to October often exceeds 34.4 º C in the daytime and 15 º C in the nighttime (National Weather Service, 2000). at an elevation of 97m.

Climate Consultant Software helps architects and other professionals understand their local climate presenting information that shows attributes of climate and its impact on built form. Climate Consultant uses annual 8760-hour, Energy Plus Weather (EPW) format climate data made available by the United States Department of Energy for thousands of weather stations around the world. EPW weather files contain weather data such as temperature, humidity, solar radiation, and other parameters specific to the location of the site or building for a typical meteorological year. The annual temperature range for the site study area was produced with Climate Consultant Software, (Figure 2.9).



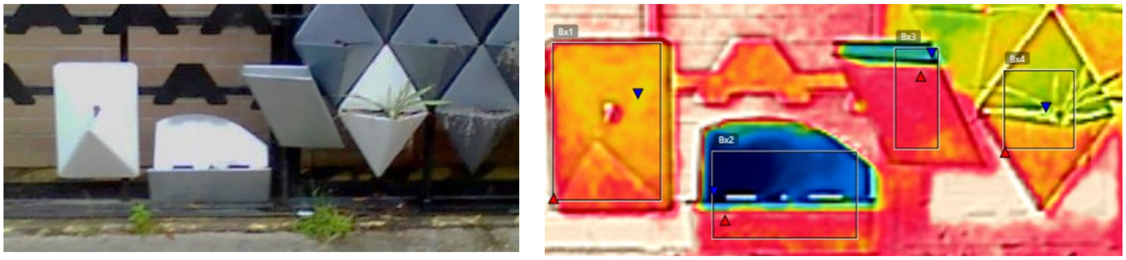
TEMPERATURE RANGE
ASHRAE Standard 55-2004 using PMV

LOCATION: **College Station Easterwood Fl, TX, USA**
Latitude/Longitude: 30.58° North, 96.37° West, **Time Zone from Greenwich** -6
Data Source: TMY3 722445 WMO Station Number, **Elevation** 96 m

DESIGN HIGH: Non-Residential
○ 1% of Hours Above
● .5% of Hours Above
○ 0% of Hours Above
DESIGN LOW: Non-Residential
○ 1% of Hours Below
○ .5% of Hours Below
● 0% of Hours Below
TEMPERATURE RANGE:
● -10 to 40 °C
○ Fit to Data

Figure 2.9: Air temperature range of site study area using Climate Consultant 6.0

Field experiments were carried out on March 5, 2019(winter) and April 26, 2019 (spring) from 7:00hrs to 22:00hrs. The four modules were located on a southeast facing wall, (Figure 2.10a). Field measurements occurred during early stages of installation. All four modules were empty for measurements on Day 1 (March 5, 2019). By day two, Design #4 contained substrate comprising two types of soils, Rooflite Extensive 700 Growing Media and Rooflite Drain 600 Drainage Layer.



a)

b)

Figure 2.10: Modules and their thermal images observed in-situ at site, April 26, 2019

2.5.3. Equipment and methods

FLIR E6 thermal imaging camera (accuracy: ±2% between -20°C to +250°C (-4 to +482°F) was used to collect surface temperature data, Figure 2.10b. Each image contained a minimum of approximately 800 observations. Images were converted to comma separated value files in excel and analyzed in R Studio. A Kestrel 5400 WBGT Heat Stress Tracker (HST) and Weather Meter (Kestrel Instruments, accuracy: wind speed | air: larger of 3% of reading, least significant digit or 20ft/min speed: ambient temperature: accuracy: 0.9°F or 0.5°C; relative humidity: 2%RH) was used to monitor outdoor air temperature at modules and brick wall. Data from FLIR E6 and Kestrel heat stress trackers were recorded between 700hrs and 2200hrs for both days. Firstly, a one-way analysis of variance (ANOVA) tests was carried out on the field data to determine significant differences between hourly mean temperatures at modules and the brick surface. Thereafter, Tukey Honest Significant Difference (HSD) tests were used to determine surface to surface differences between average hourly temperatures for the 16 hours on March 5, 2019 and April 26, 2019.

Surface temperatures and ambient air temperatures were measured in-situ in the microclimate. The seven temperatures measured were ambient air, surface temperatures of four modules, adjacent concrete wall and brick wall of study building. The configuration of modules and temperature measurements taken are shown in Table 2.3.

Table 2.3: Configuration and dates of data collection in experiment- concrete wall (CW), brick wall (BW), ambient air temperature (AAT), and design 1-4 surface temperatures (D1 – D4)

Experiment	Date/ Season	CW	BW	AAT	D1	D2	D3	D4
1	Mar. 5, 2019/ Spring	☑	☑	☑	☑	☑	☑	☑
2	Apr. 26, 2019/ Summer	☑	☑	☑	☑	☑	☑	☑

Environmental impacts were evaluated using Tally a Revit plug-in, and the United States Environmental Protection Agency WARM. This process was validated with calculations using data from existing literature on EAF processes, to show the impact of reuse over conventional recycling methods in the United States (US). In addition, calculations were carried out with available data for passenger vehicle production in the world and USA; without limiting the source of resources to a geographic region. Geographic proximity is neither necessary nor sufficient, nor a singular focus on physical resource exchange (Lombardi & Laybourn, 2012). Subsequently, annual quantity of sheet metal (Offal) waste stream from one plant in the United States (US) were used by extrapolation, to calculate material efficiency gained by reusing Offal in US and globally.

2.6. Results

2.6.1. Surface temperatures

Surface temperatures were monitored in situ from 700hrs to 2200hrs for two days in 2019, (Figure 2.11). Images were exported in comma separated value (csv) file formats from FLIR E6 camera using FLIR Tools software. Boxes on thermal images, Figure 2.10b were converted to csv files in Excel, data was analyzed in R Studio, (Appendix A). The mean hourly temperatures of the ambient air, concrete wall, modules and brick wall for both days are shown in Table 2,4; daily minimum and maximum surface temperatures are highlighted with blue and orange colours respectively.

Table 2.4: Tdb/2Tdb – ambient air temperature (March 5/ April 26), CW/2CW – concrete wall (March 5/ April 26), D1 – D4 (March 5 modules), 2D1 – 2D4 (April 26 modules), BW/2BW – brick wall temperatures for March 5/April 26.

Time	Tdb	2Tdb	CW	2CW	D1	2D1	D2	2D2	D3	2D3	D4	2D4	BW	2BW
7:00	-0.6	20.8	0.4	20.7	-4.5	17.9	-3.6	11.4	-2.0	18.0	-3.9	17.3	0.7	20.2
8:00	0.7	19.4	0.4	19.7	-4.0	17.3	-3.0	10.3	-1.2	17.4	-3.6	16.9	0.5	18.9
9:00	0.6	20.5	-1.7	21.4	-6.1	23.9	-5.5	13.8	-4.4	20.3	-5.1	NA	-1.9	21.4
10:00	8.6	22.1	-1.4	24.0	-4.0	31.7	-3.6	21.2	-4.4	29.4	-4.3	30.2	-0.4	30.9
11:00	7.2	23.4	8.2	29.9	9.6	35.3	3.5	25.7	3.4	35.3	8.3	34.2	8.9	34.1
12:00	10.1	25.5	11.3	32.3	10.9	30.7	8.6	21.5	6.0	34.0	9.4	31.0	13.4	27.8
13:00	12.3	25.7	13.1	34.1	12.5	37.4	13.8	30.1	11.1	42.9	12.8	35.9	16.3	33.3
14:00	8.9	27.0	15.2	33.7	17.6	36.7	16.9	29.3	13.2	43.9	17.7	33.9	18.7	30.9
15:00	10.3	27.0	12.8	31.3	12.2	32.3	16.7	27.8	14.2	39.5	11.5	31.7	15.2	30.9

Table 2.4 Continued: Tdb/2Tdb – ambient air temperature (March 5/ April 26), CW/2CW – concrete wall (March 5/ April 26), D1 – D4 (March 5 modules), 2D1 – 2D4 (April 26 modules), BW/2BW – brick wall temperatures for March 5/April 26.

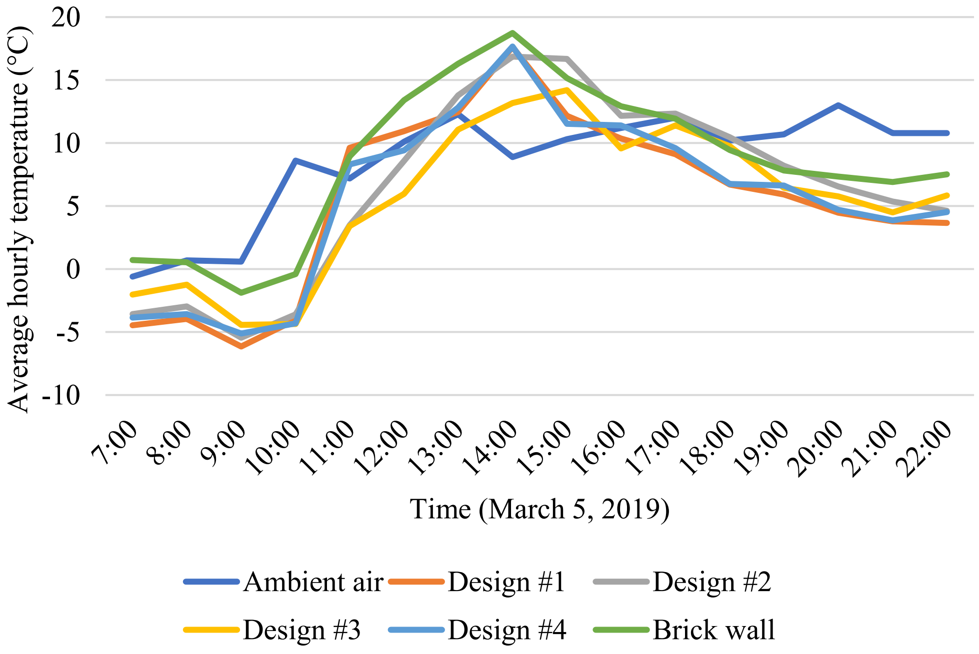
Time	Tdb	2Tdb	CW	2CW	D1	2D1	D2	2D2	D3	2D3	D4	2D4	BW	2BW
16:00	11.2	25.7	10.5	23.7	10.4	28.8	12.2	26.2	9.6	32.7	11.4	28.3	12.9	27.8
17:00	12.0	26.1	9.4	24.0	9.1	28.4	12.3	19.8	11.4	31.2	9.6	28.0	11.9	28.8
18:00	10.2	24.6	11.3	21.5	6.7	28.2	10.5	22.9	9.8	30.8	6.7	27.8	9.4	28.1
19:00	10.7	24.3	9.0	27.1	5.9	26.4	8.2	20.2	6.4	28.6	6.6	26.2	7.8	27.0
20:00	13.0	23.7	8.0	27.1	4.5	24.8	6.6	17.6	5.8	27.3	4.7	25.0	7.3	25.7
21:00	10.8	23.0	6.8	23.6	3.8	23.8	5.3	17.7	4.5	25.3	3.9	23.9	6.9	25.1
22:00	-	22.9	7.0	21.8	3.6	22.5	4.6	14.1	5.8	24.2	4.5	22.7	7.5	23.8

Minimum temperatures were observed between 7:00 and 9:00 hrs, maximum temperatures were observed between 13:00 and 15:00 hrs, Figure 2.11a. Temperature variations were maximum at design #1 in winter and at design #3 in spring. On March 5, 2019, the maximum temperature variation – difference between the highest and lowest daily temperatures, was between 13.6 - 23.8 ° C. Temperatures are listed from cool to warm in the following order – ambient air, concrete wall, Design #3, brick wall, Design #2, Design #4, and Design #1.

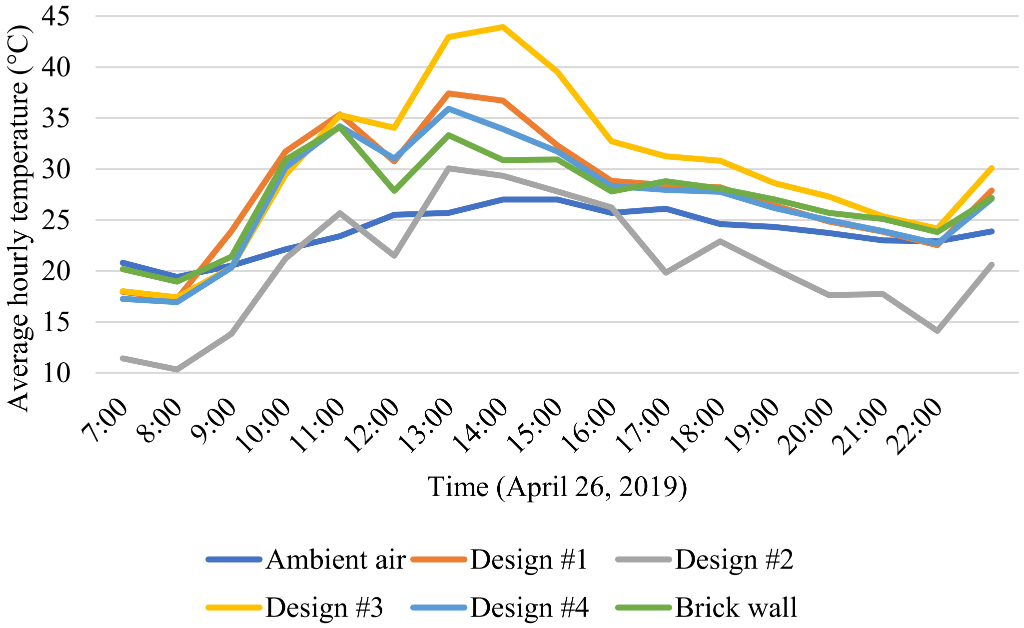
On April 26, 2019, temperature variation was between 7.6 – 26.5 ° C in the following ascending order – ambient air, concrete wall, brick wall, Design #4, Design #2, Design #1, and Design #3. At sunrise (7:00 hrs), ambient air temperature was the warmest and Design #1 surface was the coolest. Design #1 remained the coolest up to 9:00hrs. From 16:00 hrs to 22:00 hrs, Design #1 remained the coolest, although Design #1 had the coolest mean surface temperatures, maximum overall mean warmest surface temperature was also observed on Design #1. Maximum range of 11°C was observed at 14:00 hrs between Design #1 (19.8°C) and Design #2 (8.8°C).

From 7:00 hrs to 10:00 hrs, the brick wall registered the warmest surface temperatures. At 11:00 hrs, Design #1 was the warmest, at 12:00 hrs the brick wall was the warmest. By 13:00 hrs, Design #3 was the warmest and Design #1 was warmest at 14:00 hrs. From 15:00 to 19:00 hrs, Design #2 was the warmest and the brick wall was warmest from 20:00 to 22:00 hrs, Figure 2.11b.

Parameters are Tdb– ambient air temperature on March 5; 2Tdb – ambient temperature on April 26, CW – concrete wall surface temperature on March 5; 2CW- concrete wall surface temperature on April 26; D1 to D4 – surface temperature of modules on March 5, 2D1 to 2D4 – surface temperature of modules on April 26, BW – brick wall surface temperatures on March 5; 2BW – brick wall surface temperatures on April 26.



a) Average hourly temperatures on March 5, 2019



b) Average hourly temperatures on April 26, 2019

Figure 2.11: Average hourly temperatures for winter and spring full days in 2019

Approximately 800 to 58,000 hourly surface temperature data points were analysed with one-way ANOVA. Results of one-way ANOVA and Tukey HSD, showed the hours when there were no significant differences between the surface temperatures of modules were recorded (Appendix B and C).

Findings show that there were no significant differences between some surfaces during 42 of 800 hours comparison of their surface temperatures. In the 42 hours, Design #1 and #4 had the most similar surface temperatures at 33.3% due to their similar geometry. The building brick wall and Design #4 were similar 19%; Design #1 and the building brick wall were similar 14.3% and Design #3 and Design #4 were similar for 14.3% of the hours. Design #2 was the most significantly different surface of all the hours, with lower temperatures, Figure 2.12.

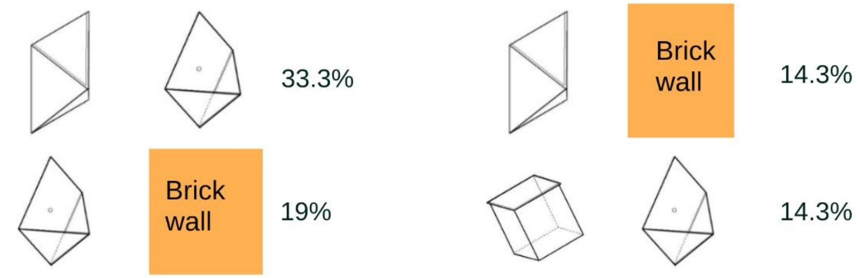


Figure 2.12: Results of statistical analysis of hourly surface temperatures

2.6.2. Longwave radiation

Austrian physicists, Stephan and Boltzmann stated that energy-temperature relationships should obey the following law when temperature is in Celsius degrees, equation (1):

$$\boldsymbol{Energy = S\ x\ (T + 273)^4} \qquad \text{Equation 1}$$

Where S = 5.670 x 10^{-8} $Wm^{-2}K^{-4}$ (Boltzmann constant) (Brown & Gillespie, 1995; English, 1999). Stephan-Boltzmann equation was used to calculate the average daily energy emitted by the surfaces. Radiation on March 5, 2019 was highest at the brick wall. Radiation was observed to be highest at Design #3 and least at Design #2 on April 26, 2019. (Figure 2.12) shows comparison of radiation on both days.

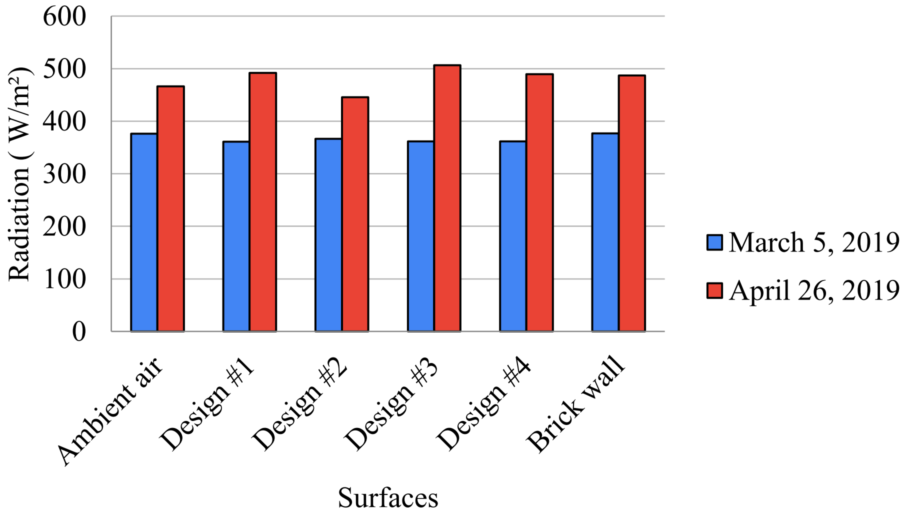


Figure 2.13: Average radiation for March 5, 2019 and April 26, 2019.

2.6.3. Resource efficiency

The possible annual quantity of modules by design was evaluated using data provided by the automotive company. Firstly, a matching of the Offal geometry to the module geometry was carried out to determine the possible number of Offal per module (Figure 2.13). Secondly, the result was used to find out the maximum number of modules for each of the four designs from the eleven Offal types. Resource efficiency of the designs was calculated by dividing the total available Offal by the total number of modules. Design #1 had an efficiency of 78%, Design #2 – 50%, Design #3 -50%, and Design #4 was 70%.

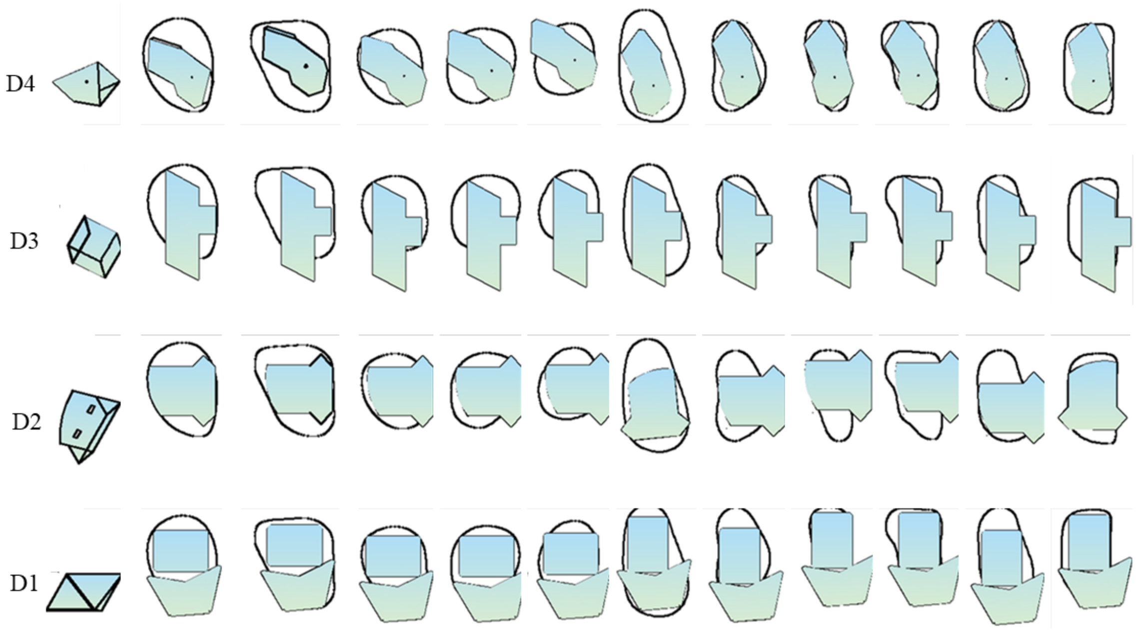


Figure 2.14: Resource efficiency of modules to Offal

2.7. Discussion

On March 5, 2019, the concrete wall was warmer than the modules with maximum temperatures of 4.9 ° C, 4.7 ° C, 5.3 ° C, and 4.6 ° C for Design #1 to #4 respectively. Also, the brick wall was warmer by 5.2 ° C, 5.4 ° C, 7.4 ° C, and 4.6 ° C for Design #1 to #4 respectively. Design #4 had similar temperature differences towards concrete and brick. Maximum temperature differences were observed at Design #3.

On April 26, 2019, three modules were warmer than the adjacent concrete wall by 7.7 ° C, 10.2 ° C and 6.3 ° C for Design #1, #3 and #4 respectively. Design #1 and #3 were warmer than brick wall by 5.8° C and 9.6 ° C. The brick wall was warmer than Design #2 and #4 by 9.7 ° C and 2.9 ° C.

Modules were cooler than concrete and brick during the morning hours from 7:00 to 12:00hrs and at 22:00hrs. The modules were 100% Offal and they required a supporting frame made from metal. The fabricated support frame could support Design #1, #3 and #4; it was not suitable for Design #2.

2.7.1. Global impact of reuse

This study focused on transforming consistent waste-flow of Offal into raw materials for modules. Figure 2.14, (created using average data from Table 2.1) shows countries with maximum passenger car production and Offal. Removing zinc from prompt metal during recycling leads to pollution and recycling leads to extra energy consumption. The modules are presented and compared to a similar traditional product. The economic and environmental impacts are reported.

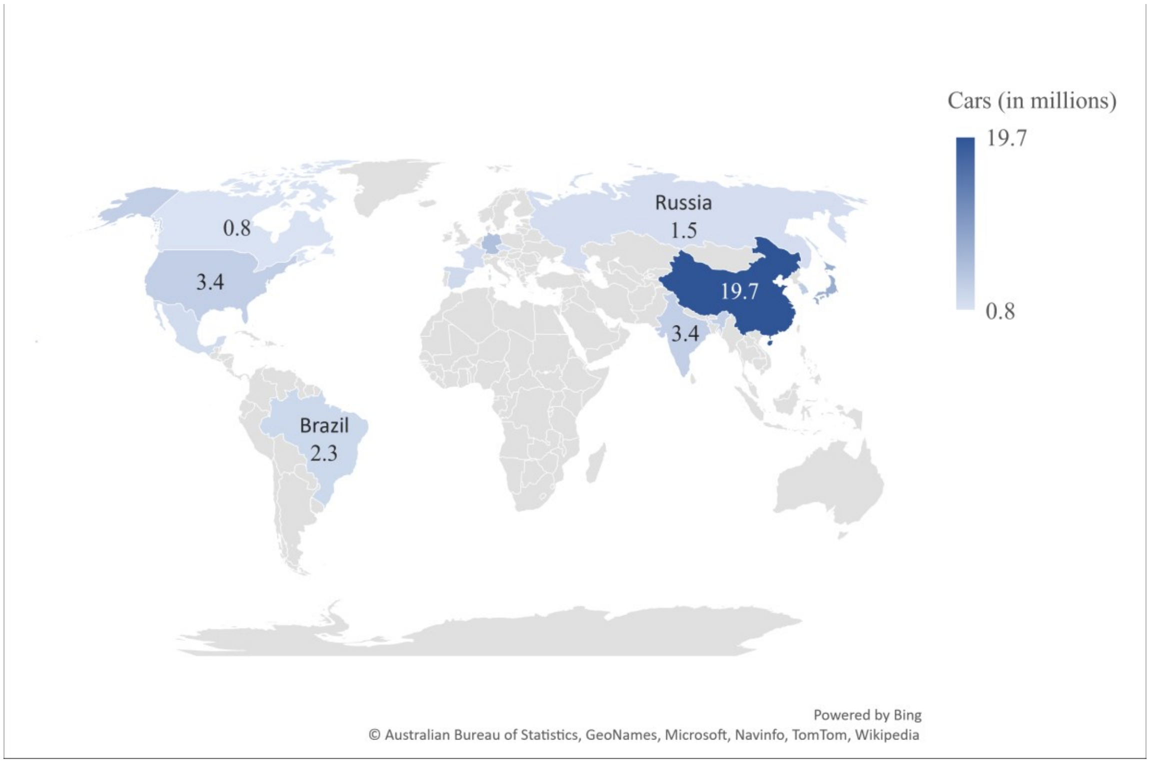


Figure 2.15: World map showing countries with maximum passenger cars from 2010 to 2020

2.8. Environmental and economic impacts

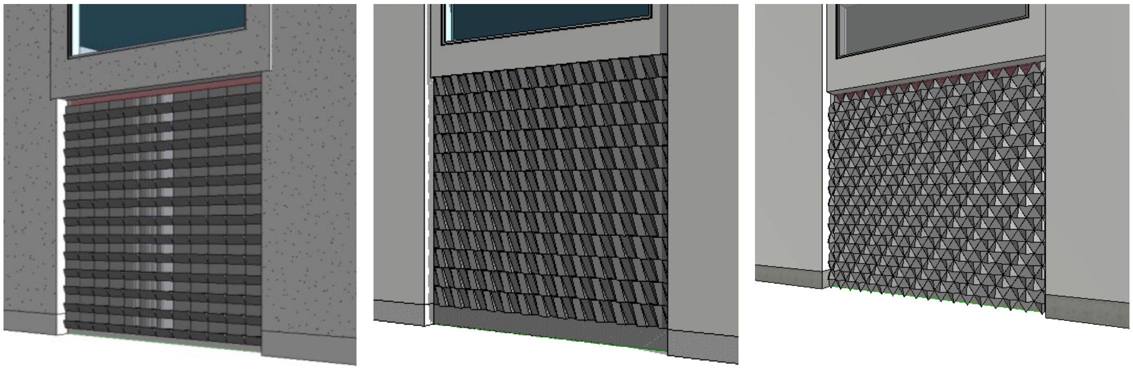
Previous study for this industrial symbiosis for building envelopes used methodology of existing literature (Ali et al., 2020) and the United States Environmental Protection Agency's Waste Reduction Model (USEPA WARM) version 15 (Ali et al., 2021). In this study, the USEPA WARM model was used to evaluate environmental and economic impacts and Tally a Revit plug-in. The annual mass of Offal from passenger vehicles at a plant in US was approximately 568,500 kg (568.5 metric tons).

2.8.1. WARM model

The baseline scenario of total recycling was input in the model and the alternative management scenario of reuse was indicated by "reduced at source" with the corresponding percentages of material efficiency. Annually reusing Offal as modules annually could save 232.28 – 362.89 MTCO$_2$e (greenhouse gas emissions), 4910.58 – 8.1 MJ (7671.80 million BTU) of energy, 19,788 – 30,915 labor hours, \$460,640.84 – \$719,972 of wages, and \$106,018.84 – \$165,633.27 in taxes. Appendix E to Appendix G show avoided MTCO2E and energy for the modules.

2.8.2. Tally plug-in

Design #1 and Design #4 had similar attributes and geometry therefore, three unique geometries of Design #2, Design #3, and Design #4 were modeled using the Revit BIM software. Firstly, modules were made using the generic model pattern-based family template then loaded into an adaptive façade family. Subsequently they were placed on existing building in three different scenarios applying materials through object styles for imported materials in Revit. The existing building with brick façade was used as a baseline to compare with the three proposed module scenarios. In Tally, full building study option was selected, all categories and project were selected. Similar materials were applied to the three scenarios (Figure 2.15). Galvanized steel with epoxy finishes and reports were generated.



a) Design #2 b) Design #3 c) Design #4

Figure 2.16: Three unique adaptive façades from the types of modules.

Environmental impacts from the category entry for Tally for the three scenarios are shown in Table 2.5. For an area of 25.92 square meters, Design #2 and Design #4 has equal environmental impacts of 0.61kgSO2eq of acidification potential, 0.08 kgNeq of eutrophication, 425.06 global warming, 2.53E-10 CFC-11eq of ozone depletion, 12.13 kgO3eq of smog formation, 8,641.24 MJ (123,602 million BTU) of primary energy, 7,612.25 MJ of non-renewable energy, 1,036.92 MJ of renewable energy for 39.5kg total mass. Design #3 has 50% the environmental impacts of Design #2 and #4. For all nine classes of impacts, choosing Design #3 results in half the impacts of the other two designs. Carrying out life cycle analyses of designs for reuse prior to design choice could reduce up to 50% of environmental impacts.

Table 2.5: Environmental impacts of reusing Offal as modules vs virgin material

Environmental impacts	**D2**	**D3**	**D4**
Acidification Potential Total (kgSO2eq)	0.61	0.31	0.61
Eutrophication Potential Total (kgNeq)	0.08	0.04	0.08
Global Warming Potential Total (kgCO2eq)	452.06	226.03	452.06
Ozone Depletion Potential Total (CFC-11eq)	2.53E-10	1.26E-10	2.53E-10
Smog Formation Potential Total (kgO3eq)	12.13	6.06	12.13
Primary Energy Demand Total (MJ)	8,641.24	4,320.62	8,641.24
Non-renewable Energy Demand Total (MJ)	7,612.25	3,806.12	7,612.25
Renewable Energy Demand Total (MJ)	1,036.92	518.46	1,036.92
Mass Total (kg)	39.50	19.75	39.50

2.9. Conclusion

This study presented four design approaches for reusing automotive prompt metal known as Offal. Below the main findings are listed.

Two semester studio courses yielded various modules for living wall systems and four of them were selected for field observation. Campaign measurements for two days, one in winter on March 5, 2019 and the second in spring on April 26, 2019 from 700 -2200 hrs. yielded in-situ data for product performance. The functional goal was to determine cooling effect of modules and test for significant difference between their average surface temperatures. Average surface temperatures of modules were compared with those of adjacent concrete and brick surfaces in the same microclimate.

Analysis of onsite data showed that temperature variations were highest at Design #3 module and least at ambient air temperature. Maximum temperatures and radiation were observed at Design #3. Although the supporting frame could work with other design, minimum temperatures and radiation were observed at Design #2.

Environmental benefits for reusing galvanized sheet metal as modules were reported by both analysis tools. Life cycle analysis carried out using Tally software, and the United States Environmental Agency's Waste Reduction Model yielded environmental and economic benefits. Impacts of modules were in the proportion of 1:2. Therefore, module design could influence impacts by 100%. Resource efficiency by matching geometry of modules to the geometry of Offal yields 50 – 78% waste reduction annually.

Limitations include that results apply to the study site climate, humid sub-tropical climate. Also, the module composition is different from other market-based modules. Future work includes investigating thermal performance of modules in a modular living wall system and techno-economic analysis of novel system to traditional systems. Reusing automotive metal waste in modular living wall systems could provide benefit for global automotive companies and promote responsible research and innovation especially in the five top producers of cars - China, Japan, Germany, USA and South Korea.

3. IN SITU EXPERIMENTAL EVALUATION OF A NOVEL MODULAR LIVING WALL SYSTEM FOR INDUSTRIAL SYMBIOSIS* (MANUSCRIPT 2)

This article was submitted to Energy and Buildings Journal on 9th May 2021, accepted with major revision on 7th July, 2021; resubmitted on 6th August 2021, accepted on 23rd August 2021 and published on 9th September 2021. The doi for this article is available at https://doi.org/10.1016/j.enbuild.2021.111405

3.1. Overview

The emerging concept of Industrial Symbiosis (IS) is becoming an important strategy to achieving goals of the circular economy paradigm shift. In this interdisciplinary study between academia and the industry, large and consistent volumes [9]of predictably sized waste prompt sheet metals obtained from standard stamping and blanking processes at the automotive industry during production of automobile bodies were used to design and fabricate planters in a custom-designed modular living wall system (MLWS) which was installed as a retrofit on an existing building façade. This study is the second part of an attempt to foster IS between the automotive and building and construction industries through creative architectural reuse of these automotive by-products and waste-flows for more sustainable MLWS. Experimental data from field observations of a case study were used to calibrate 24-hour simulations of four seasons in ENVI-met. Life cycle analyses were carried out using Tally a Revit plug-in and United States Environmental Protection Agency’s Waste Reduction Model. Results

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showed that the MLWS has a promising cooling effect on the building façade between 8.7 - 19 °C. Applying reuse strategy in IS could reduce heat islands, greenhouse gas emissions and energy from conventional recycling practices of prompt metal.

3.2. Introduction

Urban areas have higher temperatures known as the urban heat island (UHI) effect due to the presence of hard surfaces. These surfaces store and reflect heat making air temperature in cities warmer than surrounding rural and suburban air temperatures (Salata, Golasi, Petitti, de Lieto Vollaro, Coppi, & de Lieto Vollaro, 2017). Rapid urbanization and technological advancement are contributing to UHI effect and green infrastructure such as green roofs and green walls are installed in urban areas to combat rising temperatures, provide comfort and improve urban contexts (Convertino, Vox, & Schettini, 2019; Park, Kim, Dvorak, & Lee, 2018; Roehr & Laurenz, 2008). Vertical greenery systems (VGS) provide cleaner air, improve aesthetics and lower air temperatures (Piselli, Castaldo, Pigliautile, Pisello, & Cotana, 2018).

Passive strategies to reduce building energy consumption include methods such as erecting vertical greenery systems (VGS) on building envelopes which bring energy conservation benefits (Dvorak, 2015; Perez, Coma, Sol, & Cabeza, 2017; Stav & Lawson, 2012; Sung, Chen, & Shih, 2012). VGS strategies reduce building operational energy consumption by shading and cooling building envelopes, adding aesthetic values to them (Bianco et al., 2017; Perini, Bazzocchi, et al., 2017). VGS consist of green facades and living walls (Medl, Stangl, & Florineth, 2017; Pérez-Urrestarazu, Fernández-Cañero, Franco-Salas, & Egea, 2015). Although VGS comprising of green facades and living wall systems (LWS) are effective means of reducing operational energy of buildings, they have high costs and many require high maintenance during their life span (Kharrufa & Adil, 2012; Riley, de Larrard, Malécot, Dubois-Brugger, Lequay, & Lecomte, 2019). The life expectancy of an indirect steel system is about 50 years (Dunnett & Kingsbury, 2004; Ottele et al., 2011; Perini & Rosasco, 2013b). In addition, the replacement frequency for the plants in LWS is 10% replacement/year (Ottele et al., 2011).

LWS are more expensive than green facades as they require a supporting structure, containers for variety of plants, soil and irrigation system. Current LWS rely heavily on virgin materials increasing capital cost required for new construction and retrofits. LWS have growing media in front of a vertical surface creating a cavity area between the LWS and the building behind them. LWS have major aesthetical potentialities due to the possibility of incorporating a wider variety of plants in comparison to green facades (Blanco, Schettini, & Vox, 2018). Prevalent metals used for LWS are stainless steel, galvanized steel and aluminum. Aluminum pots, stainless and galvanized steel trellises were used to support planter tiles and vessels (Coma, Pérez, de Gracia, Burés, Urrestarazu, & Cabeza, 2017; Jim, 2015; Pérez et al., 2014; Pérez et al., 2011). (Perini & Rosasco, 2013b), used coated steel to support climbing plants. Other LWS materials include geotextiles made from fabric and synthetic fibers (Pérez et al., 2014); recycled polypropylene panels and polyethylene materials (Coma et al., 2017; Mazzali, Peron, Romagnoni, Pulselli, & Bastianoni, 2013).

Metals constitute more than 75% of a vehicle (Pomykala, Jody, Daniels, & Spangenberger, 2007).

The use of sheet metal for car bodies produces unused cutouts known as Offal. During conventional recycling, de-coating occurs for aluminum recovery and it consumes at least 5% of the energy required to extract aluminum from bauxite ore (Boon, Isaacs, & Gupta, 2000). Offal is currently de-galvanized by dissolution of zinc in caustic through reverse electroplating where loose or baled galvanized scrap is fed to an electrolytic cell where it is made the anode by being placed in contact with the positive side of a high-current/low-voltage direct-current power supply (Dudek, Daniels, & Morgan, 1993). Prompt industrial scrap containing skeletons from stampings, cutoffs and trimmings, is generated from the fabrication of iron and steel products in construction and manufacturing, and there is a relatively short time between its manufacture and its recycling to a steel plant or foundry; it averages approximately 45% of the total supply of purchased scrap (Swager, Lownie, & Mobley, 1981).

Due to the non-corrosive nature of zinc coatings, architectural zinc on building facades has enjoyed a successful history in European application for almost three centuries and has increased in popularity in North America since the early 90’s (Kweton, 2017). The benefits of galvanized sheet metal are: low initial cost compared to most treated steels, lower maintenance costs, increased durability of the finished product, protection at sharp corners and recesses, self-healing and a ready to use surface (Dole, 1985). The appearance of zinc surfaces change with time without affecting their durability and galvanized sheet metal produces patina, a protective layer, when exposed to the atmosphere for a long time (Kihira, Ito, & Murata, 1990). Time to first maintenance for galvanized sheet metal varies from 20 to 35 years depending on the average thickness of zinc coating and the installed environment (American Galvanizers Association, 2010). Materials used to produce car bodies are evolving to whole aluminum, light galvanized sheet metal bodies and hybrid bodies with aluminum and manganese(Carle & Blount, 1999; Cui, Zhang, Wang, Zhang, & Ko, 2011; González Palencia et al., 2012; Hynes & Velu, 2018; Tempelman, 2011). Many automotive companies have begun to incorporate aluminum into their car body production to achieve a lighter mass but due to the higher energy used in producing aluminum, galvanized sheet metal is still widely used for majority of automobile bodies and parts.

Sustainable reuse efforts for industrial waste has resulted in the reuse of waste glass and incinerated sewage sludge ash for insulating building products (Lu et al., 2019), and waste tire textile fibers as reinforcement materials for landfill liners/covers (Narani et al., 2020), offal as building envelopes (Ali et al., 2020; Ali et al., 2019), and plastic matrix trays as materials in construction products (Ali et al., 2021). New methods are needed to identify value in industrial waste for reuse and interdisciplinary approaches are essential at early design stages for efficient and exhaustive product exploration and choice.

The use of Offal as primary material for LWS could reduce carbon footprint and energy required to completion. In the automotive industry, scrap was segregated at source and at storage areas in 87% of the plants. At the plants, the methods for disposal were incineration and landfill; most plants sold their Offal to private dealers/waste collectors**.** 66% of the plants kept scrap records and higher monetary value of scrap provided incentive for keeping records. In 1969, waste scrap metal data from automotive manufacturing processes, was given in terms of volumes and weights which were estimated; (Nafziger, Hartman, & Farrell, 1990) states three types of generated ferrous scrap: (1)home or revert, (2) prompt industrial, and (3) obsolete. Available annual data and material were provided from an automotive company to the department of architecture on the specific shapes and quantity of prompt metal waste, (Figure 3.1). Information on the monthly and annual quantities of Offal (Table 3.1). Management in automotive companies are becoming more interested in what happens to Offal after removal due to sustainable goals and Automotive Industry Action Group (AIAG) minimum requirements.

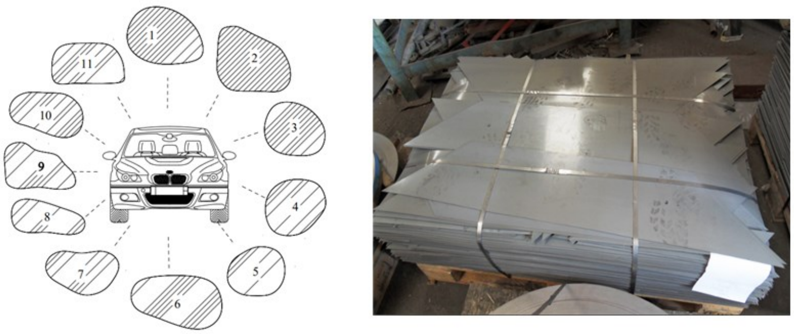


Figure 3.1: Offal from an automotive company

In addition, ethical demands on companies by their communities and customers have led to an increase in environmental awareness and pursuit of sustainable goals. Thirdly, Sustainability Development Goals (SDGs) provides an urgent call for action towards commitments to implement sustainable development.

Table 3.1: Sizes of scrap from General Motors

Offal	Monthly Volume Range	Annual Volume Range (Numbers of pieces)
1	5,000	60,000
2	N/A	100,000
3	5,000	60,000
4	3,000	36,000
5	6,000	72,000
6	N/A	1000
7	1,000	12,000
8	1,500	18,000
9	1,000	12,000
10	1,000	12,000
11	5,000	60,000

The United States Environmental Protection Agency (USEPA) developed the non-hazardous materials and waste management hierarchy recognizing that no single waste management approach is suitable for managing all material waste streams for all circumstances. The hierarchy ranks various management strategies from most to least environmentally preferred (Figure 3.2), placing emphasis on reducing, reusing and recycling as keys to sustainable materials management.

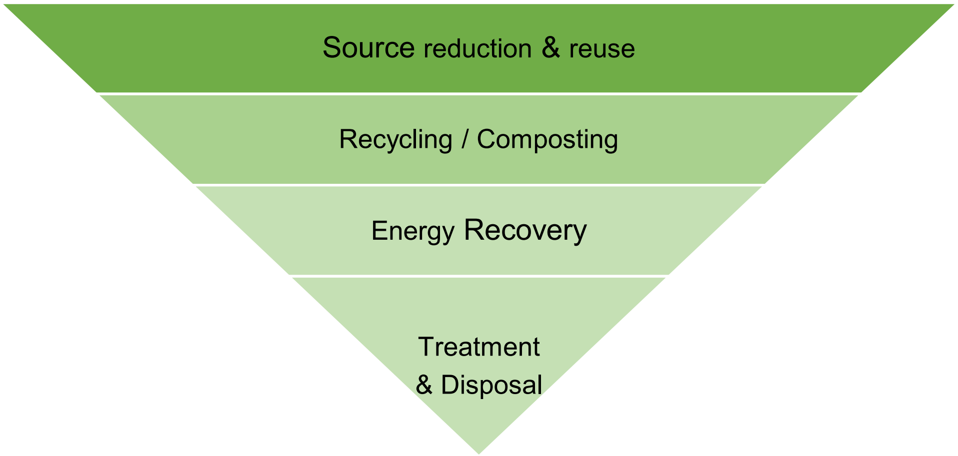


Figure 3.2: Waste Management Hierarchy from United States Environmental Protection Agency

Circular economy (CE) seeks to prolong the life span of materials in circulation discouraging waste and production of virgin materials. Applying industrial symbiosis (IS), a strategy applied for establishing CE, a collaboration between industry and academia resulted in a circular product. A modular living wall system (MLWS) was created through a multidisciplinary approach. Although, CE has been attempted for metal waste, architectural reuse has not been attempted for MLWS using Offal. This study introduces a MLWS as a means to reduce the urban heat island phenomenon, promote industrial symbiosis and circularity. On-site experimental measurements are validated by simulations in ENVI-met. The annual quantity of Offal was the functional unit for Tally software – a Revit plugin, and the USEPA Waste Reduction Model to calculate environmental and economic benefits.

3.3. Literature review

3.3.1. Automotive industry and circular economy

Annual sustainability reports from automotive companies show the practice of sustainable strategies such as: reduction of carbon emissions from new vehicles, upstream activities, vehicle manufacturing and end-of-life treatment of vehicles; landfill-free commitments; water stewardship; materials management; biodiversity protection; minimizing environmental impacts along the entire life cycle; working with suppliers to improve energy, air and greenhouse gas emissions; fuel economy; reducing volatile organic compounds (VOCs) and providing customers with innovative technology in products (GRI, 2021). Each auto manufacturer defined their sustainability metrics measuring it with baselines of previous years; some metrics include: measurements of direct and indirect carbon emissions, water consumption, energy usage; and fuel economy. Some companies undertook measures towards embracing the circular economy.

An initiative by Chrysler through circular economy, involves donating remnants from fabric and seatbelts from their plant for fashion accessories using 38 tons of material and producing 270,000 products. Industrial symbiosis (IS) mutual sharing of by-products, is evident at Porsche which gets heat from a nearby heating plant using 80% carbon neutral heat; also waste water is recycled at Foshan, China. Also, General Motors (GM) has collected over 4 million used water bottles in the City of Flint and transformed them into coats for the homeless, air-filtration components and noise reducing fabric to cover the engine of the Equinox crossover.

(Geldermans, 2016), stated that circularity-values emerge at the intersections of unique intrinsic properties (material and product characteristics) and relational properties (design and use characteristics). Significant opportunities for greater material efficiency especially for steel are yet to be widely implemented as steel is one of the most ‘circular’ manufactured materials (Walker et al., 2018); and producing steel accounts for nearly 25% of industrial carbon emissions, consuming a high amount of energy and polluting the environment (Hasanbeigi et al., 2017; Pauliuk et al., 2013). The industrial sector uses more than one-third of all energy used in USA; manufacturing is the largest user within the industrial sector (Mukherjee, 2008). IS enhances circularity and provides opportunities for more connections between participating companies. Cross-industry networks have evolved by the circular economy model and many industries have applied industrial and urban symbiosis approaches (Domenech et al., 2019; Tseng et al., 2018; Wen & Meng, 2015). Many other materials industries have exchanged are wood, pulp, paper, chemicals, metals, waste energy, heat, water and steam (Chertow & Lombardi, 2005; Domenech et al., 2019; Jacobsen, 2008).

Linking the auto and construction industry through applying waste streams for MLWS could: decrease company costs for procuring MLWS, reduce UHI, and promote circularity. The reuse of Offal could improve the image of automotive companies, increase customer satisfaction, foster community acceptance and enable them attain the minimum requirements of the AIAG.

3.3.2. Thermal performance of living wall systems

A review of scientific literature on the thermal performance of VGS showed that many studies were prone to research design problems, lacked replication and provided insufficient information about the microclimatic parameters measured (Hunter, Williams, Rayner, Aye, Hes, & Livesley, 2014). A search was carried out in the Energy and Building Journal using the term “thermal performance of modular living wall”. 136 results were screened and 15 contained studies of living walls.

LWS are cooling instruments that remove heat from the air and nearby wall surfaces (Chen, Li, & Liu, 2013). (Nan, Yan, Wu, Shi, & Bao, 2020) assessed the effect of external LWS on indoor thermal environments in winters with low temperatures and high humidity levels. (He, Zhang, Zhang, & Zhou, 2020) produced a 3D printed modular vertical concrete green wall system and quantified its energy-saving potential by developing a thermal network model to simulate the thermal behavior of the supporting building for thermal comfort analysis. The whole-building energy simulation was carried out using Chinese Standard Weather Data (CSWD) of Nanjing, China. (Charoenkit, Yiemwattana, & Rachapradit, 2020) examined the role of plant characteristics on thermal and carbon sequestration performances of living walls. (Sanchez-Resendiz, Ruiz-Garcia, Olivieri, & Ventura-Ramos, 2018) illustrated the behavior of living walls and their beneficial effects under semi-arid environments in central Mexico. Using an experimental method, (Olivieri, Grifoni, Redondas, Sánchez-Reséndiz, & Tascini, 2017) established a thickness above which the behavior of the green façade becomes isothermal and its performance does not improve. (Djedjig, Belarbi, & Bozonnet, 2017) carried out an experimental study of a green wall on a scaled-down mockup of buildings located in La Rochelle city. (Blanco, Convertino, Schettini, & Vox, 2021) assessed the thermal behavior of a double-skin green façade under different summertime weather scenarios, plants influence were identified by comparing microclimatic conditions and energy transfer at the covered wall, behind the vegetation and at an un-vegetated wall. (Hoffmann, Šuklje, Kozamernik, & Nehls, 2021) modelled the cooling energy saving potential of façade greening in summer proposing a validated numerical heat-mass transfer model.

3.3.3. Architecture and life cycle analysis

Building Information Modelling (BIM) based life cycle analysis (LCA) has been recommended to overcome the challenges of producing data intensive life cycle inventory and impact assessments (Anand & Amor, 2017; Basbagill, Flager, Lepech, & Fischer, 2013; Nwodo & Anumba, 2019; Soust-Verdaguer, Llatas, & García-Martínez, 2017). In the field of architecture in the United States of America (USA), Tally, a BIM tool was created in 2013 as a software tool to allow designers and other users to evaluate the environmental impacts of their building material selections and design choices at the speed of design (Timberlake, 2019). Tally is a plug-in to Autodesk Revit as provision for LCA towards whole building and comparative design options assessments (Nwodo & Anumba, 2019). The basic procedure involves matching materials specifications from Tally's life cycle inventory with the model objects from Revit family. Major challenges include: low level of development of the BIM at early design stage, limited information on building (Najjar, Figueiredo, Palumbo, & Haddad, 2017) and interoperability issues between BIM tools (Antón & Díaz, 2014). Tally has LCA database from GaBi and SimaPro and it is a product analysis tool. (Al-Ghamdi Sami & Bilec Melissa, 2017) compared three different LCA tools - Athena Impact Estimator for Buildings, Tally and SimaPro for a large hospital in Pittsburgh. Results indicated that given the same building, LCA results produced by the software tools varied in the global warming potential category by approximately 10% in the embedded impact, and approximately 17% in the operational impact. A literature review and case study comparing Tally to the Athena Impact Estimator showed discrepancies between the two environments' inputs and outputs (Schultz, Ku, Gindlesparger, & Doerfler, 2016). In this study Tally and WARM are used to calculate impacts of virgin galvanized sheet metal and reused Offal as modules in a LWS. Their annual environmental and economic impacts were calculated with available Offal data from an automotive company.

3.4. Materials and method

This study was carried out by designing, fabricating and installing a case study modular living wall system (MLWS). Thereafter, there was an assessment of the MLWS thermal performance. On-site measurements were carried out from 700hrs to 2200 hrs. for specific days in the four seasons – spring, summer, fall and winter. Data from these field measurements were used to calibrate simulation in ENVI-met software. In addition, a life cycle analysis (LCA) was also carried out with Tally the plug-in for Revit building information modeling software and United States Environmental Protection Agency's Waste Reduction Model, for environmental and economic impacts. Figure 3.3 shows the methodology for this study.

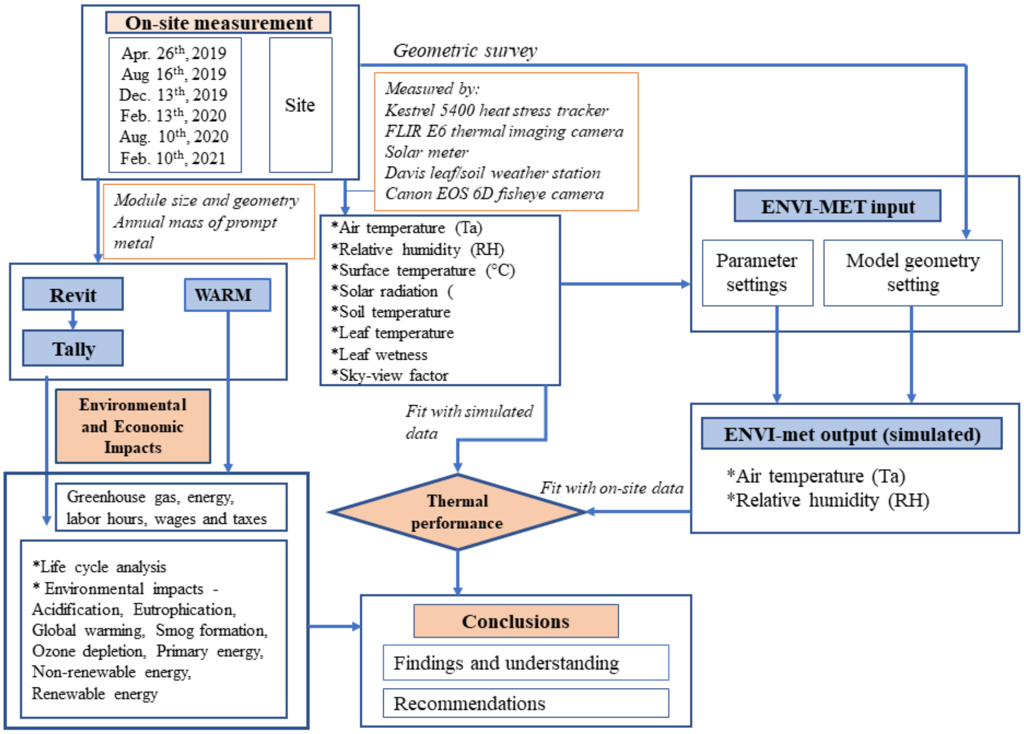
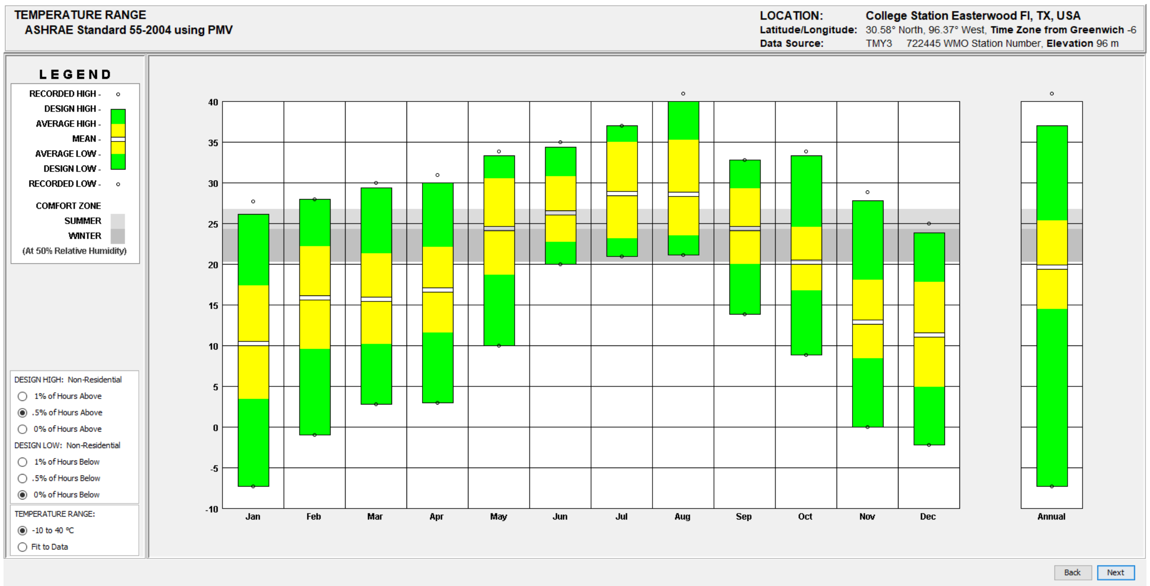


Figure 3.3: Methodology for thermal performance and environmental impacts of modular living wall system

3.4.1. Site study area

The humid sub-tropical climate is characterized by hot and humid summers, and cold to mild winters. Temperature in the warm months from May to October often exceeds 34.4 º C in the daytime and 15 º C in the nighttime (National Weather Service, 2000). at an elevation of 318 feet. In this humid subtropical climate, the hottest months are July and August. Records from the closest weather station show that August has been the recurrent hottest month in recent years. August was the hottest month for 2017, 2018 and 2019. Variables measured include ambient air temperature (AAT), air layer temperature (ALT), soil temperature (ST), leaf temperature (LT), relative humidity (RH), and solar radiation (SR). Climate normal records show that in August, the maximum air temperature was 38.9 º C, the minimum air temperature was 23.9 º C, and the mean temperature was 30 º C. The relative humidity was from 84% to 92%. The average wind speed was 7.2m/s. The average daily incident shortwave solar energy ranged from 6.5 kWh to 5.7 kWh over the month of August. The extremes, normal and annual summaries indicate global warming and urban heat island effect as high temperature records are tied and broken and recent low temperatures are usually higher than old ones. Climate consultant 6.0 reads the local climate data in EnergyPlus Weather Data (EPW) format and displays the yearly weather attributes for air temperatures in Figure 3.4 and radiation in Figure 3.5. When surfaces are tilted at 45° less radiation occurs at surfaces Figure 3.6.



TEMPERATURE RANGE
ASHRAE Standard 55-2004 using PMV

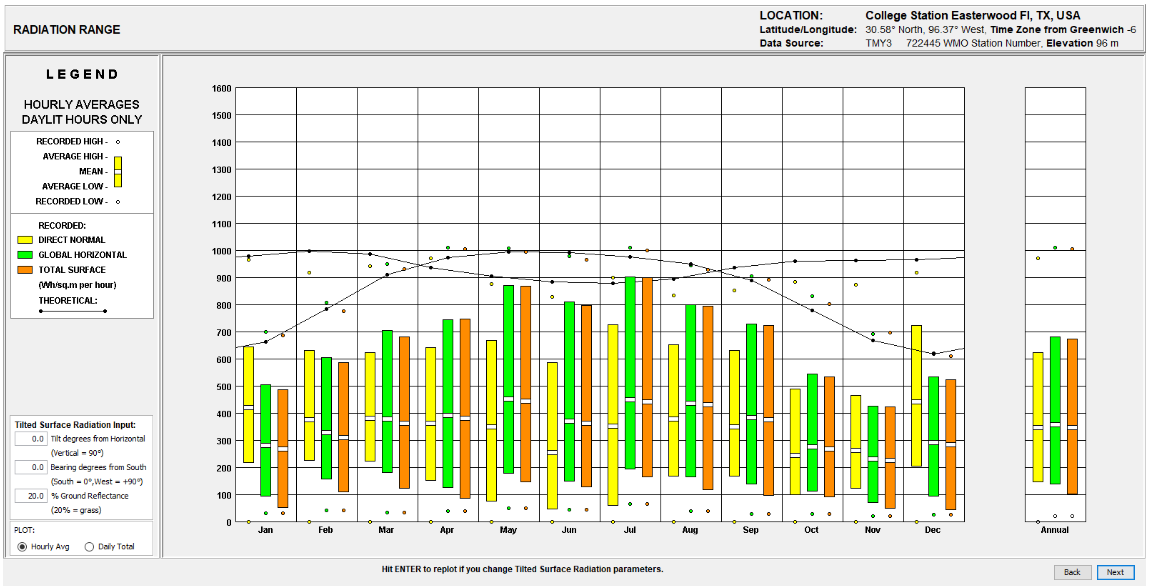
LOCATION: College Station Easterwood Fl, TX, USA
Latitude/Longitude: 30.58° North, 96.37° West, **Time Zone from Greenwich** -6
Data Source: TMY3 722445 WMO Station Number, **Elevation** 96 m

DESIGN HIGH: Non-Residential
○ 1% of Hours Above
● .5% of Hours Above
○ 0% of Hours Above

DESIGN LOW: Non-Residential
○ 1% of Hours Below
○ .5% of Hours Below
● 0% of Hours Below

TEMPERATURE RANGE:
● -10 to 40 °C
○ Fit to Data

Figure 3.4: Air temperature range of site study area using Climate Consultant 6.0



RADIATION RANGE

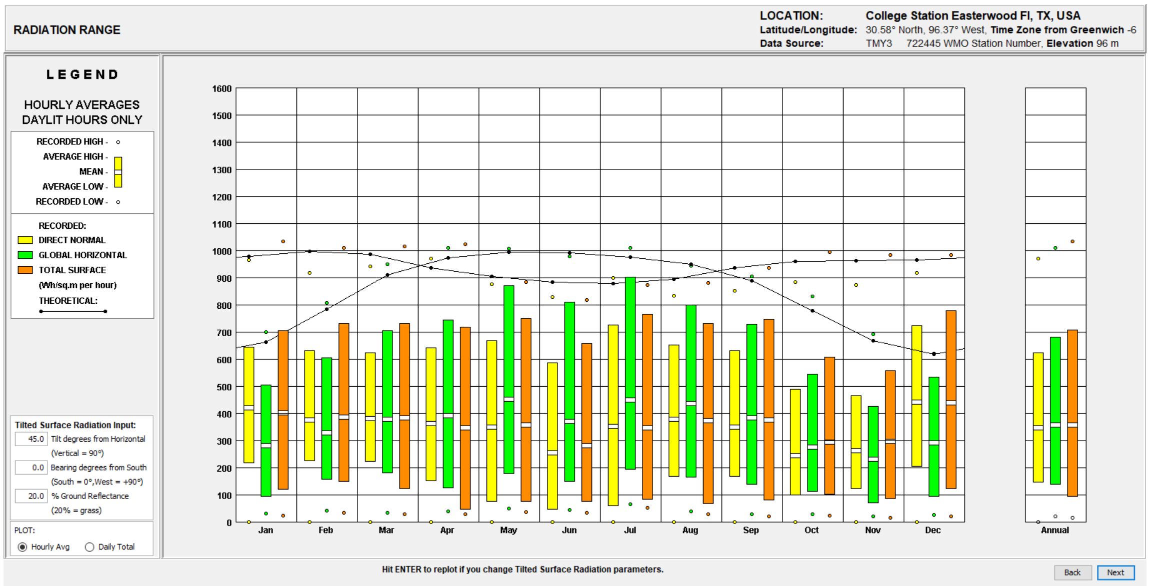
LOCATION: College Station Easterwood Fl, TX, USA
Latitude/Longitude: 30.58° North, 96.37° West, **Time Zone from Greenwich** -6
Data Source: TMY3 722445 WMO Station Number, **Elevation** 96 m

Tilted Surface Radiation Input:
0.0 Tilt degrees from Horizontal (Vertical = 90°)
0.0 Bearing degrees from South (South = 0°, West = +90°)
20.0 % Ground Reflectance (20% = grass)

PLOT:
● Hourly Avg ○ Daily Total

Hit ENTER to replot if you change Tilted Surface Radiation parameters.

Figure 3.5: Radiation range of site study area using Climate Consultant 6.0



LOCATION: **College Station Easterwood Fl, TX, USA**
Latitude/Longitude: 30.58° North, 96.37° West, **Time Zone from Greenwich** -6
Data Source: TMY3 722445 WMO Station Number, **Elevation** 96 m

Tilted Surface Radiation Input:
45.0 Tilt degrees from Horizontal (Vertical = 90°)
0.0 Bearing degrees from South (South = 0°,West = +90°)
20.0 % Ground Reflectance (20% = grass)

PLOT:
● Hourly Avg ○ Daily Total

Hit ENTER to replot if you change Tilted Surface Radiation parameters.

Figure 3.6: Radiation range of site study area with 45° tilted surfaces using Climate Consultant 6.0

3.4.2. Sky view factor

As the MLWS was erected in front of a brick wall, concluding experiments 6 and 7 involves using a brick wall with similar orientation as the building on which the MLWS was installed but a different sky-view factor (SVF). Increasing SVF results in increasing air temperature and differences in SVF between the suburbs and the city can produce difference in temperature between 5-7 ° C (Atkinson, 2003; Baghaeipoor & Nasrollahi, 2019). SVF were calculated in Rayman Pro with fish eye images from Canon EOD 6S fish eye camera. In Figure 3.7, sky-view factors at MLWS, courtyard in front of MLWS and bare brick wall are 0.32, 0.51 and 0.12.

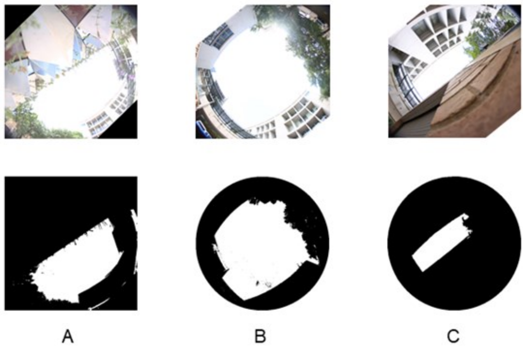


Figure 3.7: Sky view factor at modular living wall system (A) – 0.32, courtyard (B) – 0.51, and bare brick wall (C) – 0.12.

3.4.3. Modular living wall system

The modular living wall system (MLWS) is 5.8m wide by 4.3m high, and was installed on the south-east facing wall of an institutional building (Figure 3.8) at a 27 by 24-m courtyard. A supporting metal frame carried approximately 300 diamond-shaped modules creating a cavity behind the MLWS and provided framework for multiple emitter irrigation system which supplied water to each module's engineered soil independently. Plants grew upwards with sufficient space for heightened species; they were positioned and grouped to achieve variety. Their water requirements ranged from dry to medium as one of the goals was to discover the plants that could survive in extreme environment and low maintenance (Ali & Dvorak, 2019). The MLW and control surfaces constituted three experimental areas, modular living wall system (MLWS), concrete wall (CW) and shaded brick wall (SBW), CW was the control to MLWS for Experiment 1 – 5.

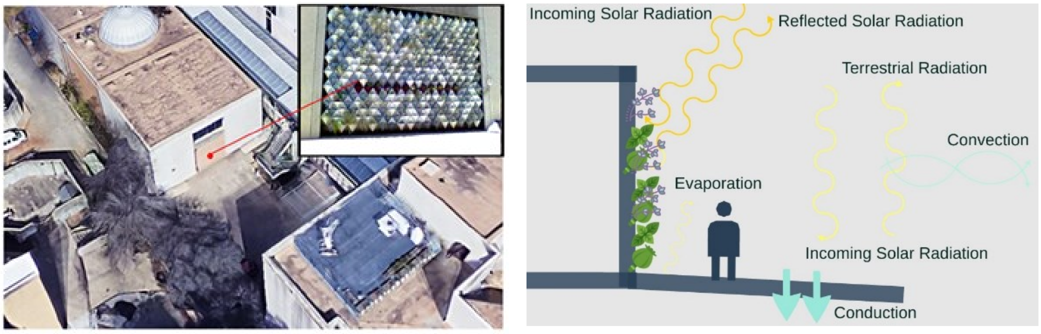


Figure 3.8: Study site, flows of energy towards and away from the study site

3.4.3.1. Substrate

Each module had a depth of 215mm for soil. Two types of soil were used a growing media on top and drainage layer below. The growing media was Rooflite Extensive 700 Growing Media and the drainage layer was Rooflite Drain 600 Drainage Layer.

3.4.3.2. Module

Galvanized sheet scrap metal (Offal) from an automobile industry, was reused as raw material for the 300 diamond shaped modules. Each module was 305mm wide, 455mm high and 230mm deep. The left and right faces were at an angle of 45 to the vertical and horizontal which could significantly change their exposure to solar incident rays, Figure 3.9.

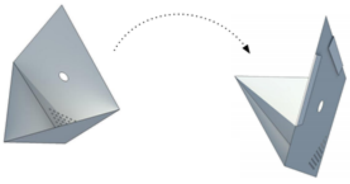


Figure 3.9: Prototype of module in modular living wall showing geometry

3.4.3.3. Cavity

The MLWS created a 300mm cavity between itself and the building surface functioning as a double-skin façade. The cavity acts as a thermal insulation layer with the ability to control heat gains and losses (Perini & Rosasco, 2016).

3.4.3.4. Water Nutrient

The frequency and rate of flow determines the length of time the soil remains wet. Each module had one emitter supplying water. Drop irrigation for both years was 1.16 gal/week with excess drainage flowing in front of and behind modules.

3.4.3.5. Vegetation

Texas native plants such as *Dichondria argentea, Agave lophantha, Hesper aloe parviflora, yucca flaccida* and *hechtia texensis* plants were chosen and designed considering their low water requirements and availability in the local region.

3.4.4. Assessment of thermal performance

Microclimatic parameters of air temperatures, relative humidity and solar radiation, were measured to characterize thermal performance of the MLWS for specific days in the four seasons - spring, summer, fall and winter from 2019 to 2020. In 2020, additional measurements were recorded for soil, vegetation and a bare brick wall. Solar radiation at each surface was observed using a solar meter. The configuration of the MLWS and measurements for seven field experiments taken are shown in Table 2 and the experimental setup is described next.

Table 3.2: Configuration and dates of data collection in experiment- concrete wall (CW), shaded brick wall (SBW), bare brick wall (BBW), air layer temperature (ALT), ambient air temperature (AAT), relative humidity (RH), solar radiation (SR), soil temperature (ST), leaf temperature (LT)

Experiment	**Date/ Season**	**MLW**	**CW**	**SBW**	**BBW**	**ALT**	**AAT**	**RH**	**SR**	**ST (1-4)**	**LT**
1	Apr. 26, 2019/ Spring	☑	☑								
2	Aug. 16, 2019/ Summer	☑	☑	☑							
3	Aug. 2019 Summer	☑	☑	☑							
4	Dec. 13, 2019 Fall	☑	☑	☑		☑	☑	☑	☑		
5	Feb. 13, 2020 Winter	☑	☑	☑		☑	☑	☑	☑		
6	Aug.10, 2020/ Summer	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
7	Jul./Aug. 2020/ Summer	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑

3.4.4.1. Experimental setup

FLIR E6 thermal imaging camera (accuracy: ±2% between -20°C to +250°C (-4 to +482°F) was used to collect surface temperature data. Each image was converted to comma separated value file in excel and analyzed in R Studio for average temperatures. A Kestrel 5400 WBGT Heat Stress Tracker (HST) and Weather Meter (Kestrel Instruments, accuracy: wind speed | air: larger of 3% of reading, least significant digit or 20ft/min speed: ambient temperature: accuracy: 0.9°F or 0.5°C; relative humidity: 2%RH) was used to monitor outdoor air condition at bare brick wall, in front of and behind MLWS. A TES 132 datalogging solar power meter (accuracy: ±0.7dB, ref 94dB@1KHz) was used to measure solar radiation on concrete, brick wall in front of and behind the MLWS. Thermal images, wind speed, air temperature and relative humidity were recorded between 700hrs and 2200hrs for daily measurements. In August 2019, daily measurements were recorded at 1600hrs at maximum air temperatures, while in 2020, surface measurements were recorded at 1400hrs at maximum surface temperatures. A Davis leaf and soil (VantagePRO2) weather station was introduced at MLWS by July and August 2020 to monitor leaf and soil temperatures, leaf wetness, and soil moisture. Equipment and positions of equipment are shown in Figure 3.10, 3.11 and 3.12.

Figure 3.10: Equipment for measurement campaign for 2019 and 2020. 1-FLIR E6 thermal imaging camera, 2- Kestrel 2400 Heat Stress Tracker, 3 – Solar Meter, 4- Canon EOS fisheye camera, 5- Davis weather station, 6- Davis Vantage Pro 2, 7 – soil moisture and temperature probes, 8 – leaf temperature and wetness sensor.

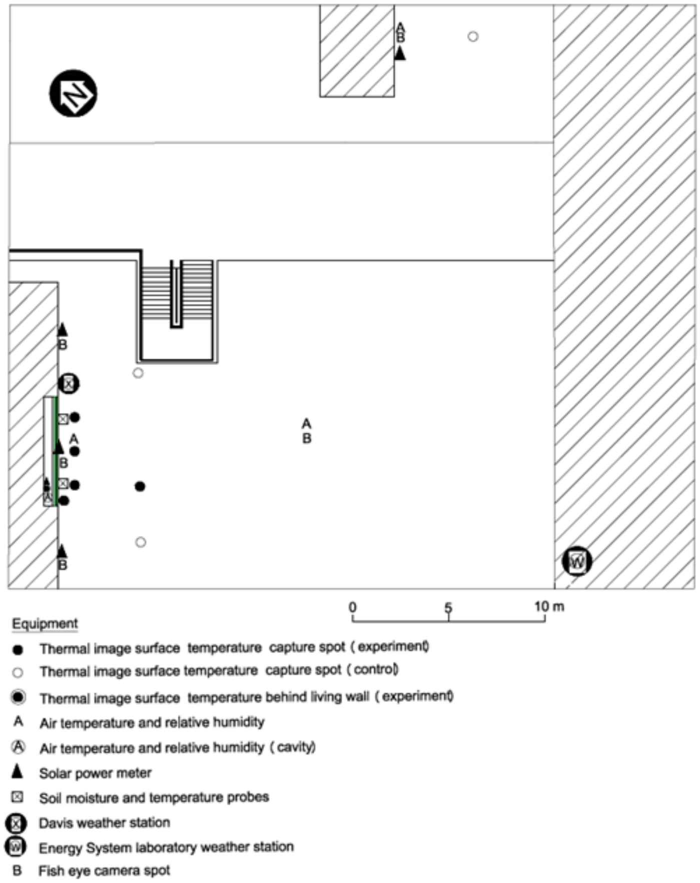


Figure 3.11: Layout of equipment at study site

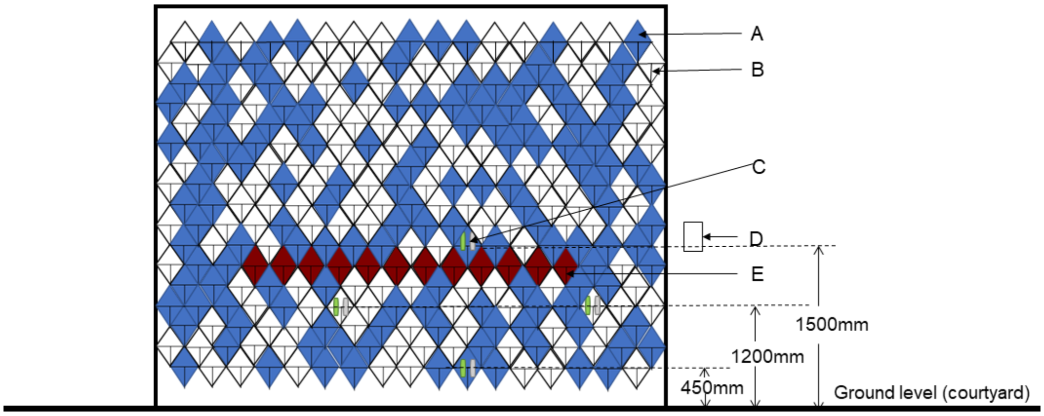
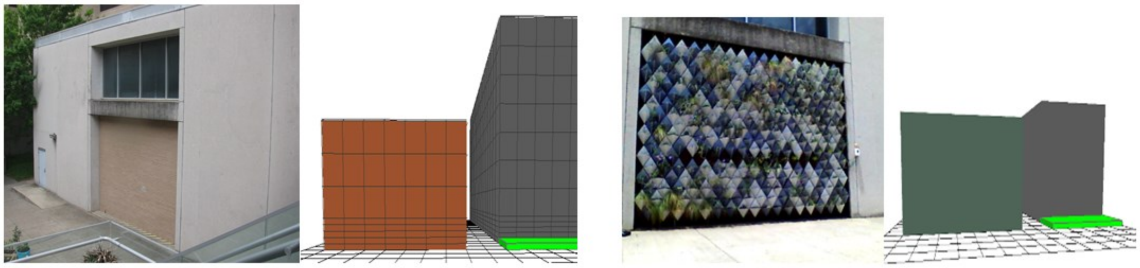


Figure 3.12: Front view of modular living wall showing positions of weather station and temperature and moisture probes. (A- Blue modules, B- White module, C- soil moisture and soil temperature probes D- Davis Weather station, E- Maroon module).

3.4.4.2. Simulated scenarios

Two scenarios were proposed for the purpose of comprehensively investigating the cooling effect of the MLWS at the site, (Figure 3.13). Scenario 1 represents the basic case where the building has a brick surface in the current microclimatic conditions of the study area. Scenario 2 involves the installation of the MLWS. Data and metafiles generated by simulation in the two scenarios (Appendix D – J), were subsequently used to investigate the effect of cooling upon the microclimates.



a b c d

Figure 3.13: Onsite and ENVI-met scenarios; a- Scenario1, onsite; b- Scenario 1, ENVI-met; c- Scenario 2, onsite; d- Scenario 2, ENVI-met

3.5. Findings and discussion

3.5.1. Onsite data

3.5.1.1. Surface temperatures

Surface temperatures were monitored in situ from 700hrs to 2200hrs on days representing the four seasons and about two summer months in 2019 and 2020. On the spring day, temperature comparisons of two exterior wall surfaces, Chart 1, CW and MLWS surfaces have similar temperature variations and MLWS had lower temperatures in 56% of the 16 hourly measurements. Both surfaces had equal surface temperatures by 900hrs and the MLWS had higher temperatures from 1000hrs to 1500hrs by a maximum of 5°C.

For the summer day, three surfaces were compared CW, MLWS and SBW in Chart 2. SBW had the least temperature range indicating lower variation, Chart 2.

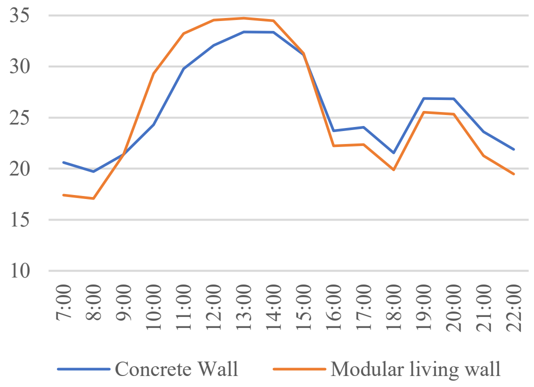


Chart 1 -April 26, 2019 / Spring

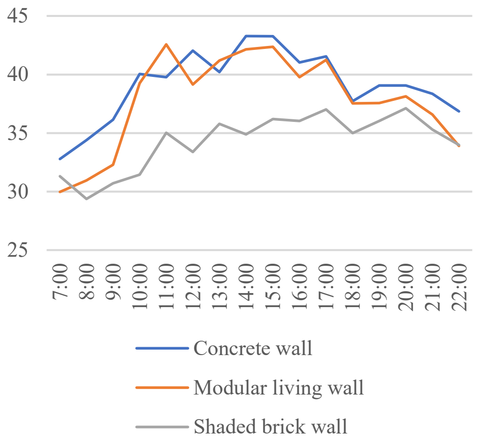


Chart 2 -August 16, 2019/ Summer

CW was warmer than MLWS for 88% of the hourly measurement for 16 hours. Also, using the exposed CW as control, the shaded wall was cooler by 1.5 °C, at 7:00hrs. up to 8.7 °C by noon similar to 8.4°C decrease in urban temperatures in Hong Kong (Alexandri & Jones, 2008). For summer days in August 2019 measurement were taken at 16:00hrs for 26 days when maximum air temperatures were observed, CW surface temperatures were higher than SBW at all hours between 3.8 – 5.7°C and 99.8% higher than temperatures at MLWS ranging from 0 – 4.1°C. Lowest temperatures were observed at air temperatures measured 1m away from the MLWS, Chart 3.

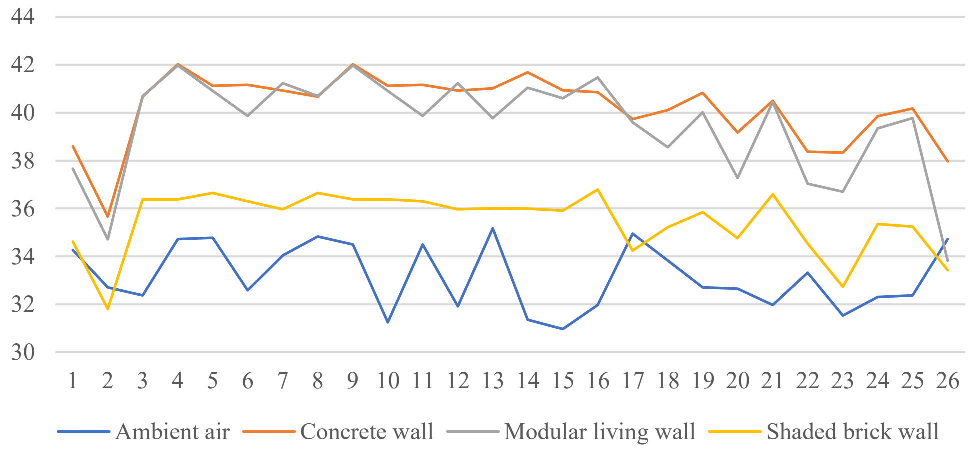


Chart 3 - August 2019 / Summer

In the fall, ambient air also had minimum temperatures, SBW was warmer than the concrete surface 87% of the time 0.1 – 8.7 °C. MLWS was warmer than concrete wall for 67% of the hourly measurements between 4.6 – 17.8 °C, Chart 4.

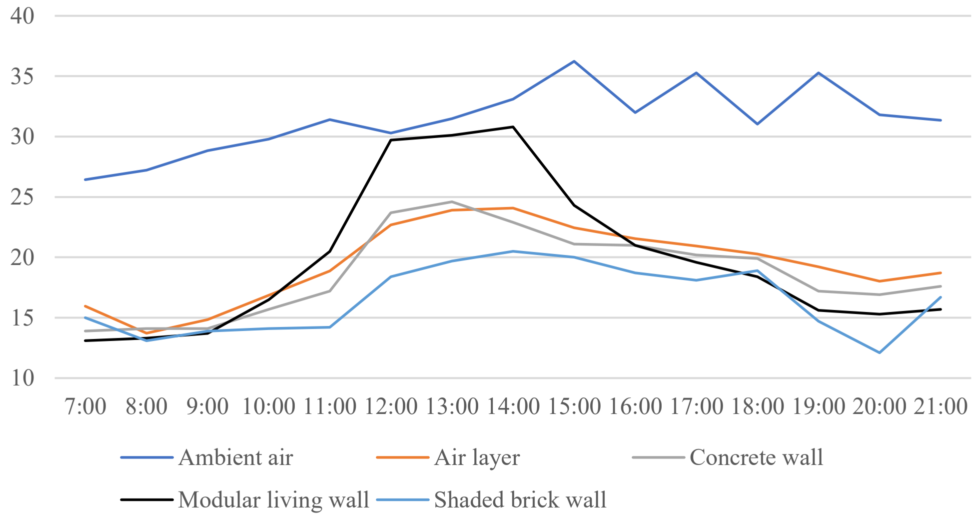


Chart 4 - December 13, 2019 / Fall

By February 13, 2020 in winter, CW was warmer than MLWS and SBW between 1.4 – 4°C and 0.1 – 5.2°C respectively, Chart 5. Ambient air and air layer behind MLW were much warmer than the other three surfaces.

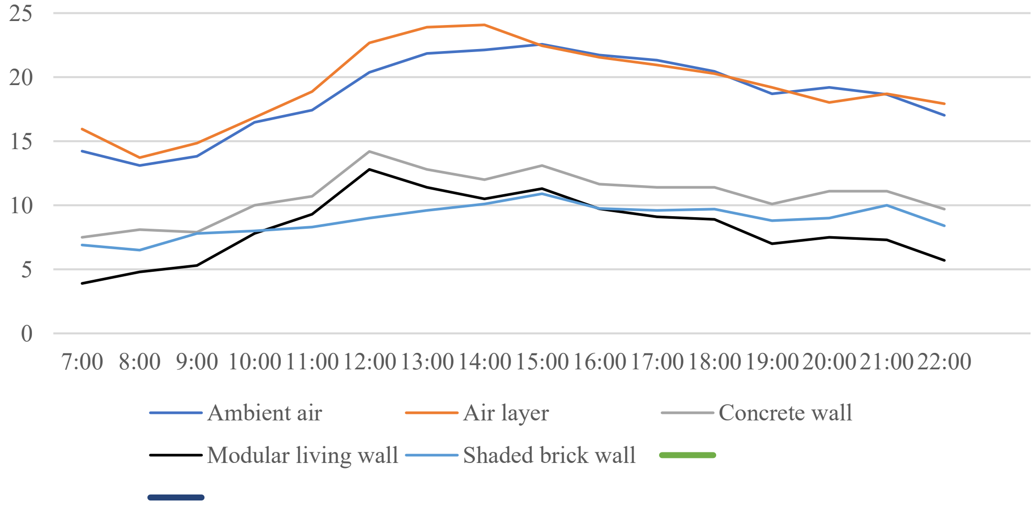


Chart 5 – February 13, 2020 / Winter

A bare brick wall (BBW) with similar façade orientation as the MLWS was included for brick to brick comparison of temperature differences. To account for the difference in sky-view factors (SVF), the lower bound of 5°C was added to BBW for surface temperatures in Chart 6 and 7.

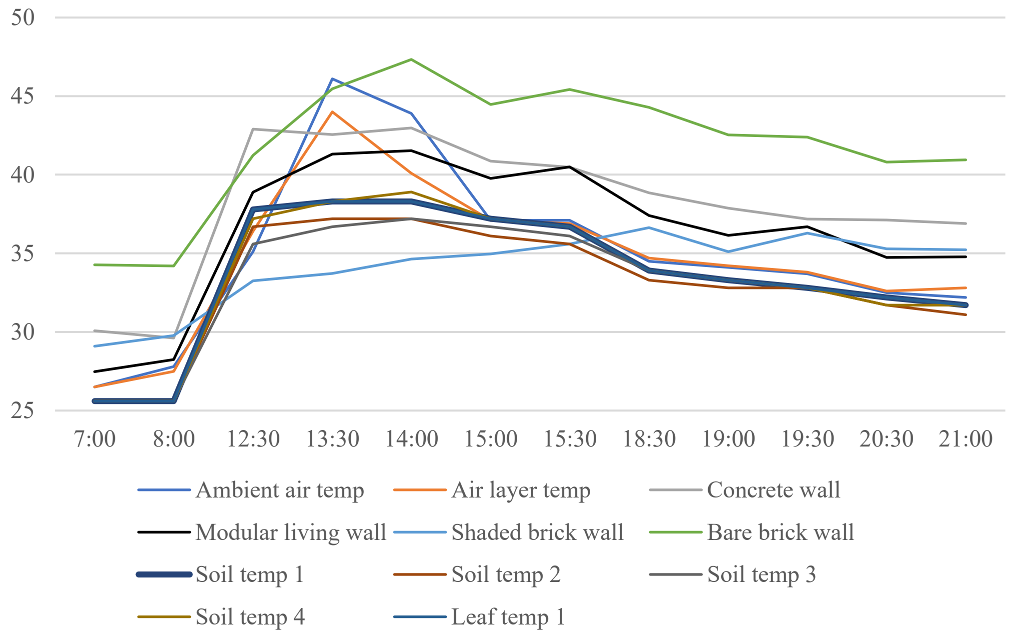


Chart 6 – August 10, 2020 / Summer

On August 10, 2020, surface temperatures were measured at twelve different times. At these times, CW was warmer than SBW, MLWS and BBW for 92%, 100% and 100% of the hours respectively. For brick to brick comparison, temperature differences between SBW and BBW were between 4.4 – 12.7 °C. Differences between BBW and MLWS were from 2.3 – 6.9 °C. Average temperatures at MLWS were higher than soil temperatures by 1.7 – 3.9 °C and leaf temperatures between 1.1 - 3.9 °C.

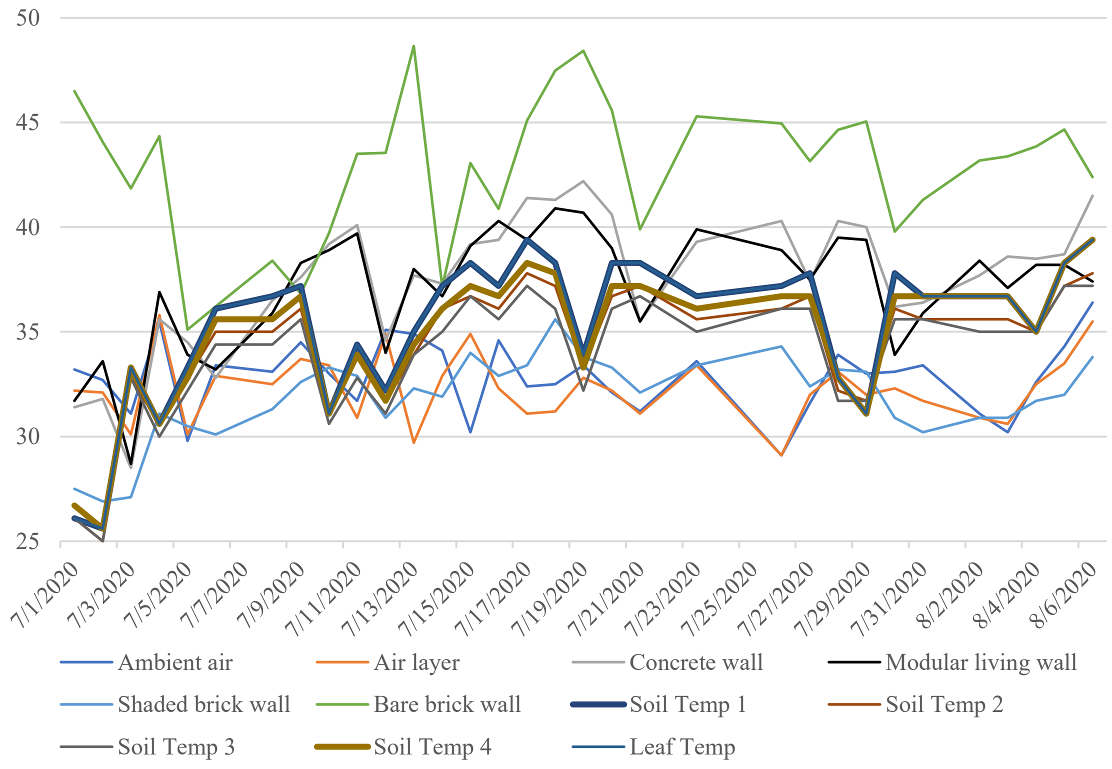


Chart 7 - July to August 2020

In daily measurements taken by 14:00hrs for 36 days in July and August 2020. BBW had the maximum surface temperatures and when compared to the SBW, temperature differences were from 4.2 – 19 °C. Comparing BBW to the front of MLWS, temperature differences were between 0.5 – 14.8 °C, MLWS had lower temperatures than BBW. The CW was warmer than SBW between 1.4 to 8.4 °C. Average MLWS temperatures were higher than soil temperatures 79.4% of the 36 days. Soil temperatures were cooler than MLWS between 0.3 – 8.3 °C. Leaf temperature was cooler than MLWS 70.6% of the days, between 0.2 - 8.3 °C. Results showed temperature differences between MLWS average surface temperatures and its parts. The soil and leaf had differences of up to 8.3 ° C.

3.5.1.2. Heat gain

In the bare wall conditions, the exterior wall surface receives heat from the direct solar radiation, diffuses radiation from the sky, reflects radiation from the ground, radiative heat exchange with surroundings, and convective heat exchange with ambient air. In the MLWS condition, the MLWS blocks incident solar radiation, which is the main contributor of heat gain in buildings. The microclimate between the building wall surface and the MLWS influences the wall. It is clear that SBW has lower temperatures than all other surfaces. SBW surface temperature is usually lower than the exterior temperature of the MLWS up to 14.8 °C. In summer ambient air temperatures are usually cooler than other exposed surfaces indicating that the MLWS is actually losing heat to the microclimate most the time. In winter vice versa occurs. Minimum and maximum temperature differences between surfaces are shown in Table 3.3. Temperature differences from studies of other living walls were listed in Table 3.4. Heat exchange processes are discussed next.

Table 3.3: Temperature decrease at modular living wall system.

Experiment	Date/ Season	MLWS to CW	MLWS to SBW	MLWS to BBW	MLWS to soil	MLWS to leaf	CW to SBW	CW to BBW	SBW to BBW
1	Apr. 26, 2019 Spring	−4.9 to 3		−6.4 to 8.2				−4.5 to 6.9	
2	Aug. 16, 2019 Summer	−2.8 to 3.8	−1.3 to 7.8				1.5 to 8.7		
3	Aug. 2019 Summer	−0.6 to 4.1	0.4 to 5.6				3.8 to 5.7		

Table 3.3 Continued: Temperature decrease at modular living wall system.

Experiment	**Date/ Season**	**MLWS to CW**	**MLWS to SBW**	**MLWS to BBW**	**MLWS to soil**	**MLWS to leaf**	**CW to SBW**	**CW to BBW**	**SBW to BBW**
4	Dec. 13, 2019 Fall	−17 to 2.6	−2 to 11				−8.7 to 1		
5	Feb. 13, 2020 Winter	−0.1 to 4	−2.5 to 3.9				0.3 to 3.8		
6	Aug.10, 2020 Summer	0 to 4	−1.6 to 7.6	2.3 to 6.9	1.7 to 3.9	1.1 to 3.9	−0.2 to 9.7	−0.4 to 6.7	4.4 to 12.7
7	Jul./Aug2020 Summer	−1.8 to 4.1	1.6 to 7.5	−6.5 to 9.8	0.3 to 8.3	0.2 to 8.3	1.4 to 8.4	−5.8 to 10.1	4.2 to 19

Table 3.4: Temperature decrease for other living walls.

Living wall temperature reduction in other studies		
(Charoenkit & Yiemwattana, 2017)	6 months (Summer)	Up to 7.2 temperature difference to reference wall
(Basher et al., 2016)	March 13–19, 2015 (Dry season)	2.4 to 6.4 reduction in surface temperature
(Rupasinghe & Halwatura, 2020b)	48 hours in tropical context	10.16 reduction in external wall surface
(Perini, Ottele, Haas, & Raiteri, 2011)	Mediterranean climate	4.5

3.5.1.3. Solar radiation

Readings from the solar meter on December 13, 2019, show that maximum radiation at modules was 611 W/m^2, concrete wall 500 W/m^2, and SBW was the least at 21 W/m^2. On August 10, 2020 maximum radiation at modules was 494 W/m^2, concrete wall 500 W/m^2, and SBW was 13.1 W/m^2. Lastly, at 1400hrs for 32 days in July and August, the maximum radiation at modules was 148 W/m^2, concrete wall was 224 W/m^2, and at SBW was 129 W/m^2.

3.5.1.4. Humidity

The presence of living wall systems could increase the relative humidity (RH) of surrounding air by irrigation activity, wet substrate and transpiration of plants. The humidity condition of air layer between the MLWS and the building wall SBW is important because it is adjacent to the building and influences air in contact with the building surface. On December 13, 2019, RH was lower in front of MLWS than behind it, in the morning and evening hours, RH was higher in front between 1100hrs and 1500hrs. By August 10, 2020, RH is consistently higher at the air layer during the daytime and relative humidity of ambient air is higher between 2000hrs and 2100hrs. Lastly during July and August 2020, relative humidity is higher behind the MLWS at the air layer for most of the days, Chart 8.

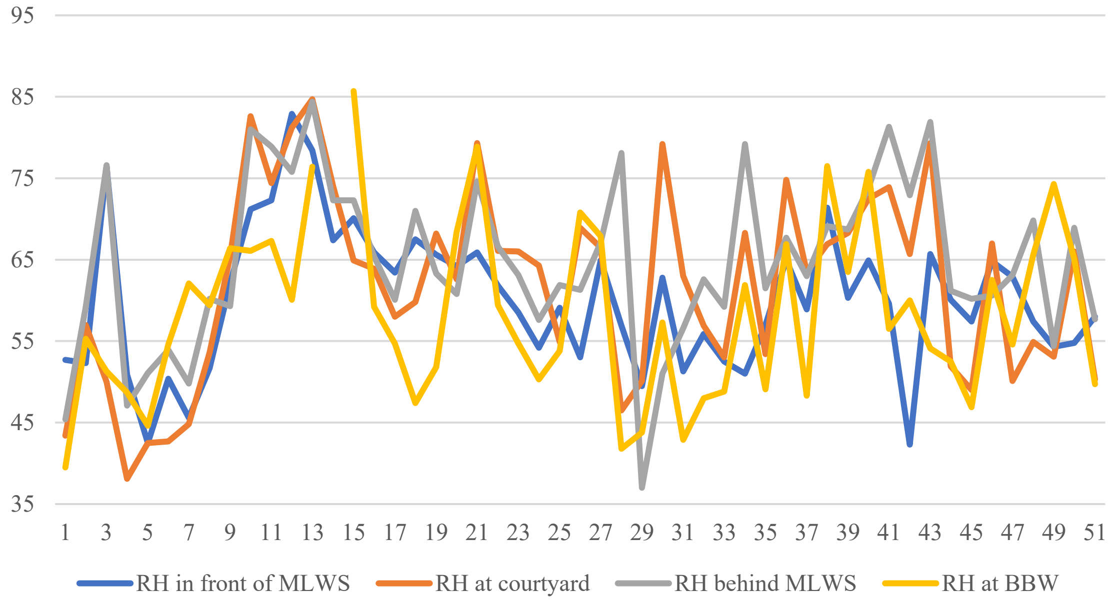


Chart 8. Relative humidity at MLWS, courtyard and bare brick wall in Summer 2020.

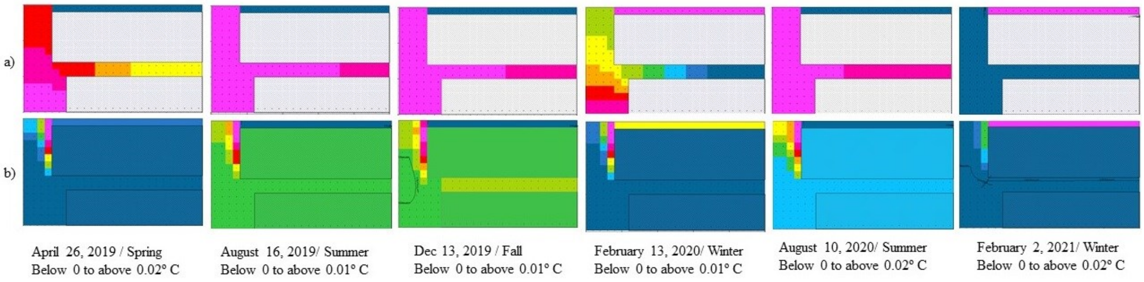
3.5.1.5. Soil and leaf temperatures

At 700hrs to 1000hrs and from 1500hrs to 2200hrs, the soil and leaf temperatures had the least temperatures while SBW was the lowest from 1000hrs to 1500hrs. From July 2020 to February 2021, soil and leaf temperatures were uniform, maximum values for both of them were 42.8°C. A minimum value of -12.8°C was recorded due to the Arctic blast in Texas during the month of February 2021.

3.5.2. ENVI-met simulation

Thermal performance was assessed from the campaign measurements and used to simulate for results in ENVI-met. Air temperature ranges and windspeed were used for simulation. Experimental study was validated using simulation with the ENVI-Met model computer simulation method. ENVI-Met V4 is a holistic three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions. It is often used to simulate urban environments and to assess the effects of green architecture visions (Shafiee, Faizi, Yazdanfar, & Khanmohammadi, 2020). ENVI-Met is designed for the microscale with a typical horizontal resolution from 0.5 to 10m and a typical time frame of 24-48 h with a time step of 1 – 5s. The resolution allows for analyzing the small-scale interactions between individual buildings, surfaces, and plants.

The comparisons of average temperatures of the two scenarios in four seasons on April 26th 2019, August 16, 2019, December 13, 2019, February 13, 2020, August 10, 2020 and February 16, 2021 are presented in Figure 3.14. The absolute difference potential air temperature at 1400 hrs., ranges from 0 to above 0.02º C in the simulation results, Chart 9.



April 26, 2019 / Spring
Below 0 to above 0.02° C

August 16, 2019/ Summer
Below 0 to above 0.01° C

Dec 13, 2019 / Fall
Below 0 to above 0.01° C

February 13, 2020/ Winter
Below 0 to above 0.01° C

August 10, 2020/ Summer
Below 0 to above 0.02° C

February 2, 2021/ Winter
Below 0 to above 0.02° C

Figure 3.14: The comparison of plan views of scenarios with brick (a), and with vertical greenery onsite simulated comparison of brick with green + mixed substrate living wall with an airgap in ENVI-met (b).

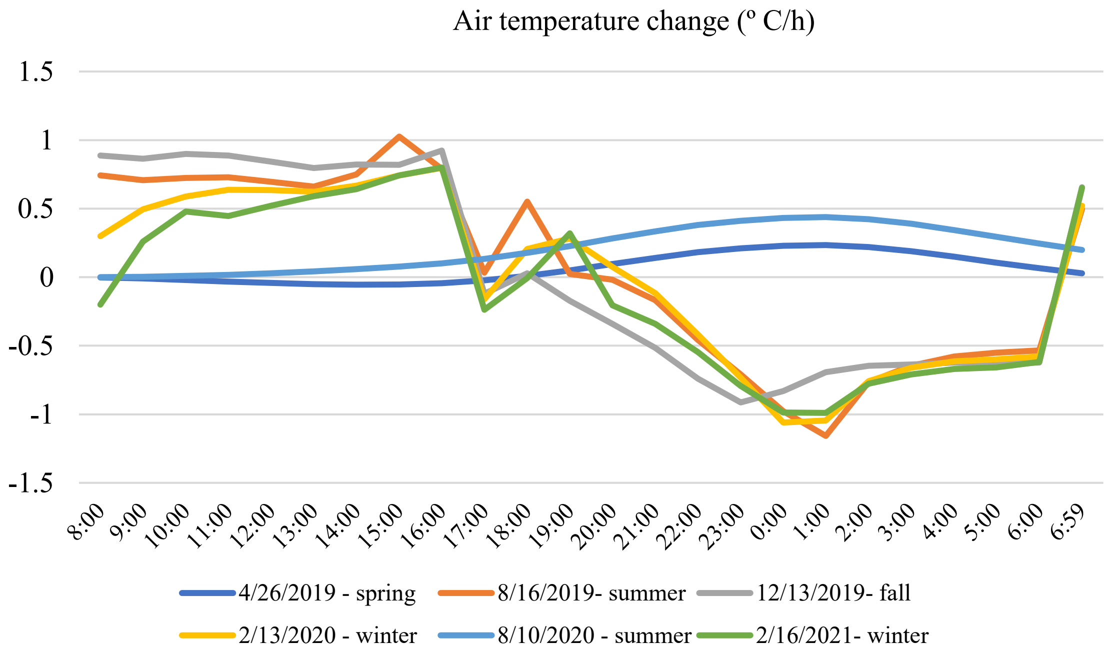


Chart 9. Air temperature changes between brick and living wall in the full day simulations.

Using scenario 2 as reference in ENVI-met, scenario 1 had higher temperatures from 8:00hrs to 17:00hrs. During summer 2019, fall 2019, winter 2020, and winter 2021, the living wall scenario became warmer than brick wall from 20:00 hrs. to about 6:50hrs.

3.5.3. Environmental and economic impacts

3.5.3.1. Life cycle analysis

Life cycle analysis (LCA) was carried out using Tally plug-in for Revit. Scenarios for reuse compared to virgin material were modelled using parametric pattern-based façade. Galvanized sheet metal was specified as the material for modules in the façade and both scenarios were analyzed using Tally. Results showed that reusing prompt metal from a plant for modules instead of virgin material could avoid 7,581 kgSO2eq of acidification, 429 kgNeq of eutrophication, 1,862,137 global warming, 3.05E-02 CFC-11eq of ozone depletion, 117,620 kgO3eq of smog formation, 30,407,441 MJ (28,820 million BTU) of primary energy, 27,808,495.37 MJ (26,357 million BTU) of non-renewable energy, 2,639,295.198 MJ (2502 million BTU) of renewable energy for 568,508.5kg of annually. For environmental and economic impacts annual weights of Offal were input into United States Environmental Protection Agency (USEPA), Waste Reduction Model (WARM). When weights are imputed, alternative waste scenario of reduced at source is selected to compare to current conventional recycling methods.

From the first phase of this study, the design of modules resulted in 78% material efficiency, therefore 22% of Offal remains as by-product after this symbiosis. The baseline scenario of total recycling was input in the model and the alternative management scenario of reuse was indicated by “reduced at source” with the corresponding percentages of material efficiency. Reusing Offal results in avoided greenhouse gas emissions, avoided manufacturing energy, reduced labor hours, reduced wages, and reduced taxes. Annually reusing Offal as modules in living wall systems annually could save 362.89 $MTCO_2e$ (greenhouse gas emissions), 8.1 MJ (7,671.80 million BTU) of energy, 30,915 labor hours, $719,972 of wages, and $165,633.27 in taxes. Calculating impacts with data on passenger vehicle production, Figure 3.15 and 3.16, show that reuse could have reduced approximately 4,500 GJ (4,252 MMBtu) of energy use and avoided 201$MMTCO_2e$ of emissions between 2009 to 2019 in the US.

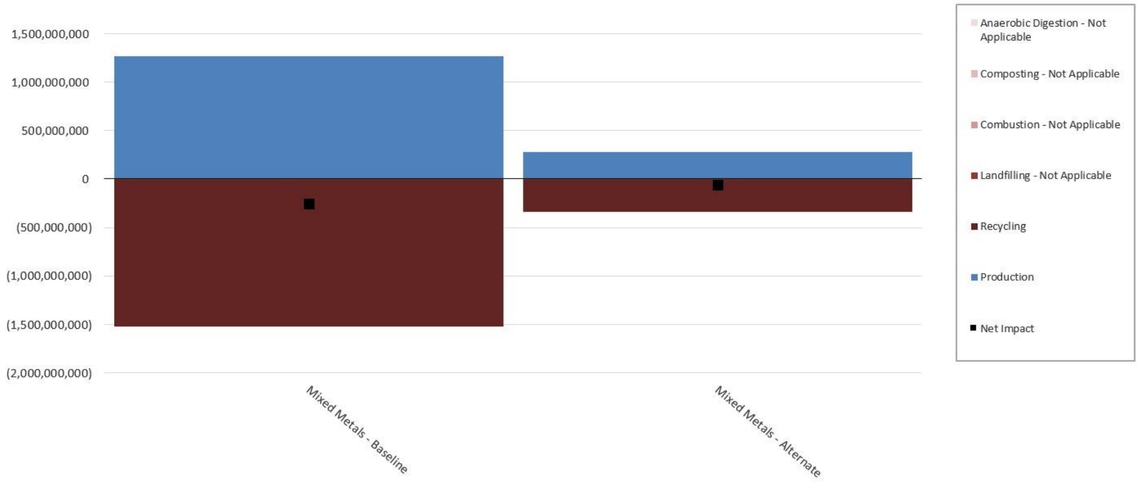


Figure 3.15: Baseline and alternate production and end-of-life emissions ($MTCO_2e$)

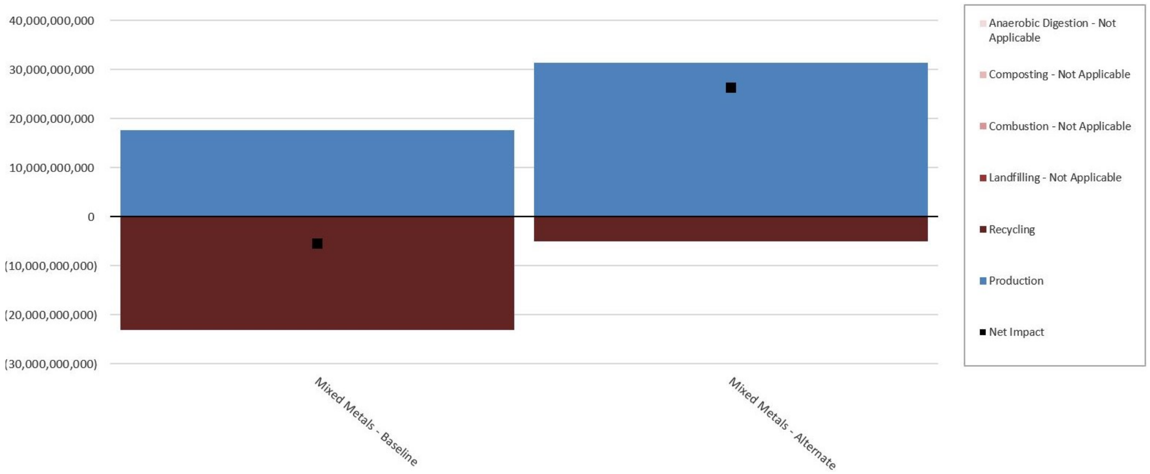


Figure 3.16: Baseline and alternate production and end-of-life energy use (Million Btu)

3.6. Conclusion

Planting modules in a novel modular living wall system (MLWS) were designed and constructed from the automotive industry galvanized sheet metal waste-flow, which are high volume of consistent cutouts left over from the vehicle body production processes. The study aimed at quantifying the MLWS thermal, environmental, and economic impacts. The MLWS shades the brick wall with a substantial cooling effect up to 19 °C when compared to the exposed brick building surface and has a cooling effect of up to 8.7 °C towards the adjacent concrete wall surface with about 50% vegetation maturity.

Increased humidity behind the living wall system has not affected the performance of the brick surface. Unwanted moisture was suspected to move between brick joints and cracks but surprisingly, the ventilated air layer kept the surface dry enough to prevent molds, crack, or discoloration.

Onsite data collection and simulation results showed that the MLWS had minimal effect on the immediate microclimate. Life cycle analysis done by Tally software, and the United States Environmental Agency's Waste Reduction Model yielded environmental and economic benefits. Energy savings for virgin and reused galvanized sheet metal were reported by both analysis tools.

Limitations were that the thermal performance of this study is based on the study site climate, a humid sub- tropical climate. Also, the MLWS prototype was compared to conventional brick and concrete materials to obtain its cooling effect. In addition, the

MLWS composition and fabrication methods was ultimately different from other market-based living wall systems.

Recommendations done by another study on the same wall system included the use of plants with broader leaves. MLWS could be installed on existing brick façade as a double building envelope to make the building surface significantly cooler thereby reducing required cooling loads. Energy calculation outputs with both simulation tools could be reported with similar description to enable better understanding of the environmental impacts. Consequently, architects and designers could alter the physical properties of the MLWS to achieve desired cooling effects using the Industrial Symbiosis concept to reduce cost and increase circular economy benefits. The methodology for this IS includes 1) Identifying industries with matching needs, 2) characterizing proposed product through design (in previous study) and in situ observation of performance and, 3) qualifying the resource stream and possible benefits from annual use of material by estimating with available data on industry operations.

The next chapter is a techno-economic analysis that compares the MLWS to other traditional living wall systems. The potential avoided energy and costs are described in detail.

4. TECHNO-ECONOMIC ANALYSIS OF MODULAR LIVING WALL CO-PRODUCTION FROM PROMPT SCRAP METAL: A CASE STUDY QUANTIFYING SYMBIOSIS IMPACTS IN BUILDING CONSTRUCTION (MANUSCRIPT 3).

This manuscript was submitted to Journal of Cleaner Production on 14th May 2021 and transferred to Cleaner Environmental Systems Journal on 27th September 2021.

4.1. Overview

Prompt sheet metal (Offal) recovered from blanking and stamping operations during vehicle production processes represent a significant yet consistent waste stream; primarily in the automotive industry and many other industries that use sheet metal in their products. Current disposal practices for Offal cutouts from these processes include landfilling and recycling. Landfilling Offal leads to pollution and conventional recycling processes preserve materials but consume manufacturing energy and emit greenhouse gases (GHG). Alternate reuse approaches that transform these Offal into valuable feedstock for products are necessary and symbiosis between industries to exchange waste, could be beneficial towards reducing manufacturing energy and GHG emissions. Quantifying and reporting expected reuse impacts could catalyze symbioses at various scales between and within industries. This study presents the third part of an alternative approach to reusing Offal. The first part explored reusing Offal as modules for modular living wall systems (MLWS). In the second part, a case study of a novel prototype MLWS made from Offal was characterized in four seasons with focus on its thermal performance. In this final study, a techno-economic analysis compared the novel MLWS to traditional living wall systems (LWS) considering the symbiosis feasibility and cradle to gate life cycle costs. Parameters include fuel consumption, electricity, net primary energy, and costs. Findings provide a sound basis for stakeholders to implement circular strategies.

4.2. Introduction

Growing plants in modules allow for fast coverage of large surfaces and the uniform distribution of vegetation by design along a vertical surface. Components of a modular living wall system (MLWS) include: supporting elements, growing media, vegetation, drainage and irrigation. MLWS have a specific dimension for their parts including the growing media. Prevalent metals used for MLWS are stainless steel, galvanized steel and aluminum (Coma et al., 2017; Jim, 2015; Pérez et al., 2014; Pérez et al., 2011). Other materials include geotextile felt (Pérez et al., 2014), recycled polypropylene (Mazzali, Peron, Romagnoni, et al., 2013), and polyethylene materials (Coma et al., 2017).

MLWS are considered a luxury installation (Kharrufa & Adil, 2012; Riley, 2017), and they are not as durable as the buildings on which they are installed leading to increased maintenance costs. This study focuses on the materials for modules in MLWS, especially metal. Metals in the construction industry are sourced in the US through virgin and recycled processes. The strategy of reusing scrap metal in place of virgin or recycled metal in building products could provide an alternate supply to demand for metal in the building construction industry.

Data from the reducing embodied energy and decreasing emissions (REMADE) Institute on materials used in manufacturing and design 2014, shows that galvanized sheet metal is a material that is used frequently in building construction and automotive industries. Also, galvanized sheet has the highest percentage of returned fabrication or new scrap.

Previous synergies between the automotive and construction industries, have utilized materials such as tires in aggregates (Landi et al., 2018; Pilakoutas, Neocleous, & Tlemat, 2004); batteries from electric vehicles for power in buildings (Cusenza et al., 2019); and scrap metal in building envelope systems (Ali et al., 2020; Ali et al., 2019). However, the impact of a symbiosis reusing scrap metal as plant module material in MLWS has not been explored. There is need to quantify and test how value could be created through circular economy (CE) in different contexts (Hopkinson, De Angelis, & Zils, 2020). Steel is considered a circular material, and due to a lack of efficacy of recovery and recycling, targets are encouraged to favor other powerful CE strategies such as repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink, and refuse (Morseletto, 2020). Applying reuse could improve the cost value of scrap metal and reduce energies and carbon emissions associated with its recycling. Reuse promotes resource efficiency, avoids new material expenditure in costs and embodied energy consumption (Ali et al., 2019).

In the automotive industry, prompt industrial scrap known as Offal are skeletons from stampings, cutoffs and trimmings, and there is a relatively short time between its existence and recycling to a steel plant or foundry; it averages approximately 45% of the total supply of purchased scrap (Swager et al., 1981). Sheet metal is used in industrial sectors and its use is expected to increase due to population rise and demand for more vehicles. Results from a study in Colombia indicated that passenger car stock would be increased by 6.6 times between 2010 and 2050, the energy consumption and CO_2 emissions would be increased by 5.5 and 4.9 times respectively (González Palencia et al., 2012).

The primary material of this study is Offal from the automotive industry, Figure 4.1. Sheet metals used for body panels in the automotive industry have high safety standards and overall reduced weigh as vehicles require stronger and lighter materials (Bae & Huh, 2012; Cho, Choi, Lee, Cho, & Han, 2013; Park & Dang, 2011). In automotive body designing, high strength steels are applied to achieve weight reduction and high crashworthiness to reduce fuel consumption and increase strength (Nonaka, Goto, Taniguchi, & Yamazaki, 2003).

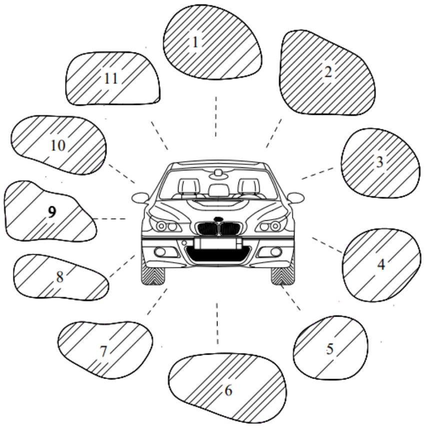


Figure 4.1: Eleven types of Offal from the automotive industry

In an interdisciplinary collaboration, an automotive company provided annual data of Offal from one plant in the United States. Although materials used to produce car bodies are evolving to whole aluminum, light galvanized sheet metal bodies, hybrid bodies with aluminum and manganese to achieve a lighter mass; many automotive companies use galvanized sheet metal widely for majority of their bodies and parts due to the higher energy required in the producing aluminum (Carle & Blount, 1999; Cui et al., 2011; González Palencia et al., 2012; Hynes & Velu, 2018; Tempelman, 2011).

Although Offal sizes have been predictable since 1969, new parametric design tools to work with irregular shapes have emerged, encouraging designers to work with unevenly sized materials. In addition, technology has provided more tools to calculate impacts of reuse interventions. Ethical demands on companies by their communities and customer have led to an increase in environmental awareness and pursuit of sustainable development goals (SDG, 2018).

This study presents a techno-economic analysis comparing the reuse method for the novel MLWS with conventional recycling methods, and presents environmental impacts of reusing Offal in MLWS over their conventional recycling. The work presented here investigates the feasibility of creatively reusing Offal to add value to it without extensive modifications. Following sections highlight the benefits of vertical greening systems, process of sourcing virgin metal materials and current conventional recycling processes as scenarios for comparison. Thereafter, the impacts of reusing Offal as an alternative circular material is calculated from the two scenarios.

4.2.1. Background

4.2.1.1. Vertical greening systems

Vertical greening systems (VGS) provide various personal and social benefits. Some personal benefits are energy savings for heating and air-conditioning, improvement of real estate value (or rent), and durability of facades. The air layer between living walls and building envelopes creates an insulating effect that reduces the energy demand for air-conditioning up to 40-60% in Mediterranean climate (Alexandri & Jones, 2008; Mazzali, Peron, & Scarpa, 2013). A panel living wall system (LWS) in Shiraz, Iran with a hot, semi-arid climate reduced ambient air temperature by up to 8.7°C (Shafiee et al., 2020) proving that living walls could effectively reduce surrounding temperatures and in turn improve urban heat island (UHI) phenomenon; when air temperature in the cities are 2 - 5°C higher than those in the surrounding rural areas mainly due to the amount of artificial surfaces compared to natural land cover and atrophic activities (Taha, 1997).

Introducing vegetation to a property adds to its values; (Peck, Callaghan, Kuhn, & Bass, 1999b) assumed that a green wall would yield the same property value increase as a “good tree cover” and estimated a value increase interval of 6 – 15% with a midpoint of 10.5%. (François, Marius, Yan, & Paul, 2002) estimated that hedges increase property value by 3.9%. (Gao & Asami, 2007) found that an increase in greenery quality level could increase land price by 1.4% in Tokyo and by 2.7% in Japan. Green walls also provide acoustic benefits for buildings because they affect sound level environment (Veisten, Smyrnova, Klæboe, Hornikx, Mosslemi, & Kang, 2012) and thin layers of vegetation provide low acoustic benefits (Giachetta & Magliocco, 2007).

Social benefits of green surfaces include improved environmental conditions in dense urban areas such as: greenhouse gases output reduction, climate change adaptation, air quality improvement, urban wildlife (biodiversity), etc (Bianchini & Hewage, 2012). Mitigation of UHI effect with trees, green roofs and green facades can reduce the United States national energy consumption for air conditioning up to 20%, saving more than $10B in energy use (Akbari, Pomerantz, & Taha, 2001).

VGS play an important role against air pollution which affects urban air; in an urban street with trees there was only 10 – 15% of the total dust particles of a similar street without trees (Johnson & Newton, 1996). Air pollution in a street in Frankfurt without trees was 10,000 – 20,000 dirty particles per liter, while a street that had trees in the same neighborhood had an air pollution of 3000 dirty particles (Minke & Witter, 1982).

VGS have the capacity to increase property values, limit heat fluxes, mitigate UHI effect and purify ambient air while cooling it. Relative humidity around living walls are higher and differences in performance of VGS are usually due to factors like foliage index, moisture content, vegetation type and materials involved. This analysis reviewed the benefits of VGS as a domain for an effective circular product. Offal as modules in VGS specifically MLWS, could replace virgin and recycled metals; their processes are discussed as follows.

4.2.1.2. Virgin metal production

Steel is produced by extracting and processing iron ore, zinc coating is applied to prevent corrosion. Galvanized sheet metal is mass produced from iron ore. After extraction, pig iron is passed through blast furnace (BF)/ basic oxygen furnace (BOF), a highly energy intensive process due to the inclusion of coke making and sintering operations, (Productivity, 2012). The process flow diagram developed for metal extraction is shown in Figure 4.2. Resulting steel are sent to rolling mills and transformed into high performance steel which undergo zinc treatments for corrosion resistance.

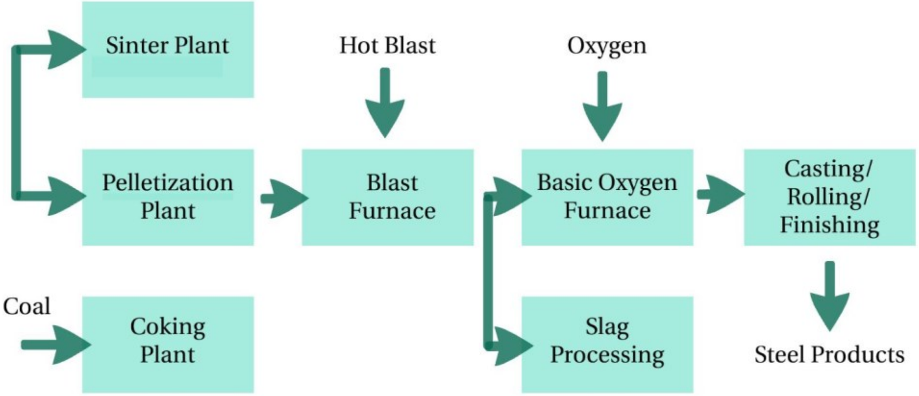


Figure 4.2: Simplified process flow showing sequence of integrated steelworks (Schoenberger, 2000)

4.2.1.3. Conventional recycling programs

Metals ought to be infinitely recyclable in principle, but in practice recycling is low, because of limits imposed by social behavior, product design, recycling technologies, and the thermodynamics of separation (Reck & Graedel, 2012). Secondary steel mills produce steel from scrap steel, pig iron, or direct reduced iron using an electric arc furnace (EAF). This study assumed that all recycled metal was produced by EAF, Figure 4.3; whose production processes is mainly utilized for melting scrap (Yellishetty, Mudd, Ranjith, & Tharumarajah, 2011).

In the automotive industry, manufacturers generating large quantities of Offal, sold their scrap to collectors through monthly or yearly competitive bidding lists based on estimated scrap grades and tonnage.

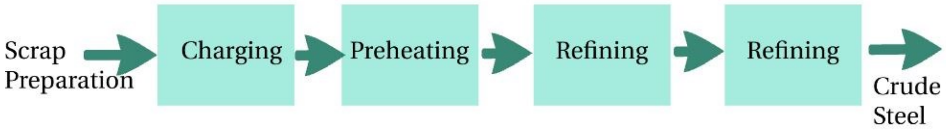


Figure 4.3: Process flow for reusing Offal as feedstock for modules

These plants tended to be consistent over the year in type and quantity of scrap generated because of their mass production operation. Small producers and custom vehicle manufacturers were usually paid monthly for their scrap, the pay based on the weight disposed of by the private collector. Cost per ton of waste collected was an indicator of efficiency. Frequency of scrap pickup at plant storage areas affected their neatness and efficiency and 80% of the plant officials were interested in scrap control. Management in plants did not appear concerned with scrap after it was removed from the plant site except self-haul setups. Some waste haulers had monopoly and charged excessively high; plants became captive customers to collection monopolies if their capitalization was not sufficient for acquiring their own hauling vehicles. There was difficulty in obtaining actual data and analyses were based on estimates; private collectors were hesitant to release any information that might prove valuable to their competitors. Contractors had little accurate data because they had not maintained accurate type, weight, or volume summaries. Most collectors charged a fixed amount on a long-term or annual contract basis.

Conventional recycling consumes manufacturing energy and causes greenhouse gas (GHG) emissions. Data from the automotive industry shows that available Offal undergo conventional recycling. Reusing Offal as feedstock for VGS could reduce energy and GHG due to conventional recycling while mitigating UHI effect in urban areas.

4.3. Material and methods

4.3.1. Offal in the automotive industry

Sheet metal for automotive assembly plant processes undergo blanking and stamping processes for openings in car bodies. The metal cutouts from these production processes are prompt metal also known as Offal. An automotive company in the U.S. provided annual data for eleven samples of galvanized steel Offal, Table 4.1.

Table 4.1: Types of Offal and their annual volume range

Offal	Monthly Volume Range	Annual Volume Range (Numbers of pieces)
1	5,000	60,000
2	N/A	100,000
3	5,000	60,000
4	3,000	36,000
5	6,000	72,000
6	N/A	1000
7	1,000	12,000
8	1,500	18,000
9	1,000	12,000
10	1,000	12,000
11	5,000	60,000

4.3.2. Methods

The technical analysis was carried out by a cradle to gate life cycle analysis. Two scenarios show the potential impacts that could be avoided when annual supply of Offal is used as feedstock in place of virgin metal and conventionally recycled metal.

The first scenario compared reusing Offal to virgin metal and the second scenario compared reusing Offal to recycled metal.

4.3.3. Life cycle analysis

Cradle to gate life cycle analyses of the two scenarios were used to determine economic and environmental impacts. The International Organization for Standardization (ISO) defines LCA as a multiphase process consisting of a 1) Goal and Scope Definition, 2) Life Cycle Inventory (LCI), 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation, (Figure 4.4)

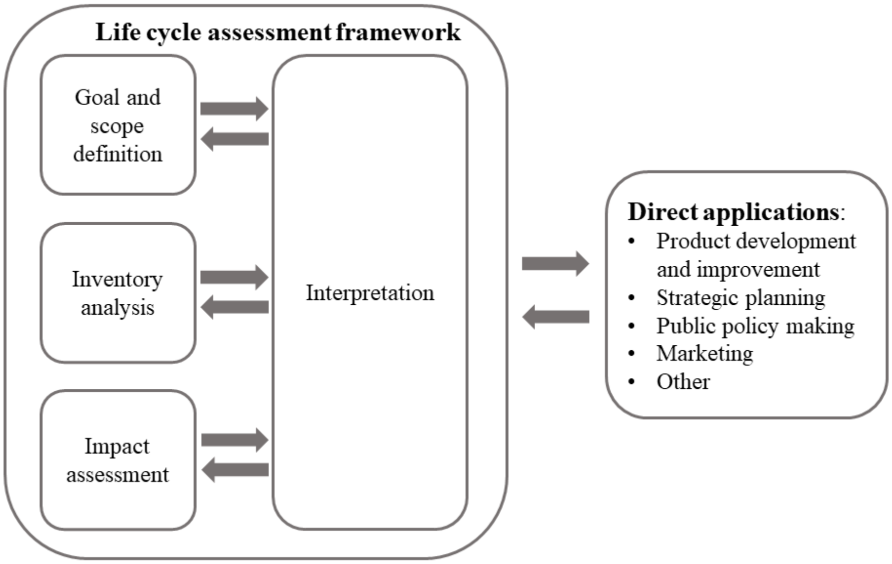


Figure 4.4: Conceptual flow-chart of a life-cycle assessment process, (EPA, 2006)

Life cycle inventory (LCI) of virgin metal production and conventional recycling was used to compute the impacts or reuse. All inputs and outputs in the LCI and the consequential life cycle impact analysis profile are related to the functional unit (ISO, 2006). The functional unit was the annual supply of Offal from the case study automotive assembly plant. Although an LCA evaluates all stages of a product's life due to interdependency, it is possible to exclude certain stages or activities and still address the issue for which the LCA is being performed (EPA, 2006).

4.3.4. Study goals and scope

The goal of this study was to determine the feasibility of reusing Offal in MLWS and quantify its impacts towards two scenarios: virgin and recycled galvanized sheet metal. The LCA of the two scenarios used available indicators to determine economic impacts and avoided greenhouse gas emissions. The intended audience include automotive manufacturers, architects, landscape architects, designers, producers of living wall systems and building owners.

4.3.5. Functional unit

The functional unit for the calculations was the annual quantity of Offal from the automotive company. The annual quantity of Offal was calculated in kilograms and tons. All data available for conversion to carbon dioxide emissions was given in kilowatt per hour, tons and kilograms.

4.3.6. System boundaries

The system boundary limited the operations for virgin steel production processes using BF/BOF and those for conventional recycling processes using the EAF. The system boundary for Offal was the annually available Offal from one plant in the U.S.

4.3.7. Data sourcing

Due to commercial sensitivity, data for sheet metal production was sourced from the following publications: Lawrence Berkeley National Laboratory titled "Energy

Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry An ENERGY STAR(R) Guide for Energy and Plant Managers", the Environmental Protection Agency (EPA) titled "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry" and "Technical Support Document for the Iron and Steel Sector: Proposed Rule for Mandatory Reporting Of Greenhouse Gases".

4.3.8. Life cycle inventory

The World Steel Association reported that every ton of steel produced in 2018 emitted on average 1.85 tons of carbon dioxide, equating to about 8 percent of global carbon dioxide emissions. Energy expended in the iron and steel industry comprises coal, net electricity, natural gas, coke and breeze. Energy due to fuel consumption, electricity consumption and net primary energy use for EAF are shown in Table 4.2.

Table 4.2: Energy use by process; energy use due to fuel consumption, electricity consumption and net primary energy use; average value is given in parentheses (Worrell, 2011)

Process	**Fuel (MBtu/ton product)**	**Electricity (final) (kWh/ton product)**	**Primary (net) (MBtu/ton product)**
Sinter	1.4 – 1.6 (1.4)	28 - 20 (26)	1.4 – 1.6 (1.6)
Coke	2.8 – 3.0 (2.8)	33 - 38 (36)	3.1 – 4.4
Hot stove	1.4 – 1.7 (1.5)	-	1.4 – 1.7 (1.5)
Blast Furnace	9.9 – 10.4 (10.0)	-	9.9 – 10.4 (10.0)
BOF	0.7 – 1.0 (0.8)	13 - 38 (23)	0.06 – 0.5 (0.3)
EAF	0.2 – 0.8 (0.4)	304 – 525 (401)	3.2 – 5.2 (3.9)
Continuous Casting	0.02 – 0.06 (0.04)	5.4 – 13 (8)	0.10 – 0.15 (0.12)
Reheating furnace	0.7 – 1.4 (1.1)	2 – 10 (6)	0.7 – 1.4 (1.1)
Hot strip mill	0.01	90 – 152 (121)	0.6 – 1.2 (0.8)

4.3.9. Case study modular living wall system

From previous study in Chapter 2, the resource efficiency of the modules in the MLWS was 70%. Therefore, the potential annual mass of Offal for MLWS was 70% of 568,508.5 kg/568.5Mt, resulting in approximately 397,956kg /398Mt of Offal for possible reuse in MLWS.

The novel modular living wall system (MLWS)- width: 5.8m; height: 4.3m; cavity: 300mm, was installed on a school building façade held up by its supporting metal frame and facing the South-East, Figure 4.5. The novel MLWS covers a surface area of 25m^2 /269.1 sq ft, with 20.2m/66.2ft perimeter. Components of the wall included, a frame made of steel angles, square tubes, sheet plates to support modules, rivets to join parts of the modules, spray painted galvanized units, engineered soil, drainage layer, irrigation system comprising pump and timer, pipes and emitters for the units and Texas native plants. Parts of the MLWS are presented in detail.

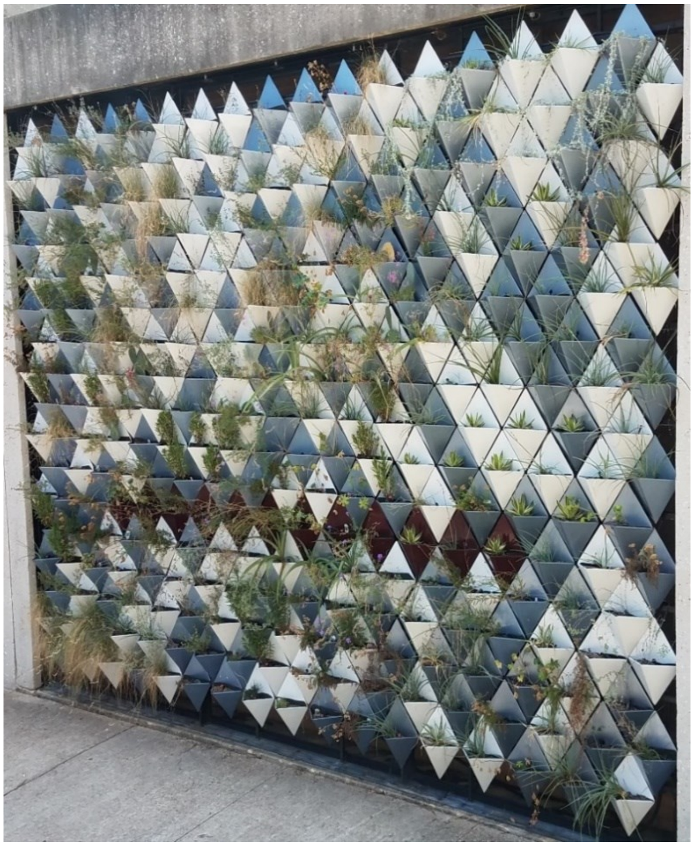


Figure 4.5: Novel modular living wall system

4.3.9.1. Substrate

Each module had a depth of 215mm for soil. Two types of soil were used a growing media on top and drainage layer below. The growing media was Rooflite Extensive 700 Growing Media and the drainage layer was Rooflite Drain 600 Drainage Layer.

4.3.9.2. Container Module

Galvanized sheet scrap metal from an automobile industry, was reused as raw material for the 300 diamond shaped modules. Each module was 305mm wide, 230mm deep and 455mm high. Modules have three surfaces, flat, left and right. The left and right faces were at an angle of 45º to the vertical and horizontal which could significantly change their exposure to solar incident rays.

4.3.9.3. Cavity

The MLWS created a 300mm cavity, between itself and the building surface functioning as a double-skin façade. The cavity acts as a thermal insulation layer with the ability to control heat gains and losses (Perini & Rosasco, 2016).

4.3.9.4. Water Nutrient

The frequency and rate of flow determines the length of time the soil remains wet. Each module had one emitter supplying water. Drop irrigation for both years was 1.16 gal/week with excess drainage flowing behind modules.

4.3.9.5. Vegetation

Native plants such as *Dichondria argentea, Agave lophantha, Hesper aloe parviflora, Yucca flaccida* and *Hechtia texensis* plants were chosen and designed considering their low water requirements. Maximum percentage of vegetation to surface area during the times of observation was 50%.

4.4. Findings and discussion

4.4.1. Technical impacts

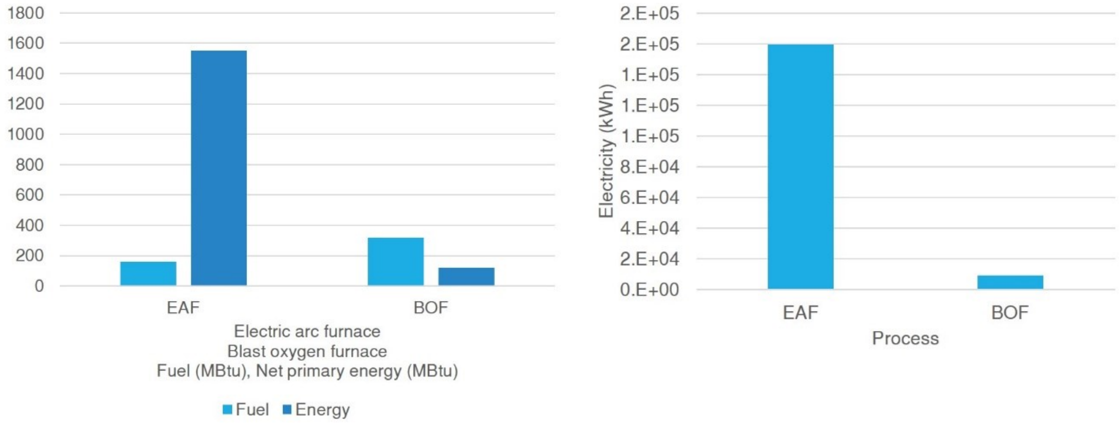
Potential impacts calculated from the LCIA with indicators of fuel consumption, electricity, and energy per ton of galvanized sheet metal. Annual emission of carbon dioxide was calculated using data from World Steel Association. Electricity consumed by a typical EAF is typically under 500kWh/cast ton (Stubbles, 2000), 500kWh/cast ton is used in this assessment. Technical impacts were calculated using EAF data in Table 4.2, results are shown in Table 4.3.

Table 4.3: Technical impacts of reusing Offal for modular living wall system vs conventional recycling

Alternative process	**Offal utilized (tons)**	**Fuel consumption (MBtu)**	**Electricity (kWh)**	**Net primary energy (MBtu)**
EAF	398	159.2	159,598	1,552.2
BOF	398	318.4	9,154	119.4
Reuse	398	-	-	-

Findings showed that reusing available Offal from one company plant in place of virgin steel materials in MLWS could reduce 335,929MJ (318.4MBtu) of fuel, 9,154kWh of electricity and 125,974MJ (119.4MBtu) net primary energy annually. Creative reuse of Offal could reduce 167,965MJ (159.2MBtu), 159,598 kWh of electricity and 1,637,447MJ (1,552.2MBtu) net primary energy annually, Figure 4.6a and b. Conventional recycling consumes the higher amount of electricity and more net primary energy than virgin material production.

Every ton of steel produced in 2018 emitted on average 1.85 tons of carbon dioxide, equating to about 8 percent of global carbon dioxide emissions. Possible avoided carbon was calculated by multiplying annual mass of Offal reused and carbon emission per ton- 398 x 1.85, resulting in avoiding 736.3 tons of carbon dioxide annually from one company plant in the U.S. The average carbon footprint per year for a person in the U.S. is 16 tons (Conservancy, 2021), therefore reusing Offal from one company plant could reduce the carbon footprint of 46 people annually.



a) Potential avoided fuel and energy

b) Potential avoided electricity

Figure 4.6: Technical parameters potentially avoided by creative reuse

4.4.2. Economic impacts

4.4.2.1. Costs of living walls

Living walls are the most expensive type of vertical greening system due to their supporting frame, maintenance and design complexity (Fernández-Cañero et al., 2018). Yet, they remain desirable as living walls increase the variety of plants engaged and offer more creative and aesthetic potential (Lambertini, 2007). Although existing research shows that living walls are suitable for green retrofits (Feng & Hewage, 2014; Pulselli, Pulselli, Mazzali, Peron, & Bastianoni, 2014; Zhao et al., 2019), they have been regarded as luxury and viewed as a high cost element (Kharrufa & Adil, 2012; Riley, de Larrard, Malecot, et al., 2019).

The cost of living walls hinder their rapid choice and development; locating cost of existing living wall systems is challenging because there is not a one-size-fits-all solution (Riley, 2017). Therefore, costs are adapted to each project and thus vary widely (Perini, Ottele, Haas, et al., 2011).

Installation costs of MLWS, (Table 4.4) begin at about €400/m^2 ($471.12) and go as high as €1200/m^2 ($1413.35), those with pre-vegetated panels cost from $436.7 to $1310.11 per square meter depending on the system conception and the material used (Ottele et al., 2013; Pérez-Urrestarazu et al., 2015). A system made of zinc-coated steel can cost up to $951.75/m^2 in Europe (Perini & Rosasco, 2013b). A wide range of $477.94 - $1,433.82 was given as the cost per square meter of living wall systems because the cost depends on the façade surface and height, location, connections, etc. (Perini, Ottele, Haas, et al., 2011).

Table 4.4: Installation costs of living wall systems

Type of construction	**Costs**		**Source**
	Location	**Price (€ or $)**	
Trough planters	Europe	40-75€/m^2 or $47.16-$88.43	(Perini, Ottele, Haas, et al., 2011)
Framed boxes modular living wall	Europe	750-1200€/m^2 or $884.29-$1414.86/m^2	(Perini, Ottele, Haas, et al., 2011)
Geotextile felt system	Europe	350-750€/m^2 or $412.67-$884.29/m^2	(Perini, Ottele, Haas, et al., 2011)
Geotextile felt system	Turkey	415.65€/m^2 or $490.07/m2	(Meral, Başaran, Yalçınalp, Doğan, Ak, & Eroğlu, 2018)
Geotextile felt system	Turin, Italy	400€/m^2 or $471.62/m^2	(Serra, Bianco, Candelari, Giordano, Montacchini, Tedesco et al., 2017)
Carrier system	Dubai	244.26€/m^2 or 288$/m^2	(Haggag & Hassan, 2015)
Zinc-coated steel living wall system	Europe	807.22€/m^2 or $951.75/m^2	(Perini & Rosasco, 2013b)

In the United Kingdom, estimates ranged from 350 to 500£/m^2 (412.23 to \$588.89/m^2) and 200£/m^2 (\$235.56/m^2) was considered the tipping point of affordability (Riley, 2017).

4.4.2.2. Cost of novel living wall

The novel MLWS covers a surface area of 25m^2 /269.1 sq ft, with 20.2m/66.2ft perimeter. Components of the wall included, a frame made of steel angles, square tubes, sheet plates to support modules, rivets to join parts of the modules, spray painted galvanized units, engineered soil, drainage layer, irrigation system comprising pump and timer, pipes and emitters for the units and vegetation. The MLWS components, corresponding costs and labor costs are shown in Table 4.5.

Table 4.5: Components of novel living wall and their costs

Item	**Cost ($)**
14'X6' frame/ steel angle	88
1-1/4"X1-1/4" square tubes	80.4
1"X1" square tubes	718.17
3/16" sheet plates	200
Rivets (90 boxes)	1350
Labor cost	5,000
Galvanized units	21.33
Spray painting units	1,800
Priming and preparation for spraying	4185
Engineered soil - Rooflite Extensive 700 Growing Media, Rooflite Drain 600 Drainage Layer. Extensive 700: saturated weight 70-80 lbs/ft^3	1005
Irrigation system	184
Pipes and emitters for 297 modules	112
315 plants	1,575
Total	**16,318.9**

The total cost of the MLWS components is \$16,318.9 and \$652.8 per square meter or \$60.6 per square foot. The unit cost of the MLWS is approximately 69% of a zinc-coated steel system in Europe. Current prices of living walls at a company in San Diego, Los Angeles USA; TrueVert (Truevert, 2021) prices living walls between \$100 to \$225 per square foot of wall. Reusing Offal for any of the designed modules in this study could result in a modular living wall which costs 27 - 60% of current prices in San Diego.

The living wall system in Italy was the most expensive system analyzed (Perini & Rosasco, 2013a); panels and plant species cost about \$241 /m^2 without irrigation and installation. Transportation prices, included in the costs for previous study were calculated for the city of Genoa, Italy and this study assumes the same distances of 300 – 350 km.

Cost of living walls vary and the trend is that costs per square foot get better as the size of the wall increases showing economies of scale and increased efficiencies for larger wall surfaces. Cost comparison of various greening systems to MLWS (in yellow) per square meter are shown in Figure 4.6. Installation costs over their life span are shown in detail Table 4.6. For metal LWS, average cost for similar zinc-coated steel living wall system was \$951.75/m^2 while the novel metal MLWS costs \$652.8/m^2, with a difference of \$298.95/m^2, giving about 30% reduction in the cost of similar metal MLWS.

Disposal costs of each element (vertical supporting system, plants, etc.) are considered at the end of their lifespan. This includes removal of plants and structures, transport to landfill, and dump taxes and building façade renewal. Cost of existing living wall was obtained from (Perini & Rosasco, 2013b).

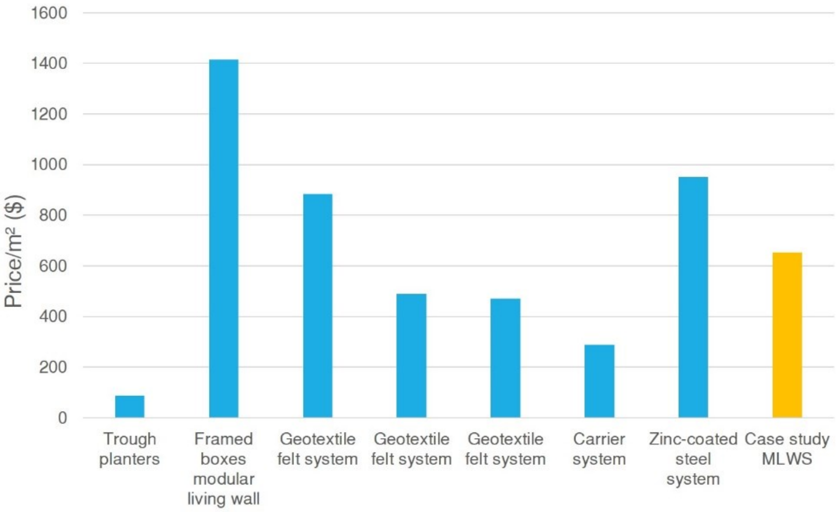


Figure 4.7: Installation costs of vertical greening systems

Installation costs were compared for living wall systems, Table 4.6. Existing literature showed that plastic systems were advantageous in the following areas: plant species in metal systems were more expensive by 17.5%; metal systems required supporting frames which cost $43.5 per square meter; metal panel and transportation were more expensive by 27.7%; irrigation system for metal systems were more expensive by 45.2%; and the installation of components for metal systems cost 99.5%. Metal systems did not require panel replacement while plastic systems required 5% panel replacement at $7.3 per square meter. Both systems had similar requirements for irrigation water, plant species and pipe replacement.

Table 4.6: Comparison of installation costs of modular living wall systems

		Plastic system		**Metal system**	
Category	**Cost**	**Time frame**	**Cost ($/m² facade)**	**Time frame**	**Cost ($/m² facade)**
Construction	Plant species	One time	33.17	One time	40.2
	Supporting frame	One time		One time	43.5
	Panels and transportation	One time	212.63	One time	294.25
	Irrigation system	One time	100.75	One time	184
	Installation	One time	90.36	One time	200
Maintenance	Pruning and panels adjustment	Annual	17.39	One time	-
	Irrigation (H_2O)	Annual	1.16	Annual	1.16
	Panels replacement (5%)	Annual	7.30	-	-
	Plant species replacement (10%)	Annual	3.32	Annual	3.32
	Pipes replacement (irrigation system)	Annual	3.44	Annual	3.44
	Cladding renovation	One time - 50th year	587.54	One time - 50th year	587.54
Disposal	Green layer disposal	One time - 50th year	263.70	One time - 50th year	263.70

4.4.3. Maintenance costs

Plastic panels were replaced at 5% frequency annually, this cost was added to other maintenance costs such as water pipes substitution, plant species substitution, and pruning. In the case of the novel MLWS modules did not require replacement and other maintenance costs for living walls are applied for both systems.

4.4.4. Disposal costs

Disposal costs include the greening systems disposal (removal of plants and structures, transport to landfill, and dump taxes), and cladding (plaster) renewal where applicable. Metal panels could be reused and did not require disposal but disassembly.

4.5. Conclusions

This study investigated technical and economic gains from creatively reusing automotive prompt metal known as Offal as replacement for metal in living wall systems. Problems encountered in existing metal MLWS included higher cost during installation of components, transportation and irrigation. Two scenarios of the impacts of replacing virgin and recycled metal with reused Offal were analyzed. A life cycle analysis compared a novel modular living wall system (MLWS) to traditional living wall systems (LWS).

Applying creative reuse could reduce electricity and net primary energy consumed during conventional recycling processes. Using data from one plant in Michigan as the baseline, reusing Offal could save 167,965MJ (159.2Btu) of fuel, 159, 598 kWh of electricity and 1,637,658MJ (1,552.2 MBtu) of net primary energy.

Economic analysis showed that reusing Offal for MLWS could lead to reduction of maintenance costs as there would be no panel replacement. Disposal costs would also be eliminated as MLWS are designed for disassembly. Metal MLWS would provide aesthetics and add value to rent in existing buildings.

MLWS made from Offal costs 69% of a zinc coated steel system in Europe and 27 – 60% of current prices in San Diego. Reusing Offal could also improve the life span of MLWS and eliminate disposal costs. Future studies to show the effect of Offal reuse globally and apply the key performance indicators of the automotive industry to reporting the gains of reusing their industrial waste streams. This techno-economic analysis provides impacts of creative reuse to stakeholders and policy makers for more circularity.

5. CONCLUSIONS

The overarching goal of this dissertation was to promote circular economy (CE) through an industrial symbiosis (IS) between the automotive and building construction industries. This research investigates the impacts of reusing prompt scrap metal (Offal) through a case study approach in novel modules and a novel modular living wall system (MLWS).

The first manuscript presented in Chapter 2, explored “design for reuse” strategy. Offal was transformed into modules for modular living wall systems by Master of Architecture students. Four designs were observed in situ for the influence of their geometry on their cooling effect. Experimental studies were carried out during two seasons, winter and spring 2019. The objective was to determine the effect of design geometry on the performance of the novel modules. In addition, the unique module resource efficiency was investigated for potential annual utility.

The second manuscript investigated the thermal performance of an installed MLWS. The novel MLWS consisted of modules from a design in Manuscript 1. In this interdisciplinary study, experimental data from field observations were used to calibrate 24-hour simulations for four seasons in ENVI-met. Environmental and economic impacts were calculated using Tally a Revit plug-in and the United States Environmental Protection Agency’s Waste Reduction Model. This study developed a methodology to test the performance of the novel MLWS and its impacts.

In the third manuscript, a techno-economic analysis investigated the technical and economic impacts of reusing Offal in MLWS. Reusing Offal was compared to utilizing virgin and recycled metal. A life cycle analysis compared the novel modular living wall system (MLWS) to traditional living wall systems (LWS). Parameters included fuel consumption, electricity, net primary energy and life cycle costs. Findings provided operational data for this example of symbiosis and show the contribution of industrial symbiosis towards a more circular economy.

5.1. Discussion

Extending the principle of IS to cities promotes the integration of socio-economic and ecological systems; it also promotes circular urban metabolism where converting resources could occur with zero-waste production (La Rosa & Ramakrishna, 2021).

Figure 5.1 shows the comparative analysis and the design and integration of both perspectives into a process for designing new IS clusters of different sizes and in different contexts (Baldassarre et al., 2019).

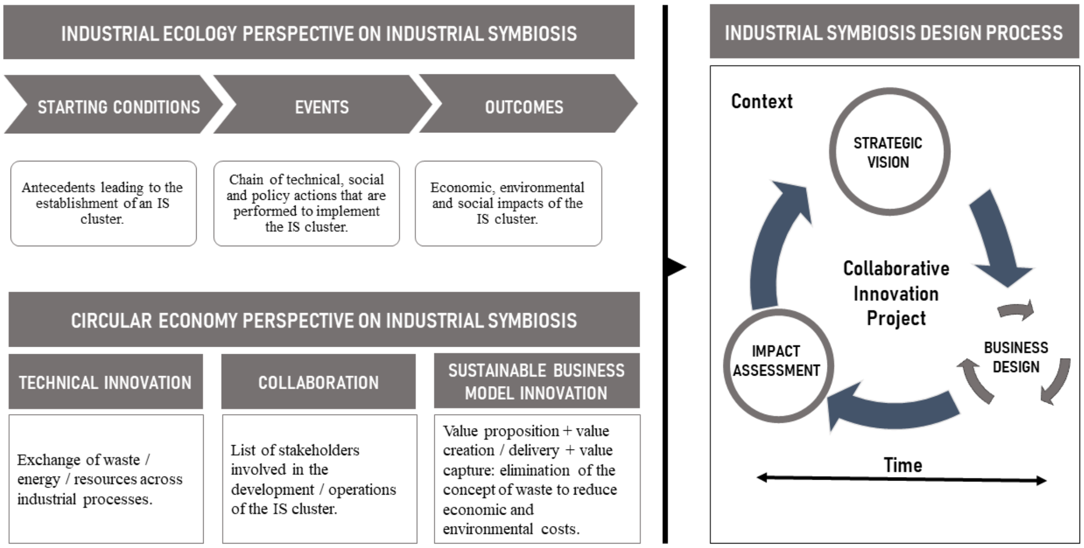


Figure 5.1: Integrating circular economy and industrial economy perspectives. Adapted from (Baldassarre et al., 2019)

In IE, IS focuses on establishing IS clusters, implementing them and determining impacts of the cluster. While the CE perspective of IS deals with exchange of waste/energy/resources across industrial processes; identifies stakeholders in the development of the IS cluster and innovates by proposing value, creating value, capturing value, eliminating the concept of waste for reduced economic and environmental costs. This study presented a material for exchange – Offal; its collaborators comprising automotive, building and construction industries; and investigated potential value showing a close looped framework for creative reuse and industrial symbiosis towards a more circular economy (Figure 5.2).

The use of IS as a strategic tool to deliver circular economy (CE) is increasing locally, regionally and nationally in Europe; although over 20,000 organizations engaged in IS, less than 0.1% of the 26 million active enterprises in Europe were known to be active in IS (Lombardi, 2017). Geographical scope of synergies seemed to be dependent upon the type of waste byproduct, transport costs and market value of secondary materials (Domenech et al., 2019).

General Motors provided the byproduct and the Resource Based Design Research Laboratory explored approaches to add value by design, hands-on fabrication at the workshop and installation of the prototype. A patent of the final product was obtained and experimental studies were carried out to investigate the performance of vegetation and materials of the modular living wall system (MLWS).

In Chapter 2, a literature review of MLWS and their components was carried out. Thereafter, design explorations resulted in many design geometries of modules. Four unique modules were selected for experimental studies. Their surface temperatures were compared to concrete and brick in similar surrounding environment. Environmental and economic impacts were evaluated comparing reuse to recycling and landfilling. Transformation of Offal showed that CE and IS when combined, could reduce energy consumption, greenhouse gas emissions, and avoid pollution.

In Chapter 3, units of modules in a living wall system were tested to determine their influence on the microclimate. In a microclimate, the human body seeks to balance itself towards a comfortable temperature in outdoor locations (Brown, 2010). Microclimates can be tweaked for good ranges to enable people adjust easily to a comfortable equilibrium. MLWS as retrofits in urban areas mitigate urban heat island effect and provide cooler temperatures during summer contributing to the attainment of thermal comfort. Results in Chapter 3 show that designing MLWS with Offal is most effective as retrofits for exterior brick surfaces. The shading effect of the MLWS reduces terrestrial energy given off from brick surfaces to the microclimate. Simulation during four seasons show that the case study MLWS at 50% vegetation cover affects the microclimate adjacent to the wall in all seasons up to 0.02º C.

Chapter 4 focuses on the potential technical savings and economic gains of the case study. A techno-economic analysis compared the novel MLWS to traditional products. Reusing materials could save up to 40% of energy required for virgin materials and costs (Stahel & MacArthur, 2019). Reusing prompt metal in MLWS could reduce cost of traditional products in Europe and San Diego between 31 - 73%.

5.2. Significance of the findings

The first manuscript determined the effect of design geometry on the thermal performance of four novel modules. In the second manuscript experimental studies which began in Chapter 2 were developed in Chapter 3 producing a methodology for investigating microclimates at living walls to determine their performance. The third manuscript in Chapter 4 investigated the technical and economic impacts of creatively reusing scrap metal as feedstock in modular living wall systems.

5.2.1. Microclimate study procedure

The steps taken to investigate the thermal performance of the modules and MLWS included, in-situ experimental studies, Table 5.1. The first stage for the modules involved the use of two equipment – FLIR E6 thermal imaging camera and Kestrel 6400 Heat Stress Tracker. The variables were surface temperatures, ambient air temperature and relative humidity measured for two full days from 7:00hrs to 22:00hrs each in winter and spring 2019. Data from the field experiment were analyzed with one-way analysis of variance and Tukey honest significant difference to determine if the geometry of modules had significant difference on the temperature of the modules.

By the second stage, the thermal performance of the novel MLWS was investigated. More equipment was added to the initial two, equipment used were FLIR E6 thermal imaging camera, Canon EOS fish eye camera, Kestrel 6400 Heat Stress Tracker, Davis leaf/soil weather station, 4 moisture and 4 temperature probes, leaf wetness sensor and Vantage PRO2 logger. The variables measured were surface temperatures of MLWS, concrete wall, shaded brick wall, bare brick wall; air layer temperature (0.1m between

MLWS and building wall at 1.2m height); ambient air temperature (1m in front of MLWS and 1.2m height), relative humidity 0.1m between MLWS and building façade and 1m in front of MLWS both at 1.2m height. Solar radiation was measured by placing the sensor on brick building surface behind the MLWS; the three surfaces (flat, left and right) of the modules and the bare brick surface all at 1.2m height.

Table 5.1: Microclimate investigation procedure

Stage	**Focus**	**Equipment**	**Parameters**	**Measurement Procedure**	**Statistical Analysis**	**Simulation**
1	Modules	FLIR E6 camera, Kestrel 6400 Heat Stress Tracker.	Surface temperatures, ambient air temperature and relative humidity.	Hourly at 7:00hrs - 22:00hrs on March 5,2021 (winter), April 26, 2021	One-way ANOVA and Tukey HSD	Tally plugin in Revit
2	Modular Living Wall System	FLIR E6 camera, Kestrel 6400 Heat Stress Tracker, TES 132 Solar Power Meter, Canon EOS fisheye camera, and Davis leaf and soil Vantage PRO2 weather station	Surface temperatures, ambient air temperature, relative humidity, solar radiation, soil moisture and temperature, and leaf temperature and wetness.	Hourly at 7:00hrs - 22:00hrs on Aug 16, 2019, Dec 13, 2019, Feb 13, 2020, Aug 10, 2020, and Feb 10, 2021 for spring, summer, fall, and winter. Once a day during summer at 16:00hrs August 2019 and 14:00hrs June, July and August 2020	-	Tally plugin in Revit and ENVI-met

The Davis instruments comprised a weather station mounted at 1.8m height on the building; four soil moisture and four temperature probes placed in modules at three different heights. One moisture probe and one temperature probe each were placed together in four different modules at heights 0.45m, 1.2m and 1.5m respectively. The leaf temperature and wetness sensor were braced on the supporting frame of the MLWS at 1.2m height from the ground.

5.2.2. Methodology to reuse prompt metal in modular living wall systems

The methodology developed to test the thermal performance of MLWS prototype was based on the novel combination of materials and equipment. After the literature review of LWS, it was clear that there was no standard method to investigate the thermal performance of LWS. This study developed and carried out a new process to determine the thermal performance of the MLWS, Figure 5.3.

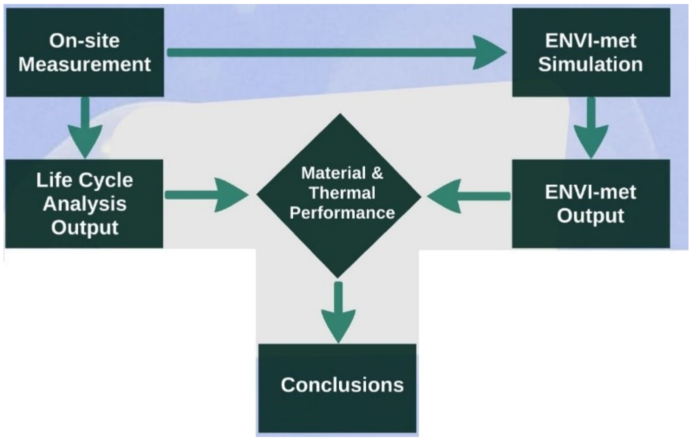


Figure 5.2: Methodology to investigate thermal performance and impacts of reusing prompt metal in living wall systems

Results revealed that the novel product with 50% vegetation, had the most effective shading effect at the shaded exterior brick walls, Figure 5.4. When parameters at the MLWS microclimate were compared to those at concrete and brick scenarios; the highest average surface temperature difference of 19° C was observed between the shaded brick and exposed brick surfaces. The concrete wall to exposed brick surface was 10.1° C and MLWS to the exposed brick surface was 9.8 ° C. The increased humidity behind the modular living wall system did not affect the aesthetics or performance of the brick surface due to ventilation in the cavity layer.

Figure 5.3: Minimum summer radiation at shaded brick wall surface.

5.2.3. Potential of reuse towards reverse logistics

Currently, reverse logistics moves goods from customers to manufacturers. Customers also have the liberty to engage in new product development. This study contributes to the field of new product development, providing automotive manufacturers an opportunity to initiate new products from wastes generated during production processes. Manufacturers act as owners/customers taking on responsibility to initiate new decisions for waste management, Figure 5.4. Waste could be converted to products, developed and tested towards commercialization.

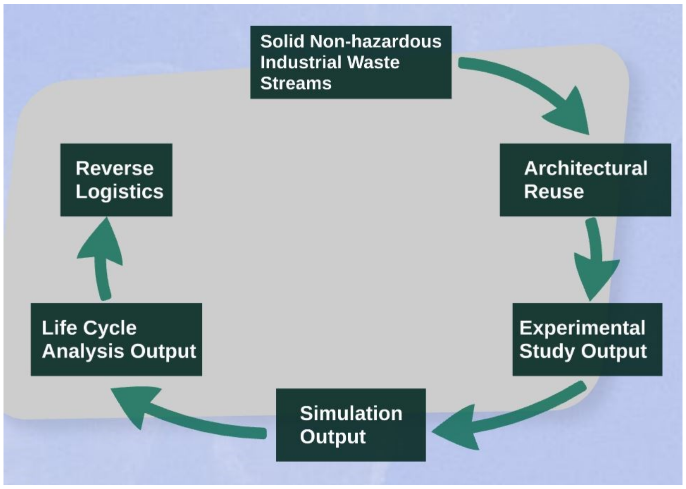


Figure 5.4: Framework for creative reuse through industrial symbiosis for circular economy

5.2.4. Implications

There are theoretical benefits and benefits to applied practice resulting from this study. Theoretical benefits include: new methods of testing a circular unit and product; new framework to promote circularity; and generalizing results towards all galvanized sheet metal waste.

In applied practice, new combination of equipment for assessing thermal performance and cooling effect of product is encouraged. Novel products and their components could be characterized; and this practice could reduce net primary energy and production costs while adding value to waste material.

5.3. Future work

A case study to activate circular economy through industrial symbiosis has been presented. Prompt scrap from the automotive industry (Offal) was used for modules in a novel modular living wall system. Future work could focus on these areas: the study of the effect of the novel MLWS on an urban scale for human thermal comfort; provide typologies to contribute to the design of microclimates with living wall systems; and creating methodologies and frameworks for other solid non-hazardous industrial waste streams.

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APPENDIX A

STATISTICAL ANALYSIS, ONE WAY ANOVA AND TUKEY HSD

(MANUSCRIPT 1)

```
# analyzing data for hourly average temperatures
rm(list = ls())
big_list <- list(list(), list(), list(), list())
index <- seq(700, 2200, 100)
index <- index[-c(9, 10)]

for (j in 1:length(index)) {
  a <- read.csv(paste0("cw", "_", index[j], ".csv"), header = T)
  x <- as.vector(as.matrix(a))
  big_list[[1]][[j]] <- x

  a <- read.csv(paste0("md", "_", index[j], ".csv"), header = T)
  x <- as.vector(as.matrix(a))
  big_list[[2]][[j]] <- x

  a <- read.csv(paste0("mlw", "_", index[j], ".csv"), header = T)
  x <- as.vector(as.matrix(a))
  big_list[[3]][[j]] <- x

  a <- read.csv(paste0("sbw", "_", index[j], ".csv"), header = T)
  x <- as.vector(as.matrix(a))
  big_list[[4]][[j]] <- x
}



box1 <- box2 <- box3 <- box4 <- matrix(NA, nrow = 180, ncol = 14)
recording_times <- c("700","800","900","1000","1100","1200","1300","1400",
                     "1700","1800","1900","2000","2100","2200")
colnames(box1) <- colnames(box2) <- colnames(box3) <- recording_times
colnames(box4) <- recording_times

temp1 <- temp2 <- temp3 <- temp4 <- temp5 <- matrix(NA, nrow = 14, ncol = 4)
colnames(temp1) <- colnames(temp2) <- colnames(temp3) <- c("Mean", "SD",
"Min", "Max")
colnames(temp4) <- colnames(temp5) <- c("Mean", "SD", "Min", "Max")

for (k in 1:14) {
  x <- sample(big_list[[1]][[k]], 180, replace = F)
  box1[,k] <- x
  temp1[k,] <- c(mean(big_list[[1]][[k]]), sd(big_list[[1]][[k]]),
                 min(big_list[[1]][[k]]), max(big_list[[1]][[k]]))

  x <- sample(big_list[[2]][[k]], 180, replace = F)
  box2[,k] <- x
```

```
  temp2[k,] <- c(mean(big_list[[2]][[k]]), sd(big_list[[2]][[k]]),
                 min(big_list[[2]][[k]]), max(big_list[[2]][[k]]))

  x <- sample(big_list[[3]][[k]], 180, replace = F)
  box3[,k] <- x
  temp3[k,] <- c(mean(big_list[[3]][[k]]), sd(big_list[[3]][[k]]),
                 min(big_list[[3]][[k]]), max(big_list[[3]][[k]]))

  x <- sample(big_list[[4]][[k]], 180, replace = F)
  box4[,k] <- x
  temp4[k,] <- c(mean(big_list[[4]][[k]]), sd(big_list[[4]][[k]]),
                 min(big_list[[4]][[k]]), max(big_list[[4]][[k]]))
}

temps <- list(temp1, temp2, temp3, temp4)
write.csv(temps[[1]], paste0("temperature_cw", ".csv"), row.names = F)
write.csv(temps[[2]], paste0("temperature_md", ".csv"), row.names = F)
write.csv(temps[[3]], paste0("temperature_mlw", ".csv"), row.names = F)
write.csv(temps[[4]], paste0("temperature_sbw", ".csv"), row.names = F)

# analyzing data for significant differences in hourly average temperatures
with one-way analysis of variance (ANOVA) and Tukey Honest Significant
Difference (HSD)

rm(list = ls())
big_list <- list(list(), list(), list(), list(), list())
index <- seq(700, 2200, 100)
for (b in 1:5) {
  for (j in 1:length(index)) {
    a <- read.csv(paste0("Box", b, "_", index[j], ".csv"), header = T)
    x <- as.vector(as.matrix(a))
    big_list[[b]][[j]] <- x
  }
}

box1 <- box2 <- box3 <- box4 <- box5 <- matrix(NA, nrow = 180, ncol = 16)
recording_times <- c("700","800","900","1000","1100","1200","1300","1400",
                     "1500","1600","1700","1800","1900","2000","2100","2200")
colnames(box1) <- colnames(box2) <- colnames(box3) <- recording_times
colnames(box4) <- colnames(box5) <- recording_times

for (k in 1:16) {
  x <- sample(big_list[[1]][[k]], 180, replace = F)
  box1[,k] <- x
  x <- sample(big_list[[2]][[k]], 180, replace = F)
  box2[,k] <- x
  x <- sample(big_list[[3]][[k]], 180, replace = F)
  box3[,k] <- x
  x <- sample(big_list[[4]][[k]], 180, replace = F)
  box4[,k] <- x
  x <- sample(big_list[[5]][[k]], 180, replace = F)
  box5[,k] <- x
```

```
}
combined_groups1 <- data.frame(cbind(box1[,1],box2[,1],
                                    box3[,1],box4[,1],box5[,1]))
combined_groups1
summary(combined_groups1)

stacked_groups1 <- stack(combined_groups1)
stacked_groups1

anova_results1 <- aov(values ~ ind, data = stacked_groups1)
summary(anova_results1)
tukey1 <-TukeyHSD(anova_results1, ordered = TRUE)
tukey1

combined_groups2 <- data.frame(cbind(box1[,2],box2[,2],
                                     box3[,2],box4[,2],box5[,2]))
combined_groups2
summary(combined_groups2)

stacked_groups2 <- stack(combined_groups2)
stacked_groups2

anova_results2 <- aov(values ~ ind, data = stacked_groups2)
summary(anova_results2)
tukey2 <-TukeyHSD(anova_results2, ordered = TRUE)
tukey2

combined_groups3 <- data.frame(cbind(box1[,3],box2[,3],
                                     box3[,3],box4[,3],box5[,3]))
combined_groups3
summary(combined_groups3)

stacked_groups3 <- stack(combined_groups3)
stacked_groups3

anova_results3 <- aov(values ~ ind, data = stacked_groups3)
summary(anova_results3)
tukey3 <-TukeyHSD(anova_results3, ordered = TRUE)
tukey3

combined_groups4 <- data.frame(cbind(box1[,4],box2[,4],
                                     box3[,4],box4[,4],box5[,4]))
combined_groups4
summary(combined_groups4)

stacked_groups4 <- stack(combined_groups4)
stacked_groups4

anova_results4 <- aov(values ~ ind, data = stacked_groups4)
summary(anova_results4)
tukey4 <-TukeyHSD(anova_results4, ordered = TRUE)
tukey4
```

```
combined_groups5 <- data.frame(cbind(box1[,5],box2[,5],
                                     box3[,5],box4[,5],box5[,5]))
combined_groups5
summary(combined_groups5)

stacked_groups5 <- stack(combined_groups5)
stacked_groups5

anova_results5 <- aov(values ~ ind, data = stacked_groups5)
summary(anova_results5)
tukey5 <-TukeyHSD(anova_results5, ordered = TRUE)
tukey5

combined_groups6 <- data.frame(cbind(box1[,6],box2[,6],
                                     box3[,6],box4[,6],box5[,6]))
combined_groups6
summary(combined_groups6)

stacked_groups6 <- stack(combined_groups6)
stacked_groups6

anova_results6 <- aov(values ~ ind, data = stacked_groups6)
summary(anova_results6)
tukey6 <-TukeyHSD(anova_results6, ordered = TRUE)
tukey6

combined_groups7 <- data.frame(cbind(box1[,7],box2[,7],
                                     box3[,7],box4[,7],box5[,7]))
combined_groups7
summary(combined_groups7)

stacked_groups7 <- stack(combined_groups7)
stacked_groups7

anova_results7 <- aov(values ~ ind, data = stacked_groups7)
summary(anova_results7)
tukey7 <-TukeyHSD(anova_results7, ordered = TRUE)
tukey7

combined_groups8 <- data.frame(cbind(box1[,8],box2[,8],
                                     box3[,8],box4[,8],box5[,8]))
combined_groups8
summary(combined_groups8)

stacked_groups8 <- stack(combined_groups8)
stacked_groups8

anova_results8 <- aov(values ~ ind, data = stacked_groups8)
summary(anova_results8)
tukey8 <-TukeyHSD(anova_results8, ordered = TRUE)
tukey8
```

```
combined_groups9 <- data.frame(cbind(box1[,9],box2[,9],
                                     box3[,9],box4[,9],box5[,9]))
combined_groups9
summary(combined_groups9)

stacked_groups9 <- stack(combined_groups9)
stacked_groups9

anova_results9 <- aov(values ~ ind, data = stacked_groups9)
summary(anova_results9)
tukey9 <-TukeyHSD(anova_results9, ordered = TRUE)
tukey9

combined_groups10 <- data.frame(cbind(box1[,10],box2[,10],
                                     box3[,10],box4[,10],box5[,10]))
combined_groups10
summary(combined_groups10)

stacked_groups10 <- stack(combined_groups10)
stacked_groups10

anova_results10 <- aov(values ~ ind, data = stacked_groups10)
summary(anova_results10)
tukey10 <-TukeyHSD(anova_results10, ordered = TRUE)
tukey10

combined_groups11 <- data.frame(cbind(box1[,11],box2[,11],
                                      box3[,11],box4[,11],box5[,11]))
combined_groups11
summary(combined_groups11)

stacked_groups11 <- stack(combined_groups11)
stacked_groups11

anova_results11 <- aov(values ~ ind, data = stacked_groups11)
summary(anova_results11)
tukey11 <-TukeyHSD(anova_results11, ordered = TRUE)
tukey11

combined_groups12 <- data.frame(cbind(box1[,12],box2[,12],
                                      box3[,12],box4[,12],box5[,12]))
combined_groups12
summary(combined_groups12)

stacked_groups12 <- stack(combined_groups12)
stacked_groups12

anova_results12 <- aov(values ~ ind, data = stacked_groups12)
summary(anova_results12)
tukey12 <-TukeyHSD(anova_results12, ordered = TRUE)
tukey12
```

```
combined_groups13 <- data.frame(cbind(box1[,13],box2[,13],
                                      box3[,13],box4[,13],box5[,13]))
combined_groups13
summary(combined_groups13)

stacked_groups13 <- stack(combined_groups13)
stacked_groups13

anova_results13 <- aov(values ~ ind, data = stacked_groups13)
summary(anova_results13)
tukey13 <-TukeyHSD(anova_results13, ordered = TRUE)
tukey13

combined_groups14 <- data.frame(cbind(box1[,14],box2[,14],
                                      box3[,14],box4[,14],box5[,14]))
combined_groups14
summary(combined_groups14)

stacked_groups14 <- stack(combined_groups14)
stacked_groups14

anova_results14 <- aov(values ~ ind, data = stacked_groups14)
summary(anova_results14)
tukey14 <-TukeyHSD(anova_results14, ordered = TRUE)
tukey14

combined_groups15 <- data.frame(cbind(box1[,15],box2[,15],
                                      box3[,15],box4[,15],box5[,15]))
combined_groups15
summary(combined_groups15)

stacked_groups15 <- stack(combined_groups15)
stacked_groups15

anova_results15 <- aov(values ~ ind, data = stacked_groups15)
summary(anova_results15)
tukey15 <-TukeyHSD(anova_results15, ordered = TRUE)
tukey15

combined_groups16 <- data.frame(cbind(box1[,16],box2[,16],
                                      box3[,16],box4[,16],box5[,16]))
combined_groups16
summary(combined_groups16)

stacked_groups16 <- stack(combined_groups16)
stacked_groups16

anova_results16 <- aov(values ~ ind, data = stacked_groups16)
summary(anova_results16)
tukey16 <-TukeyHSD(anova_results16, ordered = TRUE)
tukey16
```

APPENDIX B

RESULTS OF TUKEY HSD FOR SURFACE TEMPERATURES, MARCH, 2019 (MANUSCRIPT 1).

700

	1	2	3	4	5
1					
2					
3					
4					
5					

800

	1	2	3	4	5
1					
2					
3					
4					
5					

900

	1	2	3	4	5
1					
2					
3					
4					
5					

1000

	1	2	3	4	5
1					
2					
3				▨	
4					
5					

1100

	1	2	3	4	5
1					
2			▨		
3					
4					
5					

1200

	1	2	3	4	5
1					
2					
3					
4					
5					

1300

	1	2	3	4	5
1				▨	
2					
3					
4					
5					

1400

	1	2	3	4	5
1					
2					
3					
4	▨				
5					

1500

	1	2	3	4	5
1					
2					
3					
4					
5					

1600

	1	2	3	4	5
1					
2					
3					
4					
5					

1700

	1	2	3	4	5
1					
2					
3					
4					
5					

1800

	1	2	3	4	5
1				▨	
2					
3					
4					
5					

1900

	1	2	3	4	5
1					
2					
3					
4					
5					

2000

	1	2	3	4	5
1					
2					
3					
4					
5					

2100

	1	2	3	4	5
1					
2					
3					
4					
5					

2200

	1	2	3	4	5
1					
2				▨	
3					
4					
5					

Shaded boxes depict designs with no hourly significant difference in their surface temperatures. 1- Design #1, 2 – Design #2, 3 – Design #3, 4 – Design #4 and 5 – Brick wall.

APPENDIX C

RESULTS OF TUKEY HSD FOR SURFACE TEMPERATURES, APRIL, 2019

(MANUSCRIPT 1)

700

	1	2	3	4	5
1					
2					
3	▨			▨	
4					
5					

800

	1	2	3	4	5
1					
2					
3				▨	
4					
5	▨				

900

	1	2	3	4	5
1					
2					
3				▨	
4					
5					

1000

	1	2	3	4	5
1					▨
2					
3				▨	
4					▨
5					

1100

	1	2	3	4	5
1			▨	▨	▨
2					
3				▨	▨
4					▨
5					

1200

	1	2	3	4	5
1					
2					
3					
4	▨				
5					

1300

	1	2	3	4	5
1				▨	
2					
3					
4					
5					

1400

	1	2	3	4	5
1					
2					
3					
4					
5		▨			

1500

	1	2	3	4	5
1				▨	
2					
3					
4					▨
5					

1600

	1	2	3	4	5
1				▨	
2					
3					
4					▨
5					

1700

	1	2	3	4	5
1				▨	
2					
3					
4					
5	▨			▨	

1800

	1	2	3	4	5
1				▨	▨
2					
3					
4					
5				▨	

1900

	1	2	3	4	5
1				▨	
2					
3					
4					
5	▨			▨	

2000

	1	2	3	4	5
1				▨	
2					
3					
4					
5	▨			▨	

2100

	1	2	3	4	5
1				▨	
2					
3					▨
4					
5					

2200

	1	2	3	4	5
1				▨	
2					
3					▨
4					
5					

Shaded boxes depict designs with no hourly significant difference in their surface temperatures. 1- Design #1, 2 – Design #2, 3 – Design #3, 4 – Design #4 and 5 – Brick wall.

APPENDIX D

DATA FOR EXPERIMENT 1 (MANUSCRIPT 2)

Time	**Concrete Wall (°C)**	**Modular living wall system (°C)**
7:00	20.61	17.40
8:00	19.72	17.08
9:00	21.38	21.38
10:00	24.29	29.33
11:00	29.80	33.22
12:00	32.08	34.56
13:00	33.39	34.73
14:00	33.35	34.48
15:00	31.18	31.30
16:00	23.72	22.25
17:00	24.06	22.36
18:00	21.56	19.88
19:00	26.88	25.52
20:00	26.85	25.35
21:00	23.62	21.27
22:00	21.90	19.47

APPENDIX E

DATA FOR EXPERIMENT 2 (MANUSCRIPT 2)

Time	**Concrete wall (°C)**	**Modular living wall (°C)**	**Shaded brick wall (°C)**
7:00	32.78	29.97	31.29
8:00	34.39	30.94	29.37
9:00	36.14	32.29	30.71
10:00	40.06	39.24	31.44
11:00	39.78	42.57	35.01
12:00	42.04	39.13	33.38
13:00	40.20	41.19	35.79
14:00	43.28	42.15	34.89
15:00	43.26	42.36	36.18
16:00	41.02	39.78	36.03
17:00	41.56	41.24	37.01
18:00	37.74	37.52	34.99
19:00	39.06	37.55	36.02
20:00	39.06	38.13	37.11
21:00	38.34	36.59	35.29
22:00	36.84	33.91	33.98

APPENDIX F

DATA FOR EXPERIMENT 3 (MANUSCRIPT 2)

Days	**Concrete wall (°C)**	**Modular living wall (°C)**	**Shaded brick wall (°C)**
1	38.60	37.66	34.62
2	35.66	34.72	31.81
3	40.66	40.69	36.38
4	42.02	41.97	36.38
5	41.12	40.91	36.65
6	41.17	39.87	36.29
7	40.92	41.23	35.97
8	40.66	40.69	36.65
9	42.02	41.97	36.38
10	41.12	40.91	36.38
11	41.17	39.87	36.29
12	40.92	41.23	35.97
13	41.02	39.78	36.01
14	41.68	41.04	35.99
15	40.94	40.60	35.92
16	40.85	41.47	36.79
17	39.74	39.60	34.24
18	40.11	38.56	35.22
19	40.83	40.02	35.85
20	39.17	37.27	34.77
21	40.50	40.44	36.59
22	38.37	37.04	34.54
23	38.33	36.70	32.74
24	39.85	39.35	35.35
25	40.17	39.77	35.24
26	37.97	33.82	33.42

APPENDIX G

DATA FOR EXPERIMENT 4 (MANUSCRIPT 2)

Time	**Concrete wall (°C)**	**Modular living wall (°C)**	**Shaded brick wall (°C)**
7:00	13.87	13.26	14.35
8:00	8.10	12.74	13.09
9:00	8.13	13.86	13.89
10:00	9.96	16.03	14.14
11:00	10.74	20.99	14.18
12:00	12.77	29.43	18.43
13:00	12.80	29.96	19.74
14:00	11.97	29.76	20.72
17:00	13.12	19.69	18.06
18:00	11.44	17.71	18.64
19:00	16.86	16.29	16.83
20:00	16.94	15.09	17.07
21:00	17.80	16.90	16.77
22:00	16.74	14.16	15.77

APPENDIX H

DATA FOR EXPERIMENT 5 (MANUSCRIPT 2)

Time	**Concrete wall (°C)**	**Modular living wall (°C)**	**Shaded brick wall (°C)**
7:00	7.98	5.00	6.88
8:00	8.10	4.60	6.51
9:00	8.13	5.35	7.82
10:00	9.96	8.22	8.01
11:00	10.74	9.26	8.35
12:00	12.77	12.83	8.94
13:00	12.80	11.75	9.55
14:00	11.97	10.50	10.09
17:00	13.12	12.64	10.93
18:00	11.44	8.97	9.72
19:00	13.56	10.03	9.87
20:00	11.58	7.58	8.16
21:00	10.28	7.40	7.87
22:00	9.68	6.55	8.35

APPENDIX I

DATA FOR EXPERIMENT 6 (MANUSCRIPT 2)

Time	**BBW**	**CW**	**MLWS**	**SBW**	**ST1**	**ST2**	**ST3**	**ST4**	**LT1**	**AA**	**AL**
7:00	29.27	30.08	27.47	29.09	25.6	25.6	25.6	25.6	25.6	26.5	26.5
8:00	29.20	29.61	28.24	29.77	25.6	25.6	25.6	25.6	25.6	27.8	27.5
12:30	36.23	42.90	38.90	33.24	37.8	36.7	35.6	37.2	37.8	35.1	36.4
13:30	40.46	42.55	41.31	33.72	38.3	37.2	36.7	38.3	38.3	46.1	44
14:00	42.33	42.98	41.53	34.63	38.3	37.2	37.2	38.9	38.3	43.9	40.1
15:00	39.47	40.87	39.76	34.97	37.2	36.1	36.7	37.2	37.2	37.1	37.1
15:30	40.43	40.47	40.50	35.59	36.7	35.6	36.1	36.7	36.7	37.1	36.9
18:30	39.29	38.86	37.41	36.63	33.9	33.3	33.9	33.9	33.9	34.5	34.7
19:00	37.53	37.86	36.14	35.11	33.3	32.8	33.3	33.3	33.3	34.1	34.2
19:30	37.39	37.17	36.70	36.28	32.8	32.8	32.8	32.8	32.8	33.7	33.8
20:30	35.80	37.13	34.74	35.28	32.2	31.7	32.2	31.7	32.2	32.5	32.6
21:00	35.94	36.89	34.77	35.23	31.7	31.1	31.7	31.7	31.7	32.2	32.8

data collection in experiment- concrete wall (CW), shaded brick wall (SBW), bare brick wall (BBW), air layer temperature (ALT), ambient air temperature (AAT), soil temperature (ST), leaf temperature (LT)

APPENDIX J

DATA FOR EXPERIMENT 7 (MANUSCRIPT 2)

Day	CW	MLWS	SBW	ST1	ST2	ST3	ST4	LT1	AAT
1	31.4	31.7	27.5	26.1	26.1	26.1	26.7	26.1	34.5
2	31.8	33.6	26.9	25.6	25	25	25.6	25.6	32.6
3	28.5	28.7	27.1	33.3	32.8	32.8	33.3	33.3	35.5
4	35.6	36.9	31.1	30.6	30.6	30.0	30.6	30.6	33.7
5	34.5	33.9	30.5	33.3	32.8	32.2	32.8	33.3	33.0
6	32.8	33.2	30.1	36.1	35.0	34.4	35.6	36.1	33.0
7	36.5	35.9	31.3	36.7	35.0	34.4	35.6	36.7	32.0
8	37.6	38.3	32.6	37.2	36.1	35.6	36.7	37.2	35.1
9	39.2	38.9	33.3	31.1	31.1	30.6	31.1	31.1	34.2
10	40.1	39.7	32.9	34.4	33.9	32.8	33.9	34.4	28.2
11	34.6	34.0	30.9	32.2	31.7	31.1	31.7	32.2	27.3
12	37.7	38.0	32.3	35.0	33.9	33.9	34.4	35.0	28.8
13	37.3	36.7	31.9	37.2	36.1	35.0	36.1	37.2	26.0
14	39.2	39.1	34.0	38.3	36.7	36.7	37.2	38.3	30.1
15	39.4	40.3	32.9	37.2	36.1	35.6	36.7	37.2	29.2
16	41.4	39.4	33.4	39.4	37.8	37.2	38.3	39.4	30.4
17	41.3	40.9	35.6	38.3	37.2	36.1	37.8	38.3	32.2
18	42.2	40.7	33.8	33.9	33.3	32.2	33.3	33.9	32.1
19	40.6	39.0	33.3	38.3	36.7	36.1	37.2	38.3	30.1
20	35.5	35.5	32.1	38.3	37.2	36.7	37.2	38.3	35.8
21	39.3	39.9	33.4	36.7	35.6	35.0	36.1	36.7	30.1
22	40.3	38.9	34.3	37.2	36.1	36.1	36.7	37.2	32.9
23	37.4	37.5	32.4	37.8	36.7	36.1	36.7	37.8	32.5
24	40.3	39.5	33.2	32.8	32.2	31.7	32.8	32.8	33.7
25	40	39.4	33.1	31.1	31.7	31.7	31.1	31.1	33.4
26	36.2	33.9	30.9	37.8	36.1	35.6	36.7	37.8	30.9
27	36.4	35.9	30.2	36.7	35.6	35.6	36.7	36.7	34.9
28	37.7	38.4	30.9	36.7	35.6	35.0	36.7	36.7	29.7
29	38.6	37.1	30.9	36.7	35.6	35.0	36.7	36.7	32.9
30	38.5	38.2	31.7	35.0	35.0	35.0	35.0	35.0	34.9
31	38.7	38.2	32.0	38.3	37.2	37.2	38.3	38.3	32.3
32	41.5	37.4	33.8	39.4	37.8	37.2	39.4	39.4	31.1
33	40.2	39.1	33.1	38.9	37.8	37.8	38.9	38.9	31.2
34	41.8	41.2	33.7	37.8	36.7	37.2	38.3	37.8	32.8

Data for experiment 7 continued

Day	CW	MLWS	SBW	ST1	ST2	ST3	ST4	LT1	AAT
35	40.8	40.6	34.6	38.3	37.2	37.2	38.3	38.3	32.2
36	41.8	41.0	34.6	38.9	37.8	37.8	38.9	38.9	31.1
37	41.7	40.2	35.0	38.9	37.8	37.8	39.4	38.9	33.4
38	41.7	41.6	34.3	38.3	37.2	37.2	38.9	38.3	29.1
39	42.0	39.7	34.9	38.3	37.2	36.7	38.9	38.3	32.0
40	42.9	41.6	34.6	39.4	37.8	37.8	40.0	39.4	33.1

Data collection for experiment- concrete wall (CW), shaded brick wall (SBW), bare brick wall (BBW), air layer temperature (ALT), ambient air temperature (AAT), soil temperature (ST), leaf temperature (LT)