THE SPHEROIDAL FORM IN ARCHITECTURAL MORPHOLOGY; AN EXPLORATION

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ABSTRACT: This research paper sets out to explore the following research question through exploratory case study of a real spheroidal building, the Greater London Authority (GLA) building: "what shape should a building be in order to achieve energy efficiency in the design and construction of the tall office building?" The Greater London Authority building has been acclaimed as being energy efficient, with claims of 75 % reduction in its annual energy consumption compared to a high specification office building. This research paper sets out to explore this claim and to better understand the spheroidal form. Although the building appears to have achieved a high level of energy efficiency a number of problems have been reported. However, it is not clear how many of these are associated with the morphology of the building.

Keywords –Building morphology, Case study research, Energy efficiency, Office buildings, Spheroidal buildings.

1. INTRODUCTION

"The question of what shape a building should be is one of the most fundamental issues that confront an architect." (Hawkes 1996, p. 36) This paper aims to explore the factor of energy efficiency in relation to the spheroidal form in tall office building design and construction. It is the first stage of the first author's PhD research that aims to explore the three factors of energy efficiency, cost efficiency, and structural efficiency in relation to the spheroidal form in office design and construction. Factors one and two are identified as issues in two questions; "What shape should a building be to reduce heat losses?" (Martin and March 1972, p. 57) and "What shape should a building be to reduce its cost?" (Martin and March 1972, p. 67) Factor three is identified by Macdonald (1994, p. 36) who states that "the performance of a structural element is determined by its shape and by the properties of the constituent materials."

The focus on the spheroidal form is predicated on four statements: Statement 1: "a sphere is already efficient: it encloses the most volume with the least surface." (Baldwin, 2004 p. 1) Statement 2: "as the most economical shape for containing matter, the sphere's perfect form has fascinated the minds of men for millennia. From planets to raindrops, nature adores the sphere." (Sautoy, 2004 p. 2) Statement 3: "the sphere is a special case of the spheroid in which the generating ellipse is a circle." (Wikipedia, 2004) Statement 4: "another problem with sphere shaped building is thermal expansion and contraction. The sphere is the worst possible shape for that. Not only is it a single surface, but it also has constant curvature in all directions. A prolate spheroid or oblate spheroid would do better than a sphere, having different curvature in different directions." (Ambrose, 2002 p. 53) (refer to Fig. 1 and Fig. 2 for prolate and oblate spheroid illustration)

The following deductions are derived from the four statements: Statements 1 and 2 suggest the sphere as being the most efficient way of enclosing volume; Statement 3 identifies the relationship between the sphere and the spheroid; Statement 4 identifies two types of spheroids and suggests that they perform more satisfactorily in thermal expansion and contraction than the sphere. This research paper is an exploration of how the spheroidal form in the architectural morphology of the tall office building, performs in terms of energy efficiency. Investigations into cost and structural issues will be carried out at a later stage of the research. In conducting this first-stage exploration, a single case study of the recently built Greater London Authority Building (GLA), a good example of a prolate spheroid, has been carried out (refer to Fig. 3).

1.1 The concept of the spheroidal form

Wikipedia (2004) defines a spheroid as a quadric surface in three dimensions obtained by rotating an ellipse about one of its principle axes. Further, Ambrose (2002) identifies two types of spheroids; one is stated as a prolate spheroid and the other as an oblate spheroid. A prolate spheroid is obtained by rotating an ellipse about its major axis (refer to Fig. 1) and has morphology similar to that of the Greater London Authority Building (refer to Fig. 3). An oblate spheroid is obtained by rotating an ellipse about its minor axis (refer to Fig. 2) and has morphology similar to that of a geodesic dome, such as the US Pavilion at Expo '67 (refer to Fig. 4). The volume and surface area of a prolate and oblate spheroid are influenced by eccentricity of the ellipse, as well as by major axis length and minor axis length (refer to Table 1) Wikipedia (2004) further describes a sphere as a special case of the spheroid in which the generating ellipse is a circle, while a spheroid is a special case of an ellipsoid, where two of the three major axes are equal.

Table 1. Volume and Surface Area data for a Prolate and an Oblate Spheroid

Spheroid Type	Volume	Surface Area
Prolate Spheroid	4/3 p ab^2	p ($2a^2 + b^2/e$ 1n (1 + e/1 – e))
Oblate Spheroid	4/3 p a^2b	2pb(b + a·arcsin(e)/e)

e is eccentricity of the ellipse = $(1 – (b^2/a^2))^{1/2}$
a is the major axis length
b is the minor axis length

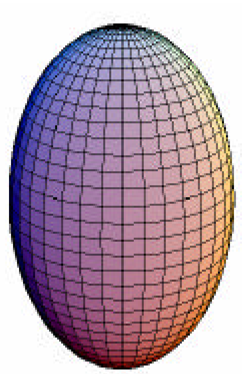

Fig. 1. A Prolate Spheroid

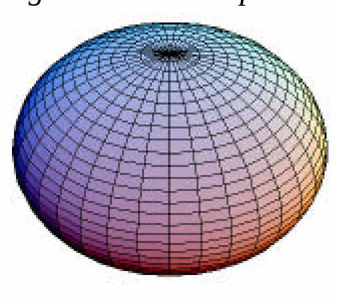

Fig. 2. An Oblate Spheroid
(Image Source: http://en.wikipedia.org/wiki/Spheroid)

Fig. 3. Greater London Authority Building

Fig. 4. US Pavilion at Expo '67
(Image sources: GLA and Image Gallery Biosphere Expo 67 US Pavilion)

1.2 Scope of the research paper

The first author's overall PhD research is aimed at examining the effectiveness of the spheroidal form in the architectural morphology of twenty-first century office buildings. However, the scope of this paper is limited to the exploration of the Greater London Authority Building as a prolate spheroid case study in order to identify the extent to which this real spheroidal building achieves its theoretical ideal of energy efficiency. This paper will assist the first author's overall PhD research programme in exploring the following issues:

- Further refinement and definition of the research problem
- Preliminary information from the outcomes of the case study
- Relevance and relationship of the selected building performance indicator, that is, energy efficiency, to the spheroidal form's performance
- Arguments from previous research in order to establish relevant research questions
- Identification and definition of the research strategy
- Further identification of suitable modes of presentation
- Relevant feedback and contacts in order to further define the research plan
- Creation of a database of existing spheroidal buildings

It is expected that certain aspects of this research paper will relate to one another and contribute to the first author's PhD research. Fig. 5 illustrates this relationship and the intersections represent anticipated areas of interaction.

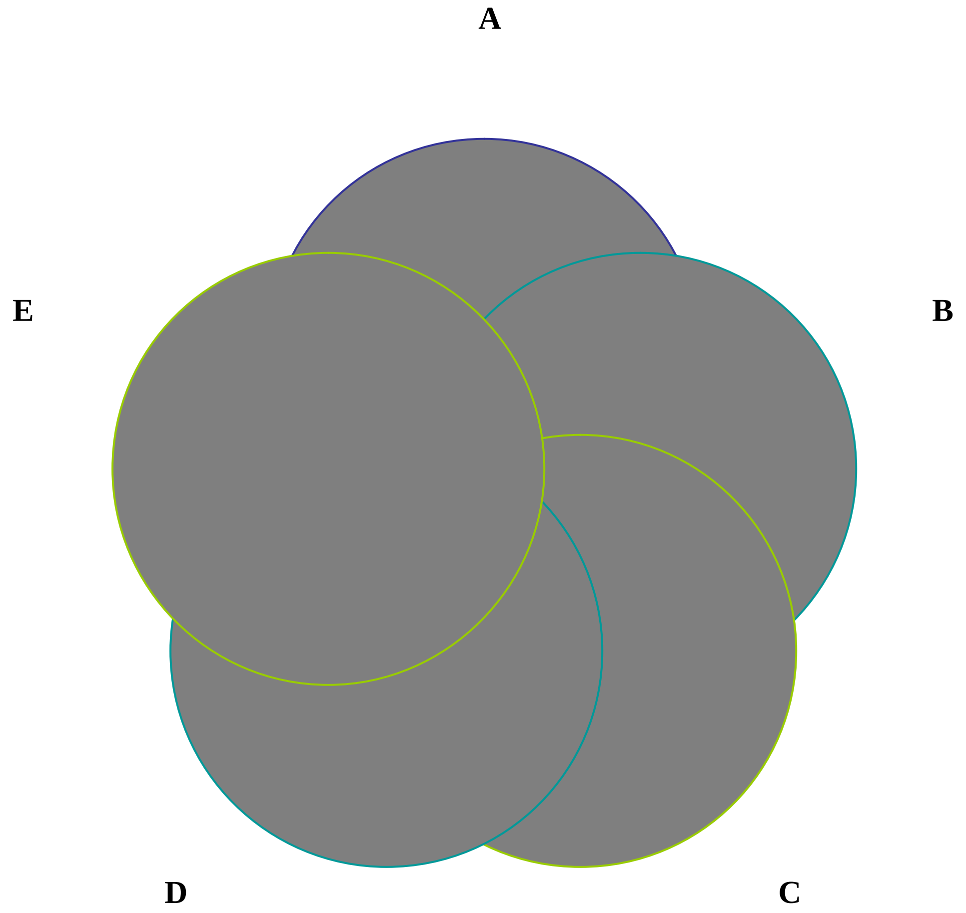

*Fig. 5. Venn diagram illustration of relationship between **(A)** Scope of Research Paper, **(B)** Prolate and Oblate Case Study Exploration, **(C)** Spheroidal Form Performance, **(D)** First Author's PhD Research, **(E)** Spheroid Database and Hybrid Proposal*

2. RESEARCH PROBLEM

Research into the issue of environmental efficiency in office buildings is identified in the following statements:

Statement 1: "The Energy Review (PIU, 2002) highlights the need to improve energy efficiency in buildings and recommends action to deliver a phased transition to low energy commercial buildings through the development of the Building Regulations." (Wade, Pett and Ramsay 2003, p. 1)

Statement 2: "Within the commercial sector, offices, together with warehouses and retail premises, are a significant contributor to energy use and carbon emissions. From these three sub-sectors, offices seem to offer the greatest potential for action to achieve significant savings: the range of technical solutions is not too large as the nature of energy service demands in offices is relatively homogenous….” (Wade, Pett and Ramsay 2003, p. 4) (refer to table 3)

Statement 3: “The rapid growth in energy consumption in offices over the last three decades reflects expansion in floor space, and increased heating, lighting, IT and air conditioning (A/C) loads in individual buildings.” (Wade, Pett and Ramsay 2003, p. 5)

Statement 4: “One commonly cited reason for the lack of investment in energy efficiency in buildings is that energy represents a small percentage of total occupancy costs, and therefore it is given little attention. However, in offices, particularly air conditioned ones, energy and the maintenance of heating and cooling equipment comprises a significant proportion of service charges.” (Wade, Pett and Ramsay 2003, p. 13)

Statement 5: “In 2000, A/C office buildings had an average annual service charge of £53.82 per m^2, compared to £37.24 for non-A/C buildings (Jones Lang LaSalle, 2001) (refer to table 2). Thus, in A/C offices energy itself represents 16% of total service charges; by including maintenance of heating and A/C systems this brings the proportion up to 35%. These are significant proportions, and therefore one might expect that tenants would be interested in lowering energy consumptions in their premises.” (Wade, Pett and Ramsay 2003, p. 14)

Table 2. Service charges in UK offices by component percentages in 2000

	A/C	Non A/C
Energy	16 %	11 %
Heating and A/C maintenance	19 %	9 %
Other	65 %	80 %

Based on Jones Lang Lasalle (2001)
(Table source: Wade, Pett and Ramsay 2003, p. 14)

Table 3. Energy consumption and CO_2 emissions in UK commercial offices

	Heating	Hot water	Catering	Light	Cooling	Small power	IT	Other	Process	Unknown	**Total**
Fossil fuels (PJ)	46	5	3	-	-	-	-	-	-	-	**54**
Electricity (PJ)	5	0	3	16	11	2	12	2	3	0.3	**56**
CO_2 (kT)	3680	469	370	2238	1319	250	1031	184	7	121	**9669**

(Table source: Wade, Pett and Ramsay 2003, p. 4)

2.2 Unanticipated Research Problem

In conducting this research, the first author has identified an unanticipated research problem which is the unavailability of an organised database of existing and proposed spheroidal buildings. This information gap has evoked an added aim to the first author's PhD research which is the identification of spheroidal buildings in existence, as well as in the design and proposed stage, in order to create a reliable print and electronic database of spheroidal buildings categorised according to name, type, location, climate, height, number of floors, date (start date and completion date), volume, surface area, energy consumption, project cost, structural elements, client(s), architect(s), construction manager(s), engineer(s).

3. RESEARCH METHODOLOGY

The case study research strategy is a multi-method nature, "involving observation, interviewing and analysis of documents and records." (Robson, 1993 p. 167) Further, Robson (1993) describes the case study approach as relevant in the identification of variables and research questions that focus on current issues associated with the research subject. The type of case study adopted for use in this research paper is the single case study, while the type of case study adopted for use in the first author's PhD research will be the Multiple Case Study. The adoption of this exploratory multiple case study research strategy involves the following amongst others:

- Environmental Impact Analysis of proposed spheroidal buildings, projects and research
- Environmental Impact Assessment of existing spheroidal buildings

Robson (1993 p. 161) states: "This activity, whether for multiple case studies or for multiple experiments (or for multiple surveys for that matter; or even for multiple studies involving a range of different research strategies), is not concerned with statistical eneralization but with a*nalytic generalization*."

The adopted research strategy is illustrated in Fig. 6:

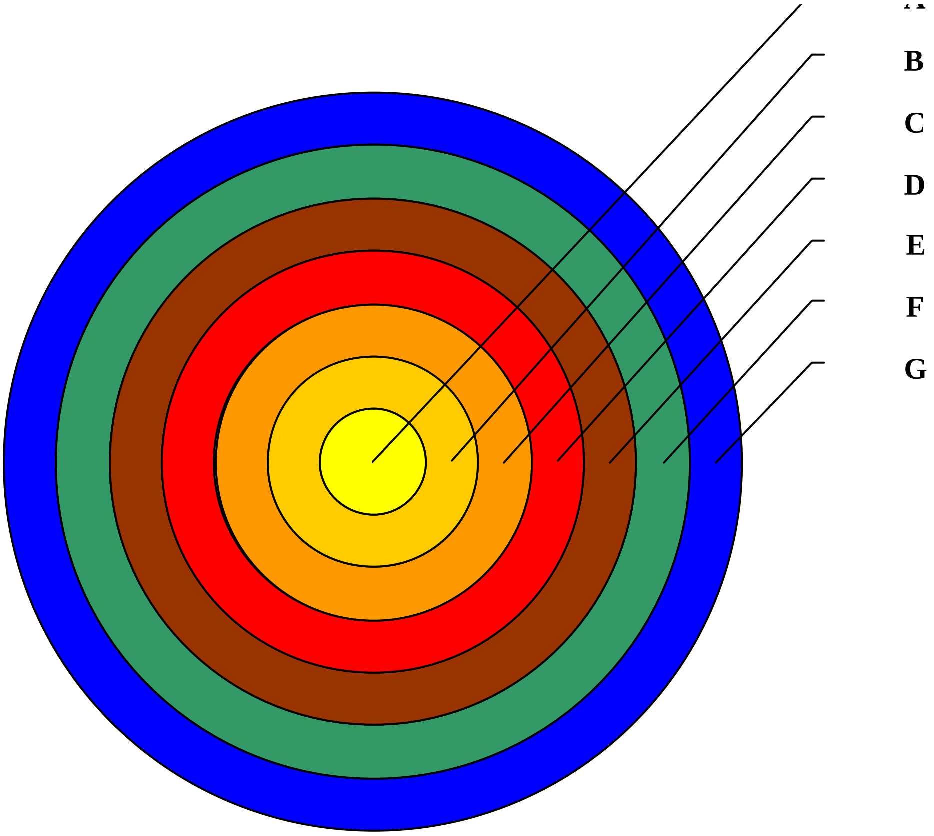

Fig. 6. Target Diagram illustration of the research methodology depicting: **(A)** Research report; **(B)** Instruments for data collection; **(C)** Sources of information; **(D)** Hypothetical solution to the research problem; **(E)** Scope and limitation of the research; **(F)** Purpose of the research; **(G)** Identification of research problem

5. CASE STUDY: THE GREATER LONDON AUTHORITY BUILDING

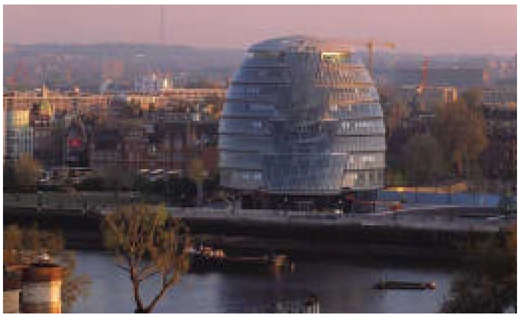

Fig. 7. City Hall at dawn

Fig. 8. City Hall at night

(Image source: Government Office for London, 2004)

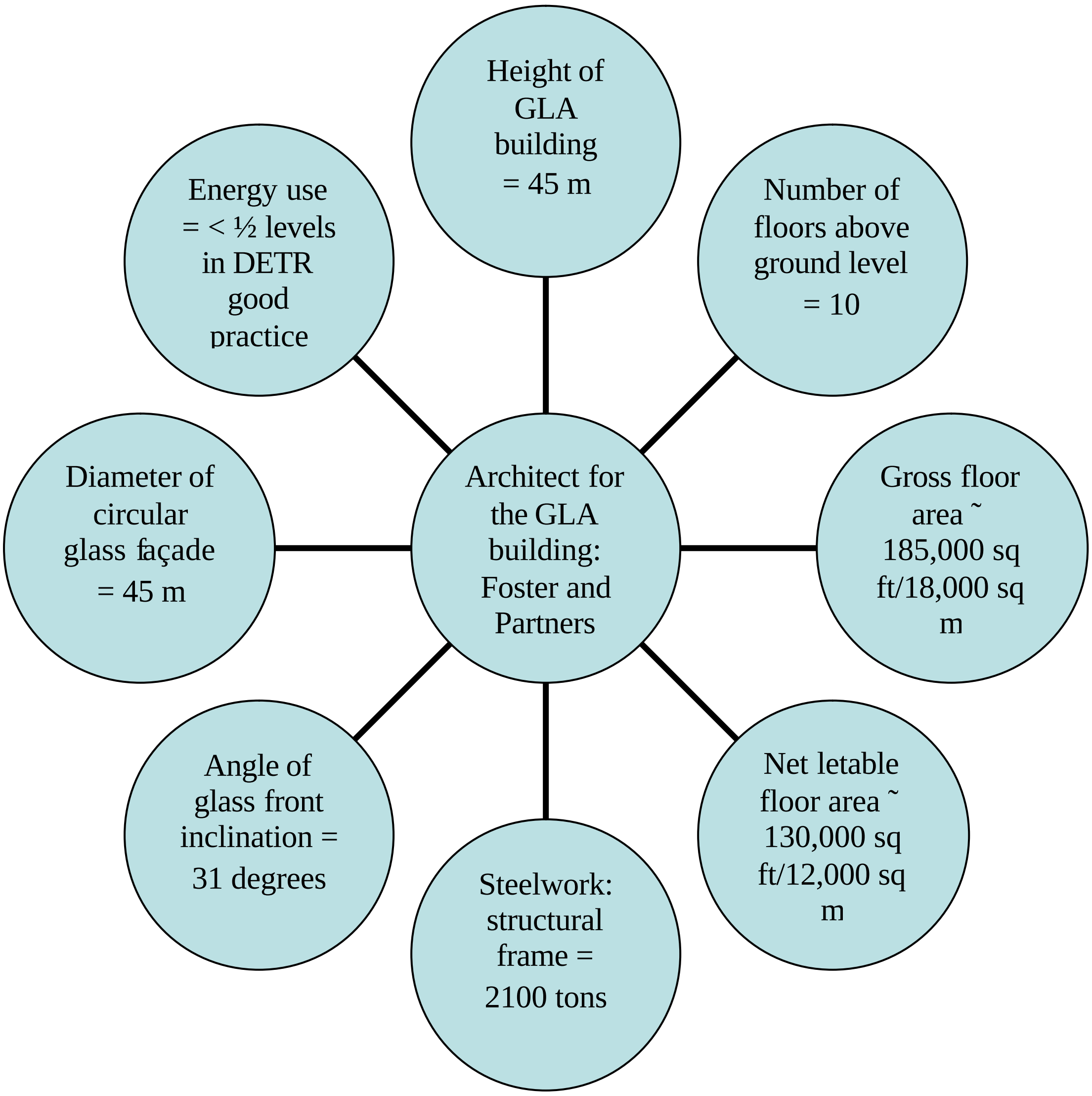

Fig. 9. Radial Diagram illustration of the Greater London Authority Profile

5.1 Energy efficiency exploration

On the 23rd of July 2002, the new City Hall, known as the Greater London Authority (GLA) building was officially opened by Her Majesty, the Queen and was heralded as a solution to the issue of environmental efficiency in tall office buildings. However, doubts have arisen regarding its claims of energy efficiency. The design and construction of the GLA building led to the emergence of arguments relating to the actual and perceived problems, as well as benefits associated with the use of the spheroidal form in attempting to achieve environmental efficiency in tall office buildings.

Greater London Authority (2005, p. 1) states: "Energy consumptions for GLA's environmental systems are less than half levels in DETR good practice office guide. (refer to Table 4) The radical shape of the building minimises the surface area (approximately 25 percent less than equivalent rectangular building), is self shading and the high performance façade ensures excellent energy efficiency."

Table 4. Typical and good practice energy consumption in offices in the UK

	kWh/m^2 of treated floor area							
	Type 1		Type 2		Type 3		Type 4	
	Good practice	Typical	Good practice	Typical	Good practice	Typical	Good practice	Typical
Heating & hot water	79	151	79	151	97	178	107	201
Cooling	0	0	1	2	14	31	21	41
Fans, pumps & controls	2	6	4	8	30	60	36	67
Humidification	0	0	0	0	8	18	12	23
Lighting	14	23	22	38	27	54	29	60
Office equipment	12	18	20	27	23	31	23	32
Catering	2	3	3	5	5	6	20	24
Other electricity	3	4	4	5	7	8	13	15
Computer room	0	0	0	0	14	18	87	105
TOTAL	**112**	**205**	**133**	**236**	**225**	**404**	**348**	**568**

Based on DETR (2000b)
(Table source: Wade, Pett and Ramsay 2003, p. 7)
(Office Type 1: Naturally ventilated cellular; Office Type 2: Naturally ventilated open-plan; Office Type 3: A/C, standard; Office Type 4: A/C, prestige)

Mean of good practice levels = (Type 1 + Type 2 + Type 3 + Type 4) ÷ 4…equation (1)
Mean of good practice levels = (112 + 133 + 225 + 348) ÷ 4 ……………..equation (2)
Mean of good practice levels = 818 ÷ 4 ……………equation (3)
Mean of good practice levels = 204.5 ……………equation (4)
If the GLA's environmental systems energy consumption is less than half levels in DETR good practice office guide then from equations (1), (2), (3) and (4) we derive;
GLA's energy consumption level = ½ (Mean of good practice levels) ……equation (5)
GLA's energy consumption level = ½ (204.5) ……………equation (6)
GLA's energy consumption level = 102.25 ……………equation (7)
GLA's energy consumption level = < 102.25 ……………equation (8)

It can be deduced from the results of Equations (1) to (8) that the Greater London Authority Building's energy consumption level is less than half mean levels in DETR good practice office guide, is less than individual DETR good practice office guide total levels for Type 1 (Naturally ventilated cellular) and Type 2 (Naturally ventilated open- plan), and is less than half levels in DETR good practice office guide for Type 3 (A/C, standard) and Type 4 (A/C, prestige) (refer to Table 4) The Greater London Authority Building's low energy consumption can be attributed not only to its spheroidal form but also to other innovative solutions, such as:

- "For cooling the building, naturally chilled borehole water is brought up 125m from the aquifer below the London clay. The boreholes use less energy than conventional chillers and cooling towers and are an economical alternative to install and maintain." (Arup 2002, p. 1)
- "The diagrid structure supports the north façade of the GLA building and is in fact the largest radiator in London. The majority of the horizontal steel elements, measuring a staggering 300mm in diameter each, have hot water coursing through them to act as a

discreet heater for the atrium space that doesn't require extra fittings or pipe work installation." (Arup 2002, p. 1)

- Detailed analysis by Arup resulted in the design of a very efficient façade. It is made up of insulated panels that reduce the solar gain, as well as heat loss to half that of a normal office building." (Arup 2002, p. 1)
- "The façade also incorporates flexible, locally controlled natural ventilation. When the natural air vents are opened, 'smart' air conditioning and heating systems deactivate themselves in the adjacent area to prevent energy waste." (Arup 2002, p. 1)

It must however be stated that the Greater London Authority Building's low energy consumption is attributed primarily to its "radical shape" (Greater London Authority 2005, p. 1) with support from its "imaginative and innovative solutions." (Arup 2002, p. 1) It must also be stated that although the Greater London Authority Building's energy efficiency appears to be good, the building appears to be deficient in other respects and these contradictions are reflected in the nature of the research problem which can be identified in arguments and counter-arguments described in this paper as pros and cons:

Pro 1: "The GLA building exemplifies the design team's commitment to creating a low energy building that sets a new standard for office buildings of the future. It shows that low energy buildings are not expensive to construct and maintain." (Arup 2002, p. 1)

Pro 2: "There is a 75% reduction in the annual energy consumption of the air conditioning, heating and ventilation systems compared to a high specification office building." (Arup 2002, p. 1)

Pro 3: "Minimising the surface area of the building results in maximum efficiency in energy terms. The building's form is derived from a sphere, which has approximately 25% less surface area than a cube of the same volume." (Greater London Authority 2005, p. 1)

Pro 4: "Up here, City Hall's complex curved profile is pronounced. The shape derives ultimately not from some political gesture, but from largely environmental concerns. By creating a kind of asymmetric sphere, Foster has shaped a building that receives a little direct southern light and as much direct northern light as possible in the height of the summer. This means that a highly glazed building, exposed on all sides, can be kept cool naturally." (Glancey 2002, p. 3)

Pro 5: "Building materials and structures expand and contract with temperature changes. It is a process that must be broken down into interlocking components. For example, walls expand vertically while roofs do so obliquely. But all areas on a spherical building shell expand into each other directly in-line. A prolate spheroid or oblate spheroid would do better than a sphere, having different curvature in different directions." (Ambrose 2002, p. 53)

Con 1: "Structurally, the GLA building demanded uncompromising and precise engineering to solve the 3-dimensional jigsaw. Its shape and natural inclination meant that Arup's structural engineers had to design the building to counteract its tendency to fall over. This combined with the innovative design of the atrium ramp and diagrid provided more than enough challenges for the design team." (Arup 2002, p. 1)

Con 2: "But on the floors below him there are murmurings among the GLA's staff that the building is too small, lets in water and is more show than substance." "But concerns about water leaks are genuine. A committee room was flooded because of a problem with an external wall and staff on an inspection visit were surprised to see buckets and plastic sheeting in the debating chamber." (O'Neill 2002, p. 1)

Con 3: "There are worries among some that City Hall may come to resemble Lord Foster's Reichstag in Berlin – where fees were withheld until deficiencies were remedied – or that further problems will emerge when the building is in use, as happened with the wobbly Millennium Bridge." (O'Neill 2002, p. 1)

Con 4: “There is talk of “plummeting lifts” and an over-sensitive fire alarm system – all dismissed by the developers.” (O’Neill 2002, p. 1)

Con 5: “The biggest complaint among staff is that office space will be overcrowded. The Government commissioned a building for 400 workers, 25 assembly members and one mayor.” “The GLA now employs 440 staff and that number is much more likely to grow than diminish.” (O’Neill 2002, p. 1)

Con 6: “Back outside, one of City Hall’s contradictions becomes clear. It feels isolated and, because of its apparently hermetic design, the public seem unwelcome. Clearly, this is wrong. The building stands alone on the riverside at the far end of a new public plaza the size of Leicester Square.” (Glancey 2002, p. 3)

Con 7: “The much-criticised computer impressions of the project depicted a transparent building. In fact City Hall reflects a grey sky for most of the time. The computer conjured up a sleek, liquid-smooth skin. The finished product is actually rather more jerky than that.” (Sudjic 2002, p. 2)

6. CONCLUSIONS

This research paper suggested, “The question of what shape a building should be is one of the most fundamental issues that confront an architect.” (Hawkes 1996, p. 36) It stated its aim as the exploration of the factor of energy efficiency in relation to the spheroidal form in tall office design and construction. It identified reasons for the research focus on the spheroidal form; these are associated with the spheroidal form’s theoretical ideal of efficiency.

In this paper, the spheroid was defined, its properties identified and its types, the prolate and oblate spheroid were illustrated. Further, these illustrated types of spheroid were linked to two existing spheroidal buildings, one of which, the Greater London Authority building, was adopted for exploration as a single case study in the context of its energy efficiency.

The scope of this research paper was established and limited to the exploration of the Greater London Authority building as a prolate spheroid case study in order to identify the extent to which this real spheroidal building achieves its theoretical ideal of energy efficiency. Areas of further research were also identified.

In stating the research problem the research paper identified five statements associated with energy efficiency issues, narrated a background to the GLA building, and listed five arguments, as well as seven counter-arguments, referred to in the paper as pros and cons. This paper adopted the single case study approach for exploration of the energy efficiency issue in the GLA building. Further, this paper explored the energy efficiency claim of the GLA building and derived an energy consumption figure for the GLA based on the DETR’s good practice office guide. The derived figure demonstrated the GLA’s energy consumption level is less than individual good practice total levels for office Type 1, office Type 2, office Type 3 and office Type 4 (refer to Table 4)

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