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• Research Question

What is the possible **workflow** for architects and architectural engineers to incorporate digital simulation-based energy performance analysis in the design of living-wall integrated facades?

The study focuses on “living-walls,” which are a specific type of green walls where the plant, substrate and structural support are directly integrated with the building wall.

Example of Living wall, Paris’s Musée du Quai Branly
Image: www.greenroofs.com
• **Background**

Lack of Simulation Tool for Nature Based Design such as Green Walls

Experimental or Numerical Evaluation Methods are Not Suitable for Design Purpose

Findings From Scientific Studies are Rarely Combined with Digital Design Platforms

• Due to complex biological properties of green walls, there is **lack of established simulation tool** for quantitative analysis of design.

• Most studies on thermal benefits are **experimental or mathematical model-based** which are not suitable for architects and designers.

• Scientific studies’ findings are **rarely combined with digital design platforms such as BIM or 3D modeling** to test context specific building case.
• **Outcome**

Simulation | Previous Research Findings | Building Design

Research Findings + Design + Simulation | Performance Analysis Workflow for Architects
• Objective

• Within the limitations of the current simulation tools, this study adopts the ‘Green-roof’ module of the widely used simulation engine Energy-Plus based on previous studies as this plug-in includes plant properties.

• Then the impact of variable changes in a living wall such as plant leaf area index, substrates, moisture and façade design aspects such as ratio, placement, and orientation of the living wall in a design case is simulated to test context specific implications.
• Research Method

**STEP 1**
Identify critical design factors of living wall that impact energy performance
(a) Case Studies (b)Literature Review

**STEP 2**
Analyze and Adapt simulation tool for living wall performance evaluation (BEPS)

**STEP 3**
Evaluating energy performance of living wall integrated façade design variations using BIM and BEPS
Step 1(a) : Case Study Analysis (Understanding Empirical Knowledge Based Design Strategies)

Observations Based on Case Studies

✓ Orientation, placement, coverage decided at an early phase based on aesthetics and intuitive decisions.
✓ Availability and quality of light influence plant choice.
✓ Stress caused by wind, shadow of draught patch can be avoided if identified and planned ahead.

Critical Stress Factor (can be assessed by simulation)

✓ Variation in Solar Exposure
✓ Shadow Stressed Area
✓ Wind Stressed Area
Step 1 (b) : Review of Critical Design Factors Influencing Energy Performance Evaluation

- **Orientation**
- **Covering Percentage**
  - Orientation
  - Covering Percentage

- **Leaf Area Index**
- **Leaf Reflectivity**
- **Substrate Thickness**
- **Substrate Thermal Properties**

**Step 1 : Review of Critical Design Factor**

- Orientation
  - Covering Percentage

**Substrate Thickness**

- The moisture contents are not manipulated in this study as irrigation is related to many other factors and the minimum fixed input value is suggested.
- Material of the wall behind living wall impact energy saving, so that is also a variable in case of energy consumption analysis.
- Substrate properties are also dependent on detail system design, so not varied in this workflow.
### Step 2: Simulation Tool Used: Green Roof Module of Energy Plus

#### Vegetation Layer

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Value / Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of plants</td>
<td>Expected height of chosen plant type</td>
<td>The range 0.01 &lt; height &lt; 1.0 m. Default is .2 m</td>
</tr>
<tr>
<td>Leaf area index</td>
<td>Projected leaf area per unit of soil</td>
<td>Range of 0.001 &lt; LAI &lt; 5.0 (dimensionless fraction), Default is 1.0</td>
</tr>
<tr>
<td>Leaf reflectivity</td>
<td>The fraction of incident solar radiation reflected by individual leaf surfaces</td>
<td>The values for this field must be between 0.05 and 0.5. The default is 0.22. Typical values are 0.16 to 0.25.</td>
</tr>
<tr>
<td>Leaf emissivity</td>
<td>the ratio of thermal radiation emitted from leaf surfaces to that emitted by an ideal black body at the same temperature</td>
<td>Values for this field must be between 0.5 and 1.0 (with 1.0 representing “black body” conditions). The default is .05.</td>
</tr>
<tr>
<td>Minimum Stomatal Resistance</td>
<td>Minimum stomatal resistance means the plants’ resistance to moisture transport</td>
<td>It has units of s/m. The values for this field must be in the range of 0.0 to 300.0. The default is 180.</td>
</tr>
</tbody>
</table>

#### Substrate Variables

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Value / Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of the soil layer</td>
<td>A user assigns a unique reference name of the soil layer for a particular green roof.</td>
<td>Unique name for created default or customized eco-roof layer</td>
</tr>
<tr>
<td>Roughness</td>
<td>This parameter influences the exterior convection co-efficient and refers to the relative roughness of a specific material layer</td>
<td>This field requires a keyword input with options of “VeryRough”, “Rough”, “MediumRough”, “Smooth”, and “VerySmooth”. Default is MediumRough.</td>
</tr>
<tr>
<td>Thickness</td>
<td>Material layer thickness is in the direction that is perpendicular to the main path of heat conduction.</td>
<td>A positive value is required between 0.05m - 0.7m. The common depths of 0.10 m (4 in) to 0.15m (6 in) are seen for green roof and the default value is 0.10m.</td>
</tr>
<tr>
<td>The conductivity of Dry Soil</td>
<td>The thermal conductivity of the material layer (dry growing media) in units W/(mK)</td>
<td>A positive value is required. Typical soil values are between</td>
</tr>
<tr>
<td>Density</td>
<td>The density of the material layer (dry growing media) in units of kg/m³</td>
<td>A positive value is required between 300 – 2000. Typical soils range from 400 to 1000 (dry to wet). The default value is 1100.</td>
</tr>
<tr>
<td>Specific heat</td>
<td>The specific heat of the material layer (dry growing media) in units of J/(kg·K)</td>
<td>A positive value is required.</td>
</tr>
<tr>
<td>Absorptance: thermal</td>
<td>The fraction of incident long wavelength radiation that is absorbed by the growing media.</td>
<td>Values for this field must be between 0.0 and 1.0 (with 1.0 representing “black body” conditions). Typical values are from .9 to .99. The default value for this field is 0.9.</td>
</tr>
<tr>
<td>Absorptance: solar</td>
<td>The fraction of incident solar radiation that is absorbed by the (dry) growing media.</td>
<td>The values for this field must be between 0.0 and 1.0. Typical values are from .01 – 0.1.</td>
</tr>
</tbody>
</table>

#### Moisture Content

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Value / Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum volumetric moisture (saturation)</td>
<td>The maximum volumetric moisture content of the soil layer depends on the properties of the soil and in particular the porosity.</td>
<td>Value is typically less than 5. Range is 0.1 - 0.5, default value 0.3.</td>
</tr>
<tr>
<td>Minimum volumetric moisture (Residual)</td>
<td>User input of the residual moisture content of the soil layer. It is the minimum possible volumetric moisture content value.</td>
<td>Value range .01 – 0.1, default is .01.</td>
</tr>
<tr>
<td>Initial Volumetric Moisture</td>
<td>User input of the initial moisture content of the soil layer at the start of the simulation. The moisture content will be updated during the simulation based on surface evaporation, irrigation, and precipitation.</td>
<td>Range 0.05 - 0.5 with the default being 0.1.</td>
</tr>
</tbody>
</table>
• Step 2 : Simulation Tool : Green Roof Module of Energy Plus

• Limitations

- The study adopts methods used by previous studies by simplified data input with the limitation of the tools.
- Improvement of the accuracy of the adopted simulation tool is beyond the scope of this research.
Step 3: Evaluating energy performance of living wall integrated façade design variations using BIM (Revit/Rhino) and BEPS (Energy Plus + Design Builder)

Living wall parameter Analysis on test cell

Performance on Various façade orientation

Performance of various coverage pattern & percentage
Step 1: Review of Critical Design Factor

Step 2: Adapting Simulation Tool

Step 3: Energy Performance Evaluation

Step 4: Evaluating energy performance of living wall integrated façade design variations using BIM (Revit/Rhino) and BEPS (Energy Plus + Design Builder)

Testing LW parameters in various orientation

Testing impact of LW in multi-storied and multi-zone buildings

Testing change of impact with surrounding buildings

Testing impact of model with different climate and LW parameters

Testing impact of various scripted parametric pattern
• Proposed Workflow

Step 1

Building Mass in Site Context

- identify building type
- identify tentative occupancy & internal load
- load local climate data
• Proposed Workflow

Step 2

Simulate Impact of Living Wall in Various Orientation

- test both summer and winter condition
- which orientation(s) reduce energy load?
- which orientation(s) add energy burden?
- if it is energy burden, can that be reduced by changing other parameters?
- In preferred orientation what coverage percentage gives beneficial results?
- If applied partially in that facade on a specific thermal subzone, does that reduce energy load?
Proposed Workflow

Step 4

Simulate Impact of Changing Plant Parameters

- What is the desired leaf area index?
- What is the impact of changing height, reflectivity, emissivity?
- In case of unfavourable orientation, does changing plant parameter help?
• Proposed Workflow

Step 5

Identify Possible Causes of Stress

- Variartion in solar exposure?
- Shadow stressed area?
- Wind stressed area?
• Proposed Workflow Testing for Design Support

Building Mass in Site Context
- Identify building type
- Identify tentative occupancy & internal load
- Load local climate data

Simulate Impact of Living Wall in Various Orientation
- Test both summer and winter condition
  - Which orientation(s) reduce energy load?
  - Which orientation(s) add energy burden?
  - If it is energy burden, can that be reduced by changing other parameters?

Simulate Impact of Living Wall in Various Coverage Percentage
- In preferred orientation what coverage percentage gives beneficial results?
  - If applied partially in that facade on a specific thermal subzone, does that reduce energy load?

Simulate Impact of Changing Plant Parameters
- What is the desired leaf area index?
- What is the impact of changing height, reflectivity, emissivity?
- In case of unfavourable orientation, does changing plant parameter help?

Identify Possible Causes of Stress
- Variation in solar exposure?
  - Shadow stressed area?
  - Wind stressed area?
• **Outcome**
  - Observations on how various design parameters influence the energy performance of green living-wall integrated façade.
  - A workflow for integrating digital simulation in the early design phase for energy performance analysis of design variations.

• **Future Work**
  - The workflow can be updated through future research with the advent of further developed dedicated simulation tools for nature-based design.


• References


