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Ecology of the Building Geometry - Environmental Performance of Different Building Shapes

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ABSTRACT

The relationship of the building geometry with ecology is often described by commonplaces such as "compact shapes - spheres and cubes - are most favourable". But is this true?

On the basis of environmental life cycle assessments of office buildings, during several years different shape and stacking typologies were studied for equal spatial demands. These studies led to interesting relationships between the building height and environmental performance.

They were brought further into focus by studies of real high-rise buildings. Furthermore, the influence of large glazed spaces was studied.

All assessments were done by means of a reference comparison model, using GreenCalc, a tool based on LCAs. Therefore, they provided outcomes that could be compared. This paper discusses these studies and their approach. The findings clarify the relationship between the building geometry and ecology, supporting ecological construction of new buildings anywhere in the world.

Keywords: Shape, Geometry, Sustainable Building, Environmental Performance, GreenCalc.

1. INTRODUCTION

The term 'ecology' originates from the Greek 'oikos', meaning house, and 'logos', meaning knowledge. Through the ages, ecology has shifted towards a nature-related concept, but we can bring it back to the very

essence by seeking knowledge of building in a sustainable way, ecological architecture.

Architecture is often defined as the shaping of spaces. Building design starts with the building shape. The relationship of the building geometry with ecology is often described by commonplaces such as "compact shapes - spheres and cubes - are most favourable for the use of energy and building materials". But is this true?

Dobbelsteen (2004) determined the environmental performance of office buildings by calculating the environmental load, by means of the LCA-based tool GreenCalc, and comparing these results to those of a theoretic reference building representing the year 1990. By using the environmental costs of building components and energy consumption from this research, different basic shapes with equal floor areas and complying with the same set of demands could be compared. More accurate studies involved different stacking variants for equal net floor areas, taking into account heavier structures (when increasing the number of stories) and spatial inefficiencies (when reducing the floor area per story). These studies led to interesting relationships between building height and environmental performance. They were brought further into focus by assessment studies of three Dutch high-rise buildings and Europe's tallest building, the Commerzbank. In addition, we determined the environmental impact of large glazed spaces.

Below, these studies are discussed subsequently, better clarifying the relationship of the building geometry and ecology.

2. COMPARISON OF THE BUILDING GEOMETRY

2.1 Basic shapes

In order to determine the environmental impact of basic building shapes, a typology study was executed (Dobbelsteen *et al.*, 2005) on six typical shapes with an equal floor area: the Cube, the Warehouse, the Caterpillar, the Fence, the Slab, and the Tower (Figure 1). The building block had an area of 1 unit. For a realistic situation, the measurements of the building block were chosen 12 x 12 m and the floor height 4 m, leading to 3 floors per cubic element. Starting-point was a total floor area of 24 units (576 m²). The amount of building materials was considered proportional to the area of floors, façades and roof. The built-in components were related to the floor area, hence constant in all cases. The Cube was taken as a reference.

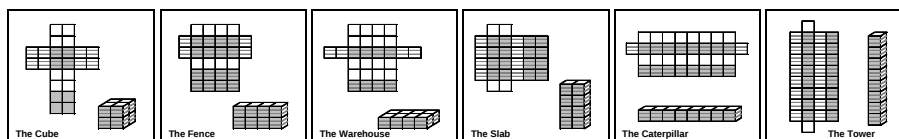


Figure 1 Shapes of different building typologies with an equal floor area

Table 1 gives the results for the integrated assessment. The calculations were based on outcomes from the assessments by Dobbelsteen (2004). Based on these findings, water consumption was assumed equal to the number of employees, hence constant.

Table 1 Improvement factors with respect to The Cube for different basic building shapes

shape type	energy	materials	water	total
contribution >	77.5%	19.5%	3.0%	100.0%
the Cube	1.00	1.00	1.00	1.00
the Slab	1.02	0.91	1.00	1.00
the Fence	1.02	0.92	1.00	1.00
the Warehouse	0.93	0.93	1.00	0.93
the Tower	0.92	0.80	1.00	0.90
the Caterpillar	0.92	0.82	1.00	0.90

The differences between the basic shapes are relatively small. In terms of environmental performance, the Cube, Slab, and Fence typologies may be considered indifferent. The Tower and Caterpillar perform only 10% less favourable, with the Warehouse typology in-between. The environmental impact by the use of land was not involved in the study presented here.

For architects these findings should be comforting: the selection of a basic geometry has only limited influence on environmental performance. Nevertheless, this study was only indicative. It is the combination of the size and extent of stacking that matters. The following section discusses a more accurate geometric study.

2.2 Different stacks for an equal floor area

A comparison can be drawn between theoretical building alternatives for the same net floor area (NFA), however with a different number of building layers. This was also done by Dobbelsteen *et al.* (2005), again using the outcome of environmental lifecycle assessments of office buildings. Five alternatives were compared: variant A with 2 stories, B with 4 stories, C with 8 stories, D with 16 stories, and E with 32 stories. In order to compare this study with the previous one, variant A and B can be considered as Caterpillar types, C as a Fence type, D between the Fence and Slab type, and E between the Slab and Tower type. Each floor plan was based on a cellular office layout (Vos *et al.*, 1999), with rooms bordering the façades and a corridor in-between. The gross/net area ratio (Gerritse, 1995) was also involved. As Gerritse studied this spatial proportion until 16 stories only, results were extrapolated for the 32-stories alternative.

Table 2 shows the Geometric properties of the alternatives for an 8400 m² office. We repeated this geometric exercise for 2100, 4200, 16800, 33600, and 67200 m².

Table 2 Geometric properties of different stories for a net floor area of 8.400 m²

characteristics	building variant					unit	info
	A	B	C	D	E		
number of building layers	2	4	8	16	32	-	
building height	7.2	14.4	28.8	57.6	115.2	m	1
NFA (net floor area)	8400	8400	8400	8400	8400	m ²	
GFA/NFA ratio	1.325	1.340	1.375	1.400	1.420	-	2
GFA (gross floor area)	11130	11256	11550	11760	11928	m ²	3
GA (ground area)	5565	2814	1444	735	373	m ²	4
short facade depth	12.6	12.6	12.6	12.6	12.6	m	5
long facade length	441.7	223.3	114.6	58.3	29.6	m	6
compactness	0.44	0.31	0.25	0.23	0.24	-	7
explanation							
1: standard layer height: 3.6 m; 2: A-C: Gerritse [1995]; D-E: extrapolation of Gerritse [1995]; 3: = total NFA * GFA/NFA ratio; 4: = GFA per layer; 5: starting point: 5.4 - 1.8 - 5.4 corridor type; 6: = GFA per layer / short facade length; 7: = envelope surface / building volume							

The chart of figure 2 gives the results of the assessment of the six floor areas stacked onto different stories (expressed by improvement factors with respect to the 2-story variant), combining the environmental costs for materials and energy. The results apply to a floor depth of 12.6 m. When the office floor is twice as deep, i.e. 25.2 m, the maximum improvement factor increases, though marginally.

This figure demonstrates that every floor area has an ecological optimum; the optimal number of stories is depicted by black markers. For large NFAs, the optimum shifts toward more building layers.

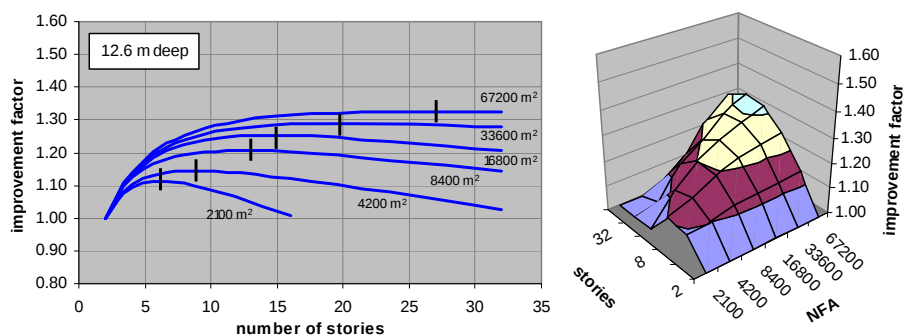


Figure 2 Relationship between integrated environmental improvement factors and the number of stories, for different NFAs, in the case of a 12.6 m deep floor plan

2.3 Considerations

Uncertainties remained about the impact of increasing building height to the supporting structure. Apart from a linear increase, 10% increase of environmental costs for the foundation and vertical building elements was added for every doubling of story numbers. However, Stafford Smith & Coull (1991) found that the amount of steel for columns increases linearly with height, whereas above 10 layers constructive steel elements for carrying wind forces increase exponentially. This suggests that the results presented in this chapter are probably not valid for heights above 16 or at least 32 stories. Therefore, the following chapter elaborates on the assessment of real high-rise buildings.

3. COMPARISON OF HIGH-RISE BUILDINGS

3.1 Three Dutch examples

Figure 2 showed little decline in environmental performance above 16 stories. This seems doubtful. In order to discover the impact of high-rise buildings, three tall Dutch office buildings (Figure 3) were assessed. They were studied on space efficiency, building materials and energy consumption, and compared to a low-rise reference building (Thijssen, 2007).

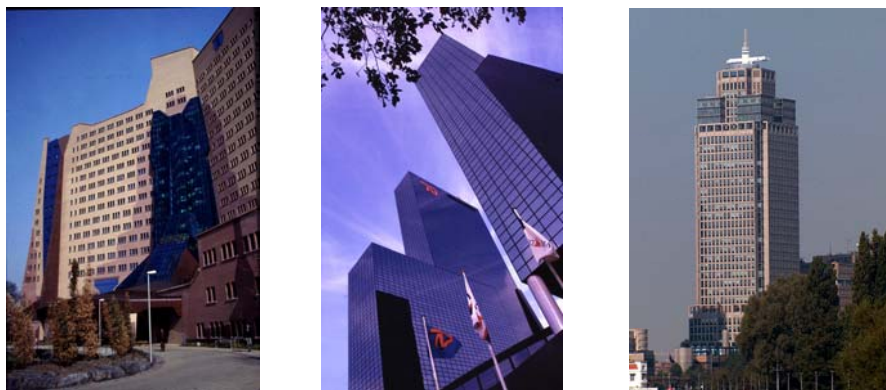


Figure 3 Three Dutch high-rises, left: Gasunie, Groningen; middle: Nationale Nederlanden, Rotterdam; right: Rembrandt Tower, Amsterdam

Table 3 draws a comparison of geometric properties of the cases. When compared to other regions of the world, these buildings are not very tall, but the Delftse Poort still is the tallest building of the Netherlands, the Rembrandt Tower the tallest of Amsterdam, and the Gasunie building a landmark to the Northern Netherlands.

The latest version of the LCA-based tool GreenCalc+ was used to determine the environmental costs; these were again used in a reference

model, resulting in environmental performance scores. In spite of doubts expressed in section 2.3, the overall scores were in line with the theoretic graphs of section 2.2.

Table 3 Geometric properties of the three Dutch high-rise buildings

	Gasunie Building	Delftse Poort	Rembrandt Tower
City	Groningen	Rotterdam	Amsterdam
Architect	Alberts en Van Huut	Bonnema Architects	ZZDP Architects
Completion	1994	1991	1995
Employees	1250	1675	1675
Height	87 m	150 m	135 m
Floors	19	36	36
GFA	23.000 m ²	36.000 m ²	32.000 m ²
RFA	14.000 m ²	27.000 m ²	26.000 m ²

Generic conclusions from the assessments are that cooling, ventilation and lighting are decisive factors to energy consumption. Furthermore, a square floor layout, with a structural and functional core in the heart, leads to better space efficiency and requires less material for the bracing structure. With beams perpendicular on the central core, it is possible to create a relatively shallow floor construction height, leading to reduced use of material for the façade and structure. Finally, a concrete tube structure proved to be environmentally favourable and a TT slab floor structure has smaller environmental costs than other floor alternatives (Dobbelsteen *et al.*, 2007). Figure 4 depicts all principles for a sustainable high-rise.

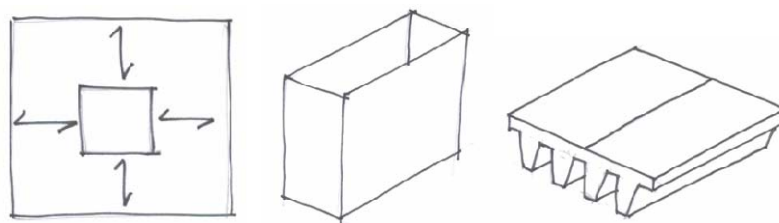


Figure 4 Principles of a sustainable high-rise: square floor plan, tube structure, TT slabs

3.2 The Commerzbank case study

With a structural height of 259 m and a total height of 299 m, the Commerzbank (Figure 5) is Europe's tallest building. It is known as an ecological high-rise tower; the four-story landscaped gardens play a role in the ventilation and enable a view of the outside world from every office.

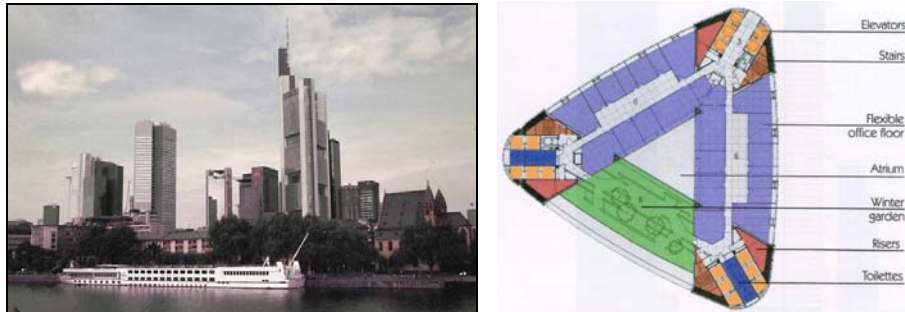


Figure 5 The Commerzbank Headquarters in the centre of Frankfurt, Germany, and a typical floor plan with a garden segment for view and natural ventilation

Colaleo (2003) compared the Commerzbank building to a theoretic reference, which was based on an equal number of users and on spatial and technical references. The theoretic reference had a common cellular floor layout and a maximum number of 24 stories. Table 4 presents the outcome of the comparison.

Table 4 Environmental comparison of the Commerzbank with a theoretical reference

	Commerzbank	reference	improvement factor
materials	€ 1,902,380	€ 516,688	0.27
energy	€ 3,687,102	€ 2,305,623	0.63
water	€ 78,292	€ 100,978	1.29
TOTAL	€ 5,667,773	€ 3,143,490	0.55
per employee	€ 2,362	€ 1,310	
per m ² GFA	€ 58	€ 47	

The improvement factors of Table 4 suggest that the Commerzbank design is not as ecological as intended. The unfavourable environmental costs of building materials are partly due to inefficient use of space in the Commerzbank building. Nevertheless, the real explanation is the supporting structure. The tower foundations are significantly heavier than for common low-rise buildings. In addition, from bottom to top the main load-bearing columns are constant in size; only the steel reinforcements were adjusted. The environmental costs for energy are also unfavourable. It seems that the tower shape is responsible for a greater demand for heating, cooling, and ventilation. The energy demand predicted for cooling, and to a lesser extent ventilation, is strikingly greater than calculated.

Table 5 presents features of the Commerzbank and two Dutch ministries of comparable size. Evident is the Commerzbank's inefficient use of floor space, mainly due to the hanging gardens. The apparent heavier structure and inefficient climate design is emphasised by substantial differences in environmental costs per m².

Table 5 Characteristics and annual environmental cost per m² GFA of two Dutch ministry buildings and the Commerzbank headquarters

	characteristics				environmental costs	
	users	stories	GFA/NFA	GFA/empl m ² /p	materials €/m ² y	energy €/m ² y
Ministry of SAE	1800	10	1.83	32.1	8.03	27.74
Ministry of HSPE	3260	16	1.97	28.3	8.47	33.17
Commerzbank	2400	62	2.48	40.5	19.56	37.94

4. INFLUENCE OF LARGE GLAZED SPACES

A large glazed space (LGS) can be an atrium, conservatory and passage-way, with a minimum size and proportion with regard to the building it has been integrated into (Metz, 2004). An LGS may reduce energy consumption for heating, cooling, ventilation and lighting, yet also require additional use of space and materials. Façades inside the glass-covered space may be subject to less frequent maintenance.

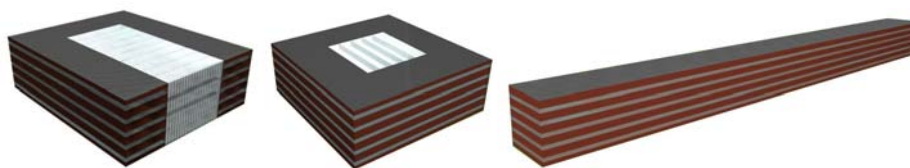


Figure 6 The alternatives assessed, left: building with an integrated conservatory; middle: building with a core atrium, and right: reference building without a large glazed space

To investigate the environmental influence of large glazed spaces, a building with a three-façade-sided conservatory and an atrium type building were compared to a conventional reference building (Figure 6). The LGS types could perform two functions: trespassing or accommodation. Every alternative needed to comply with a set of spatial, functional and technical requirements, called the functional unit. The assessment method, using calculations by the LCA-based assessment tool GreenCalc, was discussed by Metz & Dobbelsteen (2005).

All alternatives performed within a maximum margin of 7%. Taking into account possible inaccuracies and sensibilities of the model used, this difference may be neglected. These findings indicate that environmental benefits and drawbacks of large glazed spaces are in balance and that they should be used when they imply added functional or esthetic value.

5. CONCLUSIONS AND DISCUSSION

5.1 General conclusions

Based on the studies discussed, some remarkable conclusions may be drawn in terms of the ecology of the building geometry:

- Based on basic shapes with smooth envelopes, there is no clear geometrical preference. We however estimate that the actual façade design has a significant influence.
- In terms of environmental performance, every floor area has an optimal number of stories.
- A sustainable high-rise design is based on a square floor plan, with an outer core structure and TT floor slabs.
- For high-rises exceeding 36 stories, material amounts – hence environmental costs – for the foundation and load-bearing structure increase exponentially. This also applies to energy consumption – and environmental costs – by building services and equipment such as elevators.
- A large glazed space is indifferent to environmental performance. It can be recommended if it improves the aesthetic and functional quality.

5.2 High-rise advantages not taken into account

Considerations can be made, of which some will be discussed.

All of the findings of 5.1 refer to buildings only, regardless of the urban context. Some advantages of high-rise buildings and densely built urban areas were not included. Reduction of land use however is evident, so high-rises may avoid construction in ecologically valuable rural areas (Wilde & Dobbelsteen, 2004). Furthermore, dense urban areas stimulate the use of public transport and thereby reduce the demand for energy for travelling purposes (Newman & Kenworthy, 2001).

The time factor was also neglected. The environmental load of a building eventually depends on the lifespan. The functional, aesthetic and cultural value of a building is decisive to the ultimate lifespan, more than its technical quality. Therefore, high-rises as the Commerzbank are expected to last longer than average buildings. In order to get a better picture of performance differences, it is recommendable to assess more (real) high-rises types in dense urban areas.

Moreover, it is an illusion that environmental issues play a role in the ultimate geometry of an office building. Willis (1995) found that the height of high-rises in New York and Chicago constructed before World War II were defined by financial considerations, within the boundaries of local legislation. Since then, the choice between high-rise or low-rise office designs is incited by a few factors (Meel, 2000):

- History: cities bombed during WWII, such as Rotterdam, Frankfurt and London, left open spaces that were suited for high-rise reconstruction.
- Scarcity of land: high rent levels facilitate high-rises.
- Willingness to express: some cities want to demonstrate their financial importance, and they do so by means of high-rise structures.

Powerful market forces created existing high-rise cities such as Hong Kong and Manhattan. In Europe, such strong forces were either absent or overruled by the impact of the urban setting (Meel, 2000).

It will be interesting to see which criteria determine the building geometry in developing countries. We hope that the generic findings from this study will be helpful there.

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