Intelligent Building Envelopes Energy Evaluation: An Integration of Double-Skin Facades with Earth-Tubes

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Abstract

Double-Skin Facades (DSFs) are presumed as high-performance systems that embrace ecological solutions, from environmental and social standpoints. Yet, a DSF’s goal to minimize buildings’ energy use in different climatic conditions is controversial, presenting it occasionally as not the most economically viable solution. Through a simulation method, this paper studied ways to optimize the Load Intensity (LI) of buildings with a DSF via an earth-tube system integration. Located in three common U.S. climatic conditions, sixteen proposed systems were examined using TRNSYS and CONTAM softwares. Next, results coupled with the most cost-effective system are discussed indicating that the assimilation of earth-tubes into a DSF system always increases the system’s energy performance with no overheating issue if optimum DSF depth is envisioned. Finally, the impact of climate, DSF depth, shading and ventilation strategies, and earth-tubes integration on LI concluded the research.

Key Innovations

- An ecological solution addressing social, environmental, and economic dimensions
- A high-performance envelope system providing aesthetics along with thermal, visual, acoustical, physical, and psychological comfort

Practical Implications

Variable roles of climate, ventilation and shading strategies, and schedule associated with building type should be carefully examined in combination together. Be mindful that an early proposed design solution can still perform different from what had been known or read in the literature, underscoring the significance of software-driven “evaluation” throughout all design phases.

Introduction

Building envelope, if conceived as a responsive skin, can serve as a critical component of an ecological building. It is strictly linked to the environmental, social, and economical aspects of buildings and their context. Therefore, it should act in a creative, flexible, dynamic, and adaptive manner towards its context. Building skin is a living organism that should breathe. It should be “multilayered” while each layer plays diverse roles for properly responding to its surrounding shaping an energy generator that also regulates received energies (Tombazis, 1996). Technically, building skins should be able to manage moisture, heat and air transfer as well as radiation. A DSF is product of this viewpoint: a multilayered formation to provide daylight, indoor air quality, natural ventilation, thermal and visual comfort, acoustics isolation, and aesthetic. In addition to their beneficial environmental aspects, DSFs generate spatial possibilities that foster social interaction and occupants’ productivity. It consists of an external glass facade, an intermediate space, and an inner facade. The purpose of the outer layer is protection against external conditions, mainly climatic conditions and noise (Ding et al., 2005). Openings in this facade allow for ventilation of the intermediate, and accordingly, inner spaces. Usually, shading devices are employed to avoid overheating and consequently, higher cooling loads typically during hot seasons.

Background

DSF Background: Poirazis (2004) summarizes that acoustic insulation, thermal insulation, energy saving and reduced environmental impacts, transparency, low U-value, natural ventilation, and protection of shading and reflecting devices are main benefits of DSFs, while the higher construction cost, overheating, reduces square footage, additional maintenance, increased construction weight, and glare are main DSFs’ drawbacks. A DSF “leads to about 10–15% energy saving for cooling in the peak of summer because of heat exhausted by natural ventilation, 20–30% energy for heating in winter because of the greenhouse effect (Xu et al., 2007).” Therefore, well designed, shaded, ventilated DSFs decrease heating energy demands without significantly increasing cooling loads (Choi et al., 2012; Zhou et al., 2010; Hoseggen et al., 2008; Wong et al., 2008; and Gratia et al., 2007). In contrast, it is argued that in hot climates, solar gain during hot seasons leads to higher cooling loads (Ding et al., 2005; and Fuliotto et al., 2010). This is further concerning as a comprehensive empirical DSF study, compared to five simulation models, indicates that most models underestimate DSF cavity’s temperature, as a result, cooling loads during the peak solar loads (Kalyanova et al., 2009). From the economic standpoints, energy savings associated with DSFs do not defend additional costs related to construction; therefore, choosing them as options must be done for other reasons than economy (Hoseggen et al., 2008).
Earth-Tubes Background: In addition to the building envelope, the earth can also become another innovative component of an ecological building if integrated into architectural design as a system. The fact that the earth’s temperature has less fluctuation in comparison to the outside temperature should be considered as an asset, which can be used for pre-conditioning the built environments’ supply air. The temperature at around seven feet under the ground is relatively constant, and is around 50-73°F (10-23°C). It is due to the fact that the underground temperature at that level is not influenced by the immediate outside climatic condition. This temperature also depends on the climatic conditions and soil characteristics. The maximum surface temperature and the maximum soil temperature at this level, also, have a lag time around eight weeks, useful in summer cooling and winter heating (Bartok, 2012). The soil temperature, then, is always warmer during cold seasons and colder during hot seasons. “While the margin of variation is small, seasonal changes in ground temperature give geothermal heat pumps a dependable and permanent wintertime heat source and summertime heat sink (U.S. Department of Energy, 2011).” Earth tubes could be mostly used to pre-condition air, and consist of a piping system typically buried 6-12 feet below the ground level. Accordingly, this paper’s focus is on building envelope and earth-tube systems as building components, the integrations of which could be remaking them into an integrated ecological system as a whole.

Methodology

This section elaborates on “what” is to be studied under Research Statement, “why” under Research Relevance, and “how” under Research Design. Next sections of Research Quality, Emphasis, and Assumptions indicate all the details considered for the simulated model.

Research Statement: this study is a case study of an enhanced DSF system, proposed as an integrated design option. The premise shaped that the economic performance of a non-residential building with a naturally ventilated DSF system could enhance if the system is linked into the mother earth via earth-tubes. The main idea is the assimilation of a more energy-efficient ventilation system by means of naturally precooled/preheated air. The study speculates that this combination could resolve the DSF’s overheating issue leading to a lower building LI, which would then increase the economic performance of a DSF system. The enhanced system can also function as a passive system in conjunction with active mechanical systems, in the form of a hybrid system.

Research Relevance: DSFs are concrete examples derived from an inclusivist design viewpoint. The goal of this study is to showcase a design approach capable of achieving high-performance buildings. If an envelope is appropriately designed while also ecologically responsive to its contextual surroundings, it can positively enhance the building performance. As a result, new studies should address DSFs’ economic challenges that could evaluate and essentially validate this novel solution.

Research Design: the method applied in this study is a simulation technique. To investigate the new solution, the study asks the following questions: (1) How could the design practice eliminate the overheating issue associated with DSFs to make them generally applicable to most contextual conditions? (2) How do various components of an integrated DSF interact and function to shape a high-performance system as a whole? In the proposed concept, fresh air or potential outside breezes should be directed to the underground earth-tubes where it could be either precooled or preheated, depending on the outside climatic condition. During cold seasons, the preheated air via the earth-tube concept is directed to the DSF cavity (sunspace) to be exposed to the sun. Then, it gets warmer, and depending on its temperature might be channelled as the required fresh air, either: (a) directly to the building’s interior spaces (office zones) when both its temperature and humidity levels are close enough to human comfort zone (Figure 1); or (b) to the mechanical systems as the air supply and then, to the building’s interior spaces. During hot seasons, however, the precooled air via the earth-tube concept will be directed both to the cavity to moderate DSF’s temperature and be exhausted from the outlet on top of the DSF (in order to avoid the issue of overheating), and then either: (c) to the building’s interior spaces directly as the required fresh air via an enclosed duct that is not impacted by outside hot or humid condition; or (d) to the mechanical systems as the air supply and, then, to the building’s interior spaces. Altogether, the study launches this enquiry with the following hypothesis: In a non-residential building, an optimized double-skin facade linked into the earth...
eliminate the issue of overheating in hot seasons; therefore, it would minimize its Load Intensity (LI) to an extent that can turn it into a practical solution.

**Research Quality:** For the validity of the simulation results, Energy Utilization Intensity (EUI) of a conventional 4-story building (Run 2) is compared to the median EUIs in the U.S. for office buildings, 52.9 kBTU/ft² based on Commercial Buildings Energy Consumption Surveys (CBECS) in 2016. After changing a variable, the LI results of the baseline, basic DSF model, and other proposed DSF systems are compared with the studied DSF literatures as another trustful source. Also, the meteorological data of the four typical U.S. climatic conditions are used in the process of simulation. This means that the result can be generalizable to any climate although specific strategies should be considered for optimizing the system based on each contextual condition. Since the result of simulation is based on annual LI of different options, the results are quite reliable if the input data are the same. After all, no subjectivity is involved as the software calculates the results.

**Research Emphasis:** Basically, a building’s Energy Utilization Intensity (EUI) is a result of dehumidification, humidification, heating, cooling, ventilation, and providing hot water, lighting, and electricity combined (Hegger et al, 2008). This study’s focus, however, is on the Load Intensity (LI) of buildings, which is just related to thermal comfort (cooling, heating, humidification, and dehumidification) while a standard level of lighting and electricity use is presumed.

**Research Assumptions:** A hypothetical south-facing non-residential building with an unconditioned basement and four floors above the grade is modelled using Energy-Plus plugin for SketchUp (Figure 2). A software for airflow analysis, CONTAM and TRNSYS, a transient system simulation program are applied via a coupled-procedure to simulate both the building’s zones (Type 56) and preheated/precooled air temperature/humidity passed through the earth-tube system (Type 61: Hypo), illustrated in Figure 3. The module has several variables: climate, DSF depth/ventilation type/airflow destination, building ventilation/conditioning/air supply source/construction type/shading, and earth-tubes. To analyse the impact of the variables in various climates, three typical U.S. climatic conditions of Minneapolis, Phoenix, and Atlanta are chosen. The proposed DSF systems operates by both means of natural and mechanical ventilation. Three options of wide (2m), medium (1m), and narrow (0.5m) is projected for the depth of the DSFs. The sunspace has horizontal partitioning at the level of each story connected to lower and upper level through floor and ceiling grills. The mechanically ventilated DSF has three 110cfm capacity fans (on north, east, and west sides), on top of the sunspace, located 2.8 m above the level 5 for exhausting air in hot seasons. The fans do not function during the cold seasons to shape an enclosed DSF. The mechanically ventilated DSF will be integrated into the HVAC system where the pre-heated air in the sunspace is introduced to the office zones during cold seasons when building is occupied. The naturally ventilated DSF has three self-regulating vents on the exact same spot as the fans in previous options. These vents would only allow maximum airflow of 110 cfm in the positive direction of the top sunspace to the outside. For minimizing the impact of solar heat gain in hot seasons, an electronic louver system is initially assumed outside the exterior skin that creates 70% shading during hot seasons while it does not impact heat gain during cold seasons. The stated E-shading in hot seasons is then replaced by the design of a passive shading strategy. It includes 1.1 m-depth overhang at the height of 3m for all climates. Also, an added 1.1 m-depth light shelf at the height of 2.2m is designed just for Phoenix and Atlanta in southern façade. Construction type for building components were also optimized using suggested ASHRAE’s U-values for each climatic condition. Then, there are proper controlling systems, such as the introduction of air from sunspaces into the office zones via an 8 x 0.2 m opening at the height of 0.3 m (floor to the mid-height of the window). To avoid overheating issue, the building is eventually ventilated with the same self-regulating vents with the maximum of ASHRAE suggestion for each office during the unoccupied hours in hot seasons. This is very similar to the idea of night-purge except the air is introduced from the ducts instead of ambient. Finally, the DSF is linked into the earth via the earth-tubes (hypocaust system) below the building, where the pre-conditioned air in the air-tubes is directed into either the duct [to be introduced to the office zones in hot seasons] or sunspaces [to be exposed to cold season sunlight before directed to the office zones]. There are 14 earth-tubes with 20 m length, 0.5 m exterior diameter, 0.05 m thickness, heat conductivity of 7.2 kJ/(hr.K.m), heat capacity of 1000 kJ/K m³, and exchange coefficients of 7 kJ/hr.K.m² and 14 kJ/hr.K.m²/(m/s). The tubes’ material is close to characteristics of concrete and the soil. Based on the stated assumptions, table 1 depicts all the sixteen simulation Runs where Run 4, as an optimized option, is the baseline for all comparisons.

**Modeling**

TRNSYS is an inclusive energy simulation software that is capable of predicting the energy demand of a defined
zone based on given inputs. The simulated sample module in this study is a three-zone unit (office, Sunspace, and duct zone). The following generic assumptions are made in association with the elements influencing the building’s LI in TRNSYS (type 56):
- Number of Levels: 4 conditioned on 1 un-conditioned
- DSF orientation: South
- South/Adjacent Window: 2.7×8.6 m = 23.22 m²
- Office Zones Area/Volume: 8×10×3 m = 240 m³
- Sunspace Zones Area/Volume: 2×9×3 m = 54 m³, 1×9×3 m = 27 m³, or 0.5×9×3 m = 13.5 m³,
- Duct Area/Volume: 2×1×3 m = 6 m³, 1×1×3 m = 3 m³, or 0.5×1×3 m = 1.5 m³,
- Infiltration: constant value of 0.1 1/hr
- Construction Type: ASHRAE’s zones of 2, 3, and 6
- Ventilation and number of Occupants: ASHRAE’s minimum ventilation rate for the area/occupant number:
  Office 1: 6 people and 80 m² area requires 164.3 kg/hr
  Office 2: 4 people and 80 m² area requires 143.2 kg/hr
  Office 3: 8 people and 80 m² area requires 185.4 kg/hr
  Office 4: 6 people and 80 m² area requires 164.3 kg/hr
- Office Schedule: working days Monday through Friday 8:00 -18:00 and weekends of Saturday and Sunday
- Comfort Type: office activities (Clothing factor: 1 clo, 
  Metabolic rate: 1.2 met, Relative Air Velocity: 0.1 m/s)
- Heating/Cooling: set as an input of [10 Schedule + 10] (setback is 10°C)/set as an input of [-11 Schedule + 35] (setback is 35°C)
- Dehumidification: set as 50% Relative Humidity
- Humidification: N/A
- Radiation/Solar to Air factor: 0.4 with furniture
- Zone Capacitance: 80×3×1.2×10=2880 kJ/K with 
furniture and 80×3×1.2=288 kJ/K without furniture
- Heat Gains: 1) Occupants: are assumed to be seated with light work such as typing (based on iso 7730’s table will be 150 W which includes Sensible heat of 75 W as well as latent heat of 75 W). 2) Computers: 140W (PC with Monitor) × Schedule × Number of Occupants, Artificial Lighting: 10W/m², convective part of 40% fluorescent tube, 3) Others: 2 printers with 276 kJ/hr radiative power, 522 convective power, and no absorbing humidity for the office hours
In addition, the following assumptions are made in the CONTAM software (Run7 as an example) to simulate the different proposed options’ airflow characteristics in terms of amount and direction:
- Level-1 Airflow Paths: Sunspace opening (8 x 0.2m) with variable wind pressure profile based on AIVC graph at 2.8m relative height, Duct Backdraft at 0.3m relative height (this will be changed to an opening with 0.6m² cross section area starting from Run13), and VentOut One-Way Flow Orifice (opening) with variable wind pressure profile at 2.8m relative height and cross section area of 0.1m² for exhaustion.
- Level1-4 Airflow Paths: One-Way Flow Orifice Floor Grill with 1.6m² cross section area at 0 height, One-Way Flow Orifice Shaft with 2m² cross section area at 0 height, Sunspace Backdraft at 2.8m relative height that is closed for this option (this will be changed to an opening with cross section of 1.6m² at the height of 0.3m for naturally ventilated building options starting from Run13), Duct Backdraft at 0.3m relative height, and a 164.3/143.2/185.4/164.3 kg/hr Constant Mass Flow Fan with variable wind pressure profile at 2.8m relative height functioning during the occupancy. This backdraft is
changed to a 0.6m² opening starting from Run13.

- Level5 Airflow Paths: One-Way Flow Orifice Floor Grill with 1.6m² cross section area at 0 height, and three 110 cfm Constant Mass Flow Fan with variable wind pressure profile at 2.8m relative height that have a controller to turn them off when ambient air is colder than 18°C and on when the air is warmer than 20°C. These fans are replaced by self-regulating vents for options with naturally ventilated DSF.

Results & Findings

The parameter of total load intensity (LI_TOTAL) is compared for all Runs to specify the best optimized alternative. That is, the exact performance enhancement of each option is added on the right side of the tables in comparison to Run4, the baseline. Run4 is considered as the reference in accordance with ASHRAE’s suggested envelope construction type and ventilation rate. The option of having a shading device integrated with a lightshelf for Run4 is, also, repeated for all the three climates to be compared with their baseline, accordingly. This could additionally demonstrate how and to what extents the optimized conventional office building (the baseline) can be enhanced without the integration of a DSF. In comparison to the baseline, results show the best as well as the second-best strategies and third options in terms of combinations. In addition, the operating energy cost of HVAC, related to heating, cooling, dehumidification, and humidification, is provided for each option over a 30-year life cycle of building, assuming a 15-cent cost per Kwh. At the next stage, the “main effects” related to variables such as DSF Integration, DSF Depth, DSF Ventilation Strategy, Building Ventilation Strategy, and Earth-Tubes Integration for the three climates are indicated.

Minneapolis Analysis: The combined table analysis for Minneapolis (Table 2) highlights the following findings:

a) The most energy efficient option for all the alternatives is Run10 with a maximum of 21.2% higher performance compared to the baseline for the DSF depth of 2m and minimum of 16.7% for a DSF depth of 0.5m.

b) The most efficient DSF depth in this climate, the 2-meter depth is obviously the ideal option. Yet, the other two depth options are still considerably effective. Generally, the LI has an inverse correlation with the DSF depth in Minneapolis.

c) The consistent outcomes for the three DSF depths in the climate of Minneapolis suggest that a naturally conditioned building that benefits from a naturally ventilated DSF introducing air into the building zones could be also among the best alternatives.

d) The comparison between the buffer (Run8) and HVAC contributing DSFs (Run10, for instance), reveals that air

Table 1: Assumptions made for simulation Runs

<table>
<thead>
<tr>
<th>Runs</th>
<th>DSF</th>
<th>DSF Ventilation</th>
<th>Airflow Destination</th>
<th>Bldg Ventilation</th>
<th>Airflow Source</th>
<th>Bldg Conditioned</th>
<th>Night Purge</th>
<th>Occupancy</th>
<th>Construction</th>
<th>Shading</th>
<th>Earth-Tubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>✓</td>
<td>Mechanically</td>
<td>Outside</td>
<td>Mechanically</td>
<td>Outside</td>
<td>Default</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Passive</td>
</tr>
<tr>
<td>Run 2</td>
<td>✓</td>
<td>Mechanically</td>
<td>Directly Outside</td>
<td>Mechanically</td>
<td>Directly</td>
<td>Default</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Passive</td>
</tr>
<tr>
<td>Run 3</td>
<td>✓</td>
<td>Mechanically</td>
<td>Directly Outside</td>
<td>Mechanically</td>
<td>Directly</td>
<td>ASHRAE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>ASHRAE</td>
<td>Passive</td>
</tr>
<tr>
<td>Run 5</td>
<td>✓</td>
<td>Mechanically</td>
<td>Directly Outside</td>
<td>Mechanically</td>
<td>Directly</td>
<td>ASHRAE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>ASHRAE</td>
<td>Passive</td>
</tr>
<tr>
<td>Run 6</td>
<td>✓</td>
<td>Mechanically</td>
<td>Directly Outside</td>
<td>Mechanically</td>
<td>Directly</td>
<td>ASHRAE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>ASHRAE</td>
<td>Passive</td>
</tr>
</tbody>
</table>

Run 4, as an optimized option, is the baseline for all comparisons.

**Table 2: Minneapolis Combined Results**

<table>
<thead>
<tr>
<th>Minneapolis Load Intensity Breakdown (2m DSF Depth)</th>
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<tbody>
<tr>
<td>-------</td>
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<tr>
<td>Run7</td>
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<td>Run8</td>
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<tr>
<td>Run9</td>
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<td>Run10</td>
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<td>Run11</td>
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<td>Run12</td>
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<tr>
<td>Run13</td>
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<tr>
<td>Run14</td>
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<tr>
<td>Run15</td>
</tr>
</tbody>
</table>

**Table 2: Minneapolis Combined Results**

- Options with Linked Earth-Tubes
- Options with Naturally Ventilated (NV) DSF
- Options with Naturally Ventilated (NV) HVAC

ASHRAE Suggestions: Passive Shading

ASD as a Single Buffer Zone

Attached ASD as an HVAC Component

The Above Attached ASD as HVAC Component

ASHRAE Suggestion: Passive Shading

Run 2 (21.2% less than Baseline)

Best Strategy (NV DSF+HV-Airline-Tubes-Building)

Run 3 (21.2% less than Baseline)

Best Strategy (NV DSF+HV-Airline-Tubes-Building)

Best Combinations (DSF+Shading+Building)
introduction from cavity to the office zone has considerable impact on LI of a DSF system up to 11.2%.

e) Run4’s results associated with the option of an integrated, passive shading device has 39.6% higher efficiency than a conventional building that has floor to ceiling glazing without any shading strategy. The results, thus, prove the higher influence of proper shading.

Phoenix Analysis: The combined table of Phoenix (Table 3) demonstrates the following findings:

a) The integration of earth-tubes is not generally assisting in lowering LI in this climate except for Run10, a mechanically ventilated building integrated with a mechanically ventilated DSF linked into the earth via earth-tube system. The efficiency compared to the baseline is very insignificant though.

b) The most energy efficient option for all the alternatives is Run13, in which a naturally conditioned office building is integrated with a mechanically ventilated DSF. It has a maximum of 5.8% higher efficiency, compared to the baseline for the DSF depth of 2m and a minimum of 2.1% higher efficiency for DSF depths of 0.5m.

c) The most efficient DSF depth in this climate, the 2-meter depth has better performance while the difference is not as significant as the other climates. LI has similarly an inverse correlation with the DSF depth in Phoenix.

d) In the stated best option of Run13, the self-regulating vents in the office zones is essential in lowering LI.

e) The outcomes are evidently consistent throughout all the options in the climate of Phoenix.

f) A buffer DSF system, that does not introduce air from cavity into the office zones, is not lowering LI in this climate except a very insignificant better efficiency with the 2m DSF depths.

g) The comparison between the buffer and HVAC-contributing DSF in which the air in the cavity is either just exhausted (Run7) or used for heating during cold seasons (Run9), indicates that introduction of air from the cavity into the office spaces, does not considerably reduce the LI of the integrated DSFs.

h) Run’s results associated with the option of an integrated, passive shading device, which include a combined light-shelf and overhang, has 55% higher efficiency than the conventional building in Run2 underscoring higher impacts of shading strategies.

<table>
<thead>
<tr>
<th>Phoenix Combined Results</th>
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<tbody>
<tr>
<td><strong>Phoenix Load Intensity Break Down (2m DSF Depth)</strong></td>
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<tr>
<td><strong>Run #</strong></td>
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<tr>
<td>Run 1</td>
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<td>Run 2</td>
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<td>Run 3</td>
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<tr>
<td>Run 4</td>
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<td>Run 8</td>
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</table>

Phoenix Comparable Runs (2m DSF Depth)

- Run4: 39.6% higher efficiency than a conventional building that has floor to ceiling glazing without any shading strategy.
- Run13: 55% higher efficiency than the conventional building in Run2 underscoring higher impacts of shading strategies.

**Table 4: Atlanta Combined Results**

<table>
<thead>
<tr>
<th>Atlanta (load intensity) Break Down (2m DSF Depth)</th>
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<tbody>
<tr>
<td><strong>Run #</strong></td>
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<tr>
<td>----------</td>
</tr>
<tr>
<td>Run 1</td>
</tr>
<tr>
<td>Run 2</td>
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<tr>
<td>Run 3</td>
</tr>
<tr>
<td>Run 4</td>
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<tr>
<td>Run 5</td>
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</tbody>
</table>

Atlanta Comparable Runs (2m DSF Depth)

- Run13: 55% higher efficiency than the conventional building in Run2 underscoring higher impacts of shading strategies.
Interpretations & Conclusions

The following studied variables, which are put in the order of their actual effectiveness, are the conclusion outcomes of this research.

**DSF Integration:** 1) If properly designed, an integrated DSF system is capable of pre-conditioning the air in cavity throughout the course of a year in spite of the findings in DSF literature about its overheating issue in hot seasons. 2) The integration of a DSF system with an optimum depth into a non-residential building always enhances a building’s energy performance independent of its location. 3) DSF systems are more effective in cold climates, moderate climates, and hot climates respectively. It is due to fact that DSFs are primarily capable of reducing heating loads drastically. This research, thus, supports the literature findings regarding the DSF’s insignificant effect on EUI in hot climates. 4) The significance of a properly designed DSF system is interrelated to variables such as climate, DSF depth, or building ventilation strategy while the DSF ventilation strategy does not obstruct it. 5) Air temperature and relative humidity in a DSF’s cavity are always higher and lower than the outside air, respectively unless other strategies are integrated namely shading strategies. 6) Among the studied variables, DSF integration has the highest impact on heating load in an integrated DSF.

**Buildings Ventilation Strategy:** 1) LI in an integrated DSF system is primarily linked to the building ventilation strategy where cooling loads can be lowered due to both air movement making occupants feel cooler and the potential of higher air-change. 2) The ventilation strategy has the highest impact on LI in a hot climate while a cold climate with hot summers is next. It has slight impact on a DSF system in a more moderate climatic condition. 3) The effectiveness of a naturally ventilated building with a DSF system is tightly associated to the controlling strategies for restraining air introduction in cold seasons and maximizing it during hot seasons. A self-regulating vent for instance, can both control the airflow amount and direction, eliminating the unpredictability inherent to natural ventilation, which is a function of various factors such as wind characteristics or air paths’ size and height. 4) A comparison between the buffer and HVAC-contributing DSF revealed that the air introduction from the cavity into the office zone does have considerable impacts on the LI of a DSF system. 5) Among the studies variables, cooling loads are primarily impacted by building ventilation strategies followed by DSF depth. 6) Building ventilation strategies in an integrated DSF system can considerably reduce dehumidification loads in all studied climatic conditions.

**DSF Depth:** 1) Depth of a DSF has an inverse correlation with a building’s LI, as result EUI, the LI in all the studied climates was increased by decreasing the DSF’s depth. Yet, its impact on heating and cooling is the product of climate it is located in. 2) DSF depths are more important in extreme hot or cold climatic condition as opposed to moderate climates. 3) Airflow velocity is a product of a DSF depth for naturally ventilated systems as the air in the cavity has more time to be preheated during the cold seasons before it is introduced into zones for ventilation purposes in an HVAC-contributing system. 4) If properly designed, a depth of 2m is always a more practical solution for a DSF system in all climatic condition provide that relevant controlling strategies are integrated.

**Earth-Tubes Integration:** 1) The integration of an earth-tubes system into a DSF system always increases the system’s energy performance with no overheating issue or increased cooling loads provided that optimum DSF depth of 2m is designed. 2) The air-tube system’s integration into buildings with DSF has higher constructive impact on buildings’ LI in cold climates in comparison to moderate and hot climates where it has very low impact.

**DSF Ventilation Strategy:** 1) DSF ventilation strategy does not have substantial impact on LI suggesting that
natural forces of wind and buoyancy even in extreme hot climatic condition could ventilate a DSF system.

**Passive Shading Strategies:** 1) In contrast to certain studies on DSFs suggesting that the integration of a DSF system will always increase cooling loads (Gratia et al. 2007, Ding et al., 2005; and Fuliotto et al., 2010), a DSF system can considerably lower cooling loads on conditions that appropriate shading devices, construction types, DSF depths, and ventilation strategies are implemented. 2) A passive shading strategy that combines a simple overhang and light-shelf can even performs better than an automatic shading device, which provides 70% shading in hot seasons without any negative impact on heat gain during cold seasons.

**Climate:** 1) A profound understanding of DSFs’ context climate and how or to what extents it could impact LI, assists in making informed decisions. 2) If designed properly, a DSF system always assist in decreasing cooling loads without any overheating issue during hot seasons even in hot climates such as Phoenix.

**Generalizations & Implications**

Study outcomes suggest additional emphasis, especially throughout the course of architectural education and design practice, on the role and the need for systematic communication of scientific dimensions related to buildings. Another lesson-learned is to perceive building components, not as singular or added-on matters, but, as the essential parts of interrelating systems. In addition, the research process has elaborately showcased how an early theorized design solution can still perform different from what had been known or read in the literature, highlighting the importance of evaluation. A major challenge and limitation of the study and research design was its higher dependency on operating in the computer software environment making the data generation more challenging. At this final stage, the research offers a number of future prospects. In fact, possibilities that the integrated design solution of a DSF combined with earth-tubes can offer is now more intriguing than before. Promises still remain to enhance the performance of this integrated design solution, specifically, where it is linked into the earth. Finally, future studies on comparisons between construction and maintenance costs of a building with DSF, as compared to a conventional building, could be beneficial to this proposed DSF’s practicality.

**References**


