Parametric Investigation of Brick Extrusion Patterns
Using Thermal Simulation

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Abstract
Bricks are utilized for their structural and aesthetic roles. Studies demonstrate the impact of thermal mass and shading on energy performance, with limited evidence of other factors such as bonds, patterns and extrusions. This paper investigates the relationship between the location of extruded bricks and their gradient extrusion value. Patterns divide walls into zones with different extrusion values. The study integrates parametric analysis with energy performance simulations conducted on a south façade for a typical residential room in a hot arid climate. Results show 27.75% energy consumption reduction to the base case, indicating potential impact of the non-uniform distribution patterns.

Introduction
Bricks are well known materials in architecture as an exterior building material used as a structural element in building envelopes, or as veneer or paving materials. This paper is part of an ongoing research that investigates the relationship between brick bond types, shape, and extrusion and their impact on energy performance in hot arid climates. Previous work examined the relationship between brick extrusions and energy efficiency. This paper aims to provide a parametric investigation of the impact of different brick distribution and extrusion patterns on overall energy performance. Extrusions are represented by the protrusion values of bricks that affect energy consumption through two factors; thermal mass and self-shading of protruded bricks on other bricks of the façade. Custom brick shapes are utilized so the inner face of the wall on the interior side is even, as shown in Figure 1. Numerous studies have attempted to explain the relative importance and impact of thermal mass and shading on energy performance, where difference in thermal mass could be achieved by means of the extrusion of some bricks with different extrusion values.

However, the role of brick bond types, projections and ornamentation is not yet fully explored in the literature on exterior walls. Little has been published on the relationship between brick bond type, shape, thermal mass and extrusion, and the impact on energy performance. Our approach utilizes parametric analysis and building simulation to advance the potential configuration of bricks as a low cost and commonly used building material to achieve higher levels of energy efficiency while minimizing material consumption. Furthermore, the resulting brick wall ornamentations could achieve aesthetic values while balancing cost and performance.

Figure 1: Extrusion of bricks in a Flemish bond (Tarabieh et al., 2017)

Literature Review
The review is divided into three parts: (1) Traditional Brick Properties & Patterns, (2) Performance and Energy Analysis of Brickwork, and (3) Potentials and Limitations of Parametric Techniques in Brick Wall Design. A number of studies discuss traditional brick properties and patterns. Among the recent studies, Asdrubali et al. (2014) clarified the importance of material thermal flux to evaluate the in situ thermal transmittance of a material to determine actual wall performance. Lucchi (2017) explored the different thermal properties of brick masonry though a comparative analysis and in situ experiment on industrial bricks used today in Italy versus historic brick masonry. The regular measures taken simulators to examine the thermo-physical behaviour of traditional masonries were presented. The base of the evaluation was built on conventional research of brick masonry geometrical survey, VI, IRT, and hot-disk techniques.

A number of studies investigated the chronology of brickwork historically and as applied in the works of great civilizations (Campbell & Pryce 2003; Lynch 2007). Additional studies investigated brick types based on their manufacturing methods and methods of utilization in the building envelope and skin applications (Chudley et al. 2005; Hodge and Thorpe 2006; Emmitt & Gorse 2013). The types of brick arrangements and their methodologies in building construction were studied in the works of Nash (2002), Chudley et al. (2005), Neufert et al. (2012) and; Emmitt & Gorse (2013). A number of studies have utilized data on how bricks were typically manufactured,
and the applicability in the construction methods used to utilize the brickwork of various parts of buildings (Jupp 2002; Hodge and Thorpe 2006). Other studies explored the decorative, maintenance and conservation of different kinds of brick buildings (Nash 2002; Lynch 2007).

Additional studies evaluated the thermal performance and energy analysis of brickwork in exterior walls, but generally with traditional and static brick configurations. Recent work in the field of robotics has introduced interesting prospects for this research with regard to brickwork configuration and assembly, (Sharif et al. (2015); Cavieres et al., 2016). Regarding the autonomous fabrication and assembly of brick walls, recent work in the field of robotics has introduced interesting prospects for this research with regard to brickwork configuration and assembly, (Sharif et al. (2015); Cavieres et al., 2016). Rhee-Duverne and Baker (2013) examined the experimentation procedures and modelling software used in testing the thermal performance of various types of traditional solid brick walls. A few studies took into consideration the different brick flaying arrangements to achieve indoor thermal comfort. The Brick Industry Association (B.I.A., 2016) demonstrated some of the significant parameters influencing building envelope performance, including mass, wall thickness, and thermal resistance, and highlights the importance of modelling and simulation to conduct thermal analysis especially for complex buildings.

Different approaches have been proposed in the literature to demonstrate the potentials of generative and parametric approaches for brickwork design and fabrication. These primarily comprised two main topics: (1) computational models and parametric techniques for innovative brickwork pattern generation, and (2) autonomous and semi-autonomous fabrication and assembly of brick walls. Regarding parametric approaches and techniques, the work of Cavieres et al. (2011) implemented generative rules and functions to inform the construction of load bearing concrete masonry during conceptual and design development phases. The work of Gentry (2013) investigated the prospects of reaching a middle ground between brickwork design flexibility and allowing for design reasoning and material logic exploration. Afsari et al. (2014) developed a methodology for interactive brickwork design using generative techniques, where interactive arbitrary patterns are generated and mapped in real time to brick walls. Their application created several types of brick wall patterns using image analysis and parametric modelling. Several studies also explored the relationship between the structural representation of complex brickwork, and its physical construction using parametric modelling and BIM knowledge-rich systems (Sharif et al. (2015); Cavieres et al., 2016). Regarding the autonomous fabrication and assembly of brick walls, recent work in the field of robotics has introduced interesting prospects for this research with regard to brickwork configuration and assembly, particularly in relation to high precision fabrication of large scale brick walls beyond structured factory settings, and the dramatic expansion of application space for automated building construction. In an effort to implement a discrete in situ construction process and mimic an actual construction site, the work of Gramazio et al. (2013), Kohler et al. (2014), and Dörfler et al. (2016) uses location-aware mobile robots to semi-autonomously fabricate an undulating brick wall in a laboratory experiment setup. Their application developed mobile in situ robotic construction software, localization capabilities using programmed sensors, capabilities to assemble building components with a high degree of precision in space including alignment with existing site elements, and adaptive capabilities of computational models to dimensional tolerances and other site uncertainties. These investigations are specifically promising for this study, as advances in these non-standard fabrication and assembly technologies foster new, adaptable and innovative forms of brickwork configurations and assemblies that rely on a high degree of precision related to the detailed brick gradient extrusion values.

As for performance-based approaches, most of the research is directed to explore the relationship between brickwork configurations and daylighting analysis. Several techniques were adopted in this regard in hot arid climates, especially using genetic algorithms and devising solar screens for daylight optimization (Fathy et al., 2015; Abdelwahab et al., 2016). Little has been published to explore the potential of optimizing thermal transmittance in unconventional brickwork configurations. Genetic algorithms have been widely discussed and adopted in this context for form generation, daylight analysis and structural performance evaluation. According to Omidfar (2015), these approaches allow designers to examine the details of different façade variables using shading systems with decorative patterns. Based on the previous review, a gap in current research is evident in the exploitation of parametric and generative modelling techniques in the reduction and optimization of thermal transmittance in typical brick wall configurations.

Preliminary Studies

The framework for this research project in its larger picture is divided into three approaches; descriptive, analytical and comparative approaches, as shown in Figure 2.

**Figure 2: Research Framework (Tarabieh et al., 2017)**
The descriptive part handles the main parameters in the project such as building typology. The analytical approach, outlined in this paper, is divided into computer simulation using a verified energy analysis engine, and in-situ measurements with a real physical project, to be conducted as future research. Finally, the computer simulation measurements are to be compared to the in-situ measurements to validate the exact location of extruded bricks.

This study is part of an ongoing project that integrates thermal simulation tools with parametric optimization algorithms using DIVA/ArchSim and Grasshopper respectively. The previous stage of the project is used as a preliminary study for this paper.

In earlier phases of the research, three different brick bonds were investigated for their thermal performance in a “uniform” distribution condition for a south façade. A closed parametric loop was scripted through Grasshopper and DIVA to evaluate energy performance. The tested parameters were three different brick configurations (Running, English and Flemish bonds) with different brick extrusion values (baseline, ¼ brick and ½ brick extrusion) and different percentages of the extruded bricks’ area from the façade (15% to 60%). Those parameters and ranges resulted in 24 alternatives, as shown in Table 1.

Table 1: Total energy loads of the preliminary study cases showing the different area percentages of extruded bricks and values of extrusion. (Tarabieh et al., 2017)

<table>
<thead>
<tr>
<th>Ratio %</th>
<th>15 % of Wall Area</th>
<th>30 % of Wall Area</th>
<th>40 % of Wall Area</th>
<th>60 % of Wall Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running Bond</td>
<td>Quarter Brick</td>
<td>115.75 kWh/m²</td>
<td>112.78 kWh/m²</td>
<td>107.01 kWh/m²</td>
</tr>
<tr>
<td></td>
<td>Half Brick</td>
<td>109.97 kWh/m²</td>
<td>105.17 kWh/m²</td>
<td>102.60 kWh/m²</td>
</tr>
<tr>
<td>English Bond</td>
<td>Quarter Brick</td>
<td>133.14 kWh/m²</td>
<td>108.33 kWh/m²</td>
<td>104.04 kWh/m²</td>
</tr>
<tr>
<td></td>
<td>Half Brick</td>
<td>129.27 kWh/m²</td>
<td>102.15 kWh/m²</td>
<td>103.29 kWh/m²</td>
</tr>
<tr>
<td>Flemish Bond</td>
<td>Quarter Brick</td>
<td>107.46 kWh/m²</td>
<td>100.29 kWh/m²</td>
<td>99.19 kWh/m²</td>
</tr>
<tr>
<td></td>
<td>Half Brick</td>
<td>103.45 kWh/m²</td>
<td>97.90 kWh/m²</td>
<td>99.02 kWh/m²</td>
</tr>
</tbody>
</table>
From this preliminary phase, the best energy performance was acquired by the Flemish bond with either 30% wall area extruded with half brick length, or 60% bricks extruded with quarter brick length resulted in 97 kWh/m². The research outcome proved a correlation between extrusion percentage and value. As the extrusion percentage decreases, the extrusion value increases in order to maintain the thermal mass (Author names masked for the purpose of the review, 2017). Thus, the current phase of this research focuses on further investigations in the Flemish bond with different distribution patterns for the extrusion bricks, but in this case within a “non-uniform” distribution based on gradient range of extrusion location and values ranging from the baseline to half brick extrusion value. The performance of the brick masonry wall is assessed by integrating a parametric approach with energy performance simulations. Different parametric runs were conducted to reach the optimum configuration for the location and value of extruded bricks for the Flemish bond. The patterns divide the wall into different zones with different extrusion values. Therefore, this study aims to explore different approaches for reducing energy consumption in a south oriented residential space through different brick types and configurations exploring different locations and patterns for the extruded bricks within gradient extrusion values that range from the default flat case (no extrusion) to half brick extrusion value on the outer side of a Flemish bond facade in a hot arid climate.

**Evaluation Method**

The case study was chosen in Cairo, Egypt (30°6′N, 31°24′E, alt. 75m). Cairo belongs to a subtropical desert arid hot climate according to which is characterized by high direct solar radiation and clear sky that demands special façade treatments to minimize solar heat gain. The initial exploration of the brick performance was executed in the Rhinoceros 3D modelling environment. The realization of various parameters that control the gradient-based patterns required however the brick facade to be constructed in Grasshopper as a means to control each variable parametrically. DIVA-for-Rhino, a highly optimized energy modelling plug-in for Rhino and Grasshopper that interfaces with EnergyPlus for thermal simulations (McNeel 2010; Jakubiec and Reinhart 2011) were utilized to carry out the simulation runs as shown in Figure 3. The simulation results were analysed to understand and evaluate the energy performance behaviour of the brick configurations. The overall definition was generated in Grasshopper and can be divided into three main groups, as shown in Figure 4:

A. **Parametric modelling group**, which includes parametric room model and parametric brick model with its various variables and ranges.

B. **Energy performance simulations group** including cooling and heating loads and thus the total energy consumption simulation results.

C. **Performance evaluation group** through firstly collecting the data and exporting results to excel sheets and then analysing them based on the target criteria.

**Procedures**

The logic of brick extrusion depends on the idea of the attractor curve, which is a line passing through the wall, where the extrusion values depend on the distance between the line and the midpoint of each brick. The attractor curve as shown in Figure 5 passes through all the outer points of the wall. The rectangular wall is divided into two L-shaped curves with two movable points that construct the attractor line. Five points are located on each side of the wall perimeter; an attractor line is located between each two opposite points, leading to 121 possible cases. This line resembles the flat value of the bricks, and the gradient of the extrusion increases till it reaches the highest extrusion value (½ brick extrusion) away from that line. The 121 cases show all the possible locations for this line, as shown in Table 2.

![Figure 3: Grasshopper script showing the three main analysis groups](image-url)
The midpoints of all bricks are evaluated, where the furthest ones to the line have less extrusion values than those far from the line, as shown in Table 2.

Table 2: Sample of brick configuration between extruded bricks from edges or corners

Figure 4: Research Methodology (Tarabieh et al., 2017)

Figure 5: Logic of attractor line cases

Figure 6: All tested locations of attractor curve
The distance relation of the attractor curve position to the extruded bricks is set to be small stepped increments that will still maintain the stability of the bricks. The variation of the attractor line location generates various cases with different brick configurations, as shown in Figure 6. The cases are divided into two types, where the highest extrusion value is located either on one of the four corners, or on an edge of the facade, as shown in Table 2. The studied brick configurations also merged between these cases, as the extrusion can be located on two opposite corners or edges together. Extruded bricks in all cases cover around 60% of the area of the façade.

The main factor that affects energy consumption in this paper is determining the location and value of the extruded bricks. Differences in energy consumption are shown to occur within the space when the extruded bricks of the south facade are at the upper left corner or the bottom right corner. This is affected by the self-shading of the extruded bricks on the rest of the wall. Parametric thermal simulations are conducted using EnergyPlus in DIVA 4, a plugin for Grasshopper (DIVA 2018). The used simulation parameters are shown in Table 3.

**Discussion of Simulation Results**

The total annual energy consumption values for each configuration of the different 121 cases were calculated, and their values were expressed in kWh/m² for cooling and heating loads. The energy consumption of the 121 cases related to all different brick configurations are shown in Figure 7. This graph shows an overview of the energy consumption results with 60% brick extrusions, located in different areas of the façade. Based on the analysis of the results, the optimal case was shown to be case no. 23 (Figure 8), which consumes 94.6 kWh/m². Meanwhile the mid-optimal case (case no. 33) and the least optimal case (case no. 112) consume 95.1 kWh/m² and 96 kWh/m² respectively, as shown in Figures 9 and 10. The least optimal case configuration indicate the importance of the self-shaded effect of the bricks, which is the main factor in this case, as almost all the previous cases have the same thermal mass. Comparing the optimal case to the base case energy consumption, it was shown that an improvement of 62 kWh/m² was achieved.

**Figure 7:** Comparing energy consumption of the brick configurations in kWh/m² for all tested cases and base case

**Table 3: Simulation Parameters**

<table>
<thead>
<tr>
<th>Space Parameters</th>
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<tbody>
<tr>
<td>Climate Zone</td>
<td>Hot Arid</td>
<td></td>
</tr>
<tr>
<td>Floor level</td>
<td>Ground floor</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>South</td>
<td></td>
</tr>
<tr>
<td>Bond type</td>
<td>Flemish bond</td>
<td></td>
</tr>
<tr>
<td>Building type</td>
<td>Residential</td>
<td></td>
</tr>
<tr>
<td>HVAC Set Points</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating set point</td>
<td>22 °C</td>
<td></td>
</tr>
<tr>
<td>Cooling set point</td>
<td>26 °C</td>
<td></td>
</tr>
<tr>
<td>Space Thermal Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-value</td>
<td>Custom 3-layered, material: (brick, mortar &amp; brick) with 35% reflectance</td>
<td></td>
</tr>
<tr>
<td>Internal walls/ ceiling/ floor</td>
<td>Adiabatic</td>
<td></td>
</tr>
</tbody>
</table>
The results show that the optimal case (Figure 8) has extruded bricks along the top edge, with more extrusion values and bricks on the upper left corner that represents the western side. The location of the extruded bricks acts as a combined vertical and horizontal shading device. This is considered the optimal case because it blocks the high solar angle at noon on the south facade, and low angle at the afternoon. The worst case extruded bricks however lie on the top and right edge of the facade, thus shading the high solar angle while allowing the sun in the afternoon. In addition, the results indicate that the effect of both the thermal mass and self-shading are the main factors affecting energy consumption. Comparing the optimal case to the base case (typical Flemish bond without any extrusions) and the optimal case of the previous phase of this research (Condition: 60% Flemish bond ¼ brick extrusion, without extruded brick gradients) - resulting energy consumption is shown to be enhanced by 27.75% as shown in Figure 11, while the optimal case of the previous study gave 25.6% improvement in energy savings than that of the base case. It is obvious that the difference between all the tested cases is convergent; however, all the cases are better than the previously tested uniform pattern (60% Flemish bond ¼ brick extrusion). This could be explained due to the mostly constant ratio of the extruded brick (60%). Another reason could be the small range of the extrusion values, maximum ½ brick extrusion (10 cm). However, the current study introduce a wide range of potentials for further studies that not only depend on environmental enhancements but also aesthetic considerations. Thus, future exploration will investigate larger extrusion values but with an integration between the parametric thermal simulation and a structure stability simulation tool.

**Conclusion**

This paper presented a brick façade design driven by thermal performance. The thermal performance was simulated using (DIVA/ Archsim) that integrates Energy Plus and parametric modelling in Grasshopper. A previous phase of the research has found a significant impact of brick bonds and their extrusion values on energy consumption. It was shown that the Flemish bond with a trade-off 60% of the facade area and extruded with a value of a quarter brick resulted in the best energy consumption relative to other tested brick bonds. The study strengthened the idea that designed brick projections increase the thermal mass thus decrease energy consumption. The previous phase of this research investigated uniform brick distributions, while this study extends to investigate the thermal performance of non-uniform brick distributions. In this paper, several brick parameters were investigated, including gradients of extruded bricks, based on attractor curve logic. The parameters and simulations resulted in 121 different cases that varied depending on the curve location and different extrusion values. The results of this investigation achieved 27.75 % reduction in energy consumption compared to the base case of the typical Flemish bond without any extrusions. Interestingly, the optimal case was observed to have more extruded bricks in the upper band and upper left corner of the façade which can be considered as an ideal solution for a south-oriented façade. By comparing the results of the optimal case in this study with the optimal case results of the previous study, enhancements in energy consumption are demonstrated. Taken together, these results supported the findings of the previous research phase, where an extrusion of 60% of the brick wall area resulted in a reduction of energy consumption for a residential south oriented facade in a hot arid climate.
References


