



The Dynamics of Skyscrapers

Scaling, Allometry, and Sustainability

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Outline

- Defining Skyscrapers
- Defining Scaling: Competition In Cities
- London and Hong Kong: Baseline Exemplars
- The Top World Cities
- The World's Buildings
- Glimpses of Allometry
- Back to London: A Different Data Source
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Defining Skyscrapers

Tall structures whose height is much larger than their building footprint and are qualitatively different in construction from smaller ones

The steel frame, the elevator, the telephone, and the revolving door are all key to their invention

They appeared the first time in late 19th century

Chicago: Louis Sullivan, Daniel Burnham, ...



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Chicago's Monadnock Building is the proto-typical skyscraper built in 1891; 16 stories, 60 m

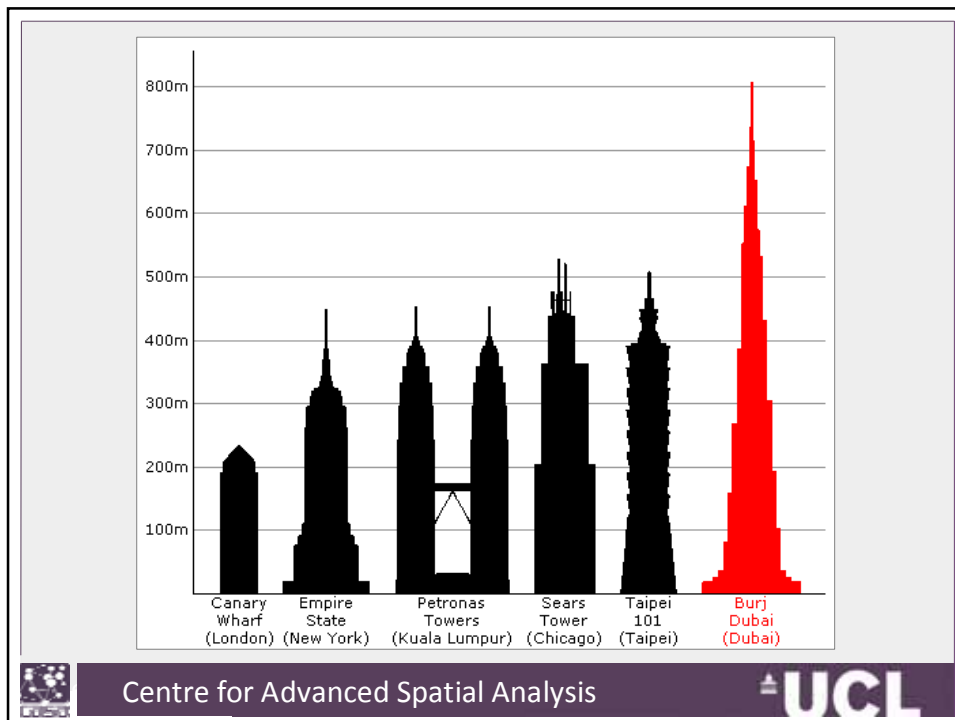


Currently the world's tallest building is the Burj Dubai standing at 818 m or 160 stories (habitable floors)



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The conventional wisdom is that we define a tall building as being greater than 30 metres or maybe greater than 8, 10 or 12 stories

In fact, buildings greater than 30 metres and less than 100 metres are “high rise” while buildings greater than 100 metres are “skyscrapers”

The average height of ‘stories’ over all high buildings is lowest in Paris at 3.27 m and largest in Dubai at 4.32 m

Defining Scaling: Competition In Cities

The ordering of elements such that there are a very small number of large objects/events and large number of small reflects 'competition'. Such systems are asymmetric in that, often but not always, to be 'big' one must be 'small' first. The upper or fat tail of such distributions can be approximated by a power law



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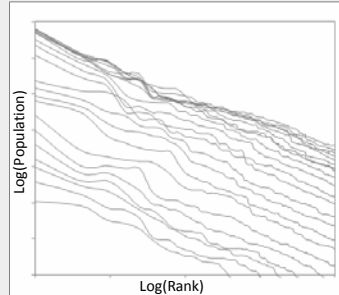
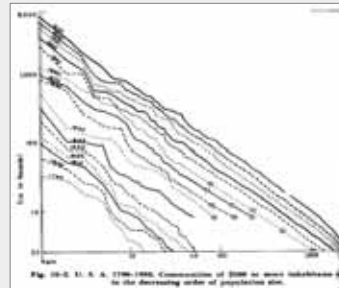
In human systems, such growth behaviour depends on competition for scarce resources and in cities, this is called 'agglomeration' (so-called positive economies of scale). Many simple models of how such scaling occurs have been proposed based on laws of proportionate effect which lead to lognormal-like distributions whose fat tail can often be approximated as one of scaling, by power laws.



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The archetypal example of such scaling is for entire city populations whose distributions can be approximated by a transformation of the frequency called the 'rank size distribution', popularised by Zipf (1949)



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There is considerable debate (and semantic confusion) about the nature of the competitive forces and the shape of the tails but for skyscrapers, there are interesting differences from other competitive phenomena

First, few have been destroyed – i.e. there is only 'growth' of new buildings; *second*, high-rise buildings are 'qualitatively' different from small; and *third*, buildings **do not actually grow**.



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That there is competition for building ever higher both within and between cities there is little doubt – examples in New York City are key

The Chrysler Building, an Art Deco skyscraper stands at 319 metres; it was the world's tallest building for 11 months before it was surpassed by the Empire State Building in 1931. After the destruction of the World Trade Center, it was again the second-tallest building in New York City until December 2007, when the spire was raised on the 365.8-metre (1,200 ft) Bank of America Tower, pushing the Chrysler Building into third position. In addition, The New York Times Building which opened in 2007, is exactly level with the Chrysler Building in height.[6]



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Two Digressions on Competition

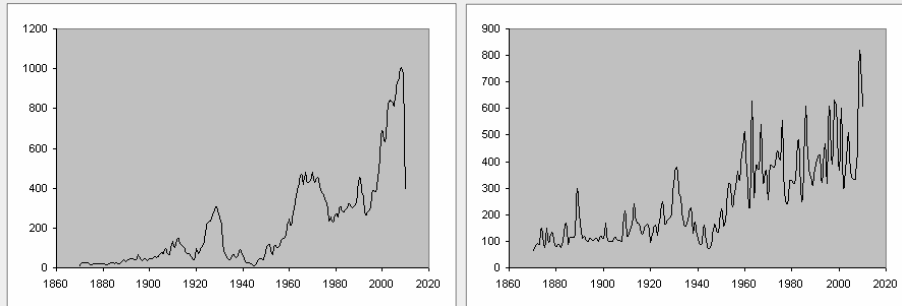
It is said that the Reverend S. Parkes Cadman dedicated the Woolworth Building as a "cathedral of commerce" at its official opening on April 23, 1913. Such buildings tend to become ever higher during times of irrational exuberance. Here is the distribution of the top 29000 high buildings in the world from 1876



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Here is the frequency of buildings > 30 m (left) and highest building constructed by year since 1870s



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And here is an recent extreme example of competition within a world city: Hong Kong



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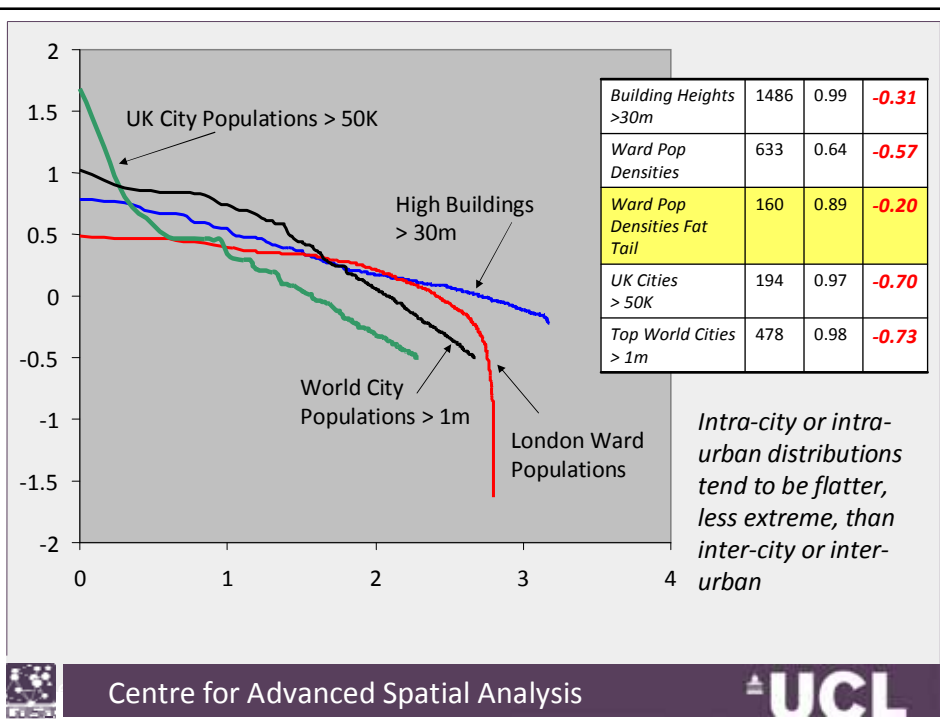


It is easy to guess that high buildings follow a scaling law, but how does this competition compare to other urban distributions such as population densities in cities, populations of different cities, and so on.

To begin, let us look at some distributions of these entities for London, for the UK and for the world



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London and Hong Kong: Baseline Exemplars

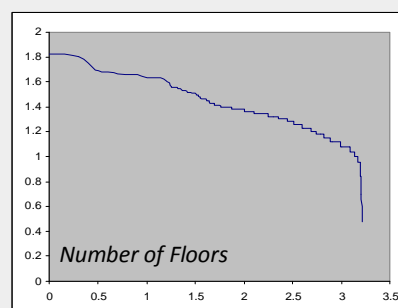
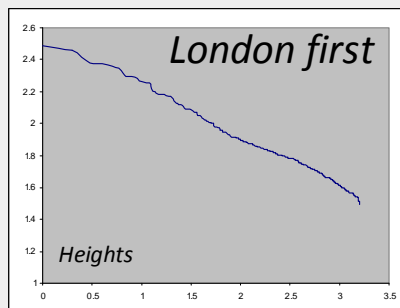
The ***Emporis*** Database: data on high rise buildings > 30 m for many cities, e.g. 8 in UK, 340,000 buildings world-wide with height, stories, floor area, land use type, year of build, Many of these data fields are missing so a much reduced set is only usable for each city; e.g. London has 2495, but 1598 have height data.



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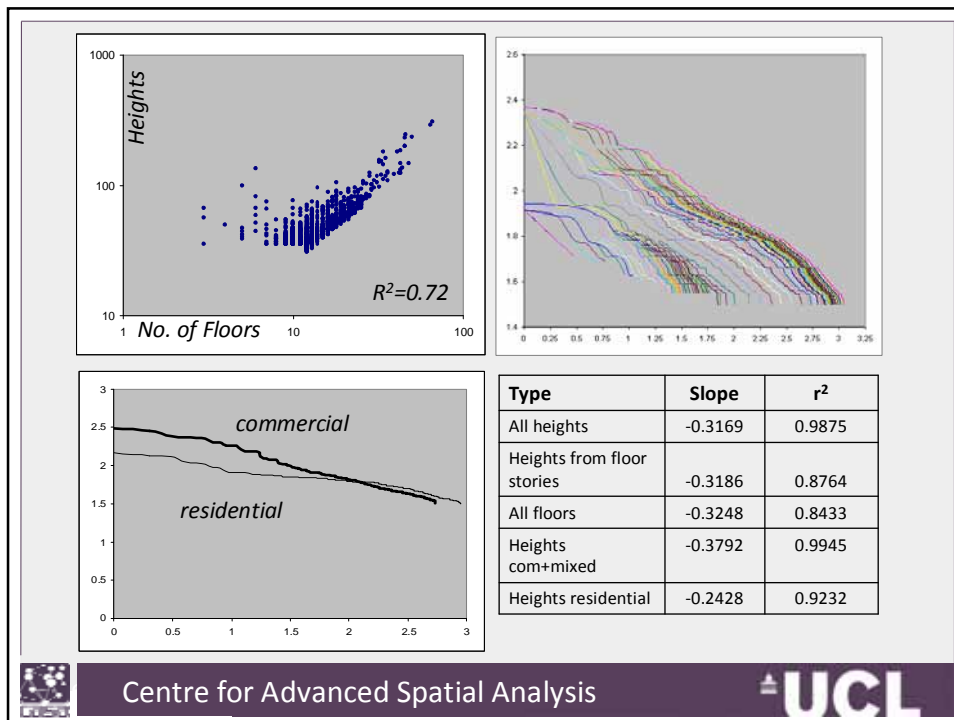


We will look first at three distributions for each city: the scaling of height and number of stories, the prediction of height from stories, and change in scaling from the late 19th C

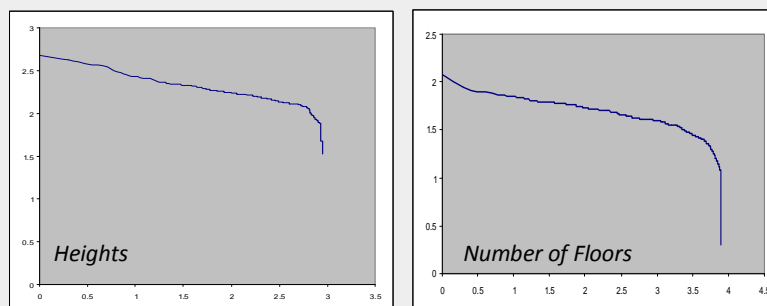


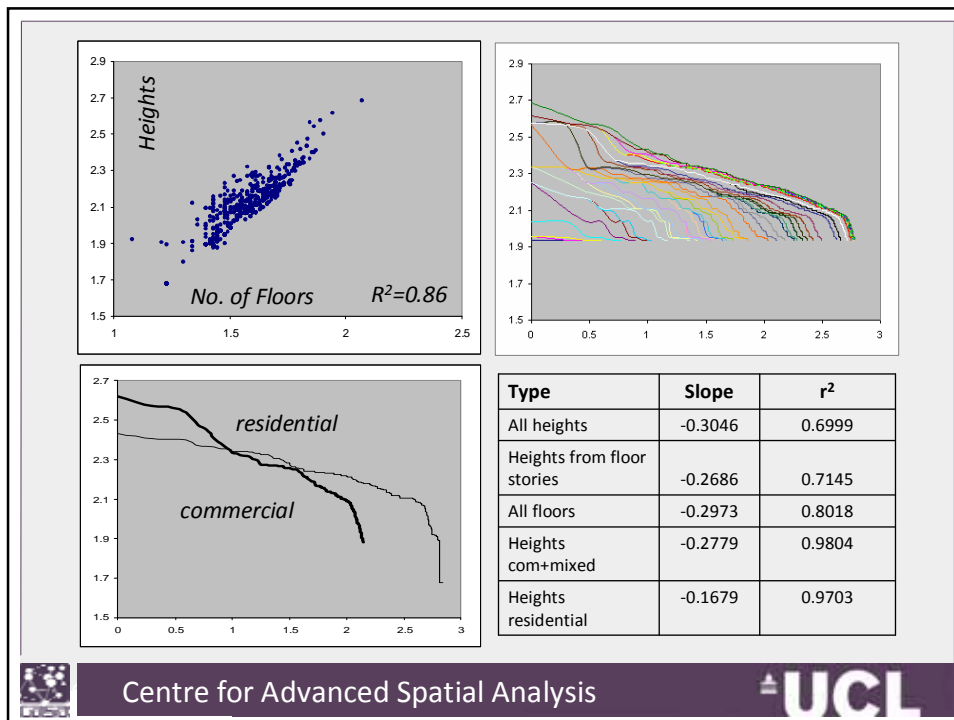
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We can do the same for Hong Kong, our other exemplar, and we will simply show the heights scaling for now, and then for the rest of the cities, simply the results





The Top World Cities

We have taken the top 50 cities in terms of population starting with Tokyo (28 million) down to Melbourne (3 million)

Only 38 have good enough data, and thus we have selected these plus three other iconic cities – Dubai, Barcelona, Kuala Lumpur that have unusual high buildings



Tokyo, Japan - 28,025,000 - 3 478	Santiago, Chile - 5,261,000 - 1587
Mexico City, Mexico - 18,131,000 - 1637	Guangzhou, China - 5,162,000 - 603
Mumbai, India - 18,042,000 - 1366	St. Petersburg, Russian Fed. - 5,132,000 - 962
São Paulo, Brazil - 17, 711,000 - 6850	Toronto, Canada - 4,657,000 - 2883
New York City, USA - 16,626,000 -78 523	Philadelphia, USA - 4,398,000 - 703
Shanghai, China - 14,173,000 – 1222	Milano, Italy - 4,251,000 - 747
Los Angeles, USA - 13,129,000 - 1771	Madrid, Spain - 4,072,000 - 1429
Calcutta, India - 12,900,000- 527	San Francisco, USA - 4,051,000 - 1230
Buenos Aires, Argentina - 12,431,000 - 1893	Washington DC, USA - 3,927,000 - 1402
Seoul, South Korea - 12,215,000 - 3099	Houston, USA - 3,918,000 - 3292
Beijing, China - 12,033,000 - 1122	Detroit, USA - 3,785,000 - 696
Osaka, Japan - 10,609,000 - 1326	Frankfurt, Germany - 3,700,000 - 6632
Rio de Janeiro, Brazil - 10,556,000 - 3042	Sydney, Australia - 3,665,000 - 1190
Jakarta, Indonesia - 9,815,000 - 837	Singapore, Singapore - 3,587,000 - 6801
Paris, France - 9,638,000 - 971	Montréal, Canada - 3,401,000 - 550
Istanbul, Turkey - 9,413,000 - 2553	Berlin, Germany - 3,337,000 - 1125
Moscow, Russian Fed. - 9,299,000 - 2330	Melbourne, Australia - 3,188,000 – 723
London, United Kingdom - 7,640,000 - 2507	Barcelona – 716 – 1605602
Bangkok, Thailand - 7,221,000 - 949	Dubhai 1175 – 1241000
Chicago, USA - 6,945,000 - 2761	Kuala Lumpur – 766 - 1 800 674
Hong Kong, China - 6,097,000 - 8086	



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	Av St	Slope	r ²		Av St	Slope	r ²
LA	4.1940	-0.6773	0.8197	Barcelona	3.9358	-0.4431	0.8993
Frankfurt	3.8447	-0.6135	0.8768	Sao Paolo	3.7728	-0.4429	0.7170
Houston	4.1404	-0.5884	0.7849	Sydney	3.8094	-0.4348	0.9561
Moscow	4.0626	-0.5654	0.8380	Beijing	3.9287	-0.4290	0.7999
San Francisco	4.0334	-0.5649	0.8409	Mumbai	3.5377	-0.4262	0.9250
Madrid	3.9703	-0.5469	0.9293	Shanghai	4.2147	-0.4122	0.8598
Detroit	4.0277	-0.5448	0.9203	Buenos-Aires	3.5224	-0.4110	0.6520
Toronto	3.4009	-0.5195	0.8406	Tokyo	4.1029	-0.4033	0.8271
Philadelphia	3.9459	-0.5156	0.8608	Mexico-City	3.9656	-0.3863	0.7881
Singapore	3.5658	-0.5128	0.8129	Santiago	3.5315	-0.3834	0.8000
St Petersburg	4.0417	-0.5078	0.7607	Seoul	3.9230	-0.3825	0.8550
All Cities-World	3.6714	-0.4874	0.8898	Istanbul	4.0284	-0.3264	0.7179
Chicago	3.5154	-0.4856	0.7909	Milano	3.3808	-0.3225	0.9796
Dubai	4.3194	-0.4786	0.8273	Jakarta	3.8144	-0.3177	0.7146
New York	3.4649	-0.4750	0.9305	Washington	4.0746	-0.3153	0.9145
Melbourne	3.7390	-0.4735	0.9006	Rio de Janeiro	3.3043	-0.3122	0.9107
Paris	3.2732	-0.4724	0.5742	Bangkok	3.7959	-0.3024	0.7780
Guangzhou	4.0083	-0.4678	0.8447	Calcutta	3.4231	-0.2715	0.6600
Montreal	3.9423	-0.4625	0.7441	Osaka	4.1274	-0.2679	0.8348
Berlin	3.4974	-0.4514	0.8737	KL	4.2134	-0.4492	0.9195

London and HK are not in this list yet ...



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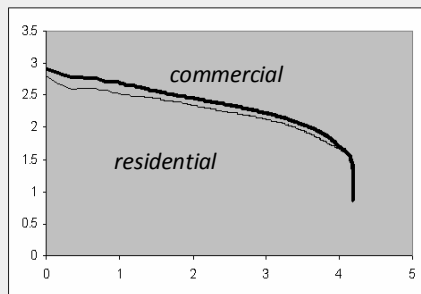
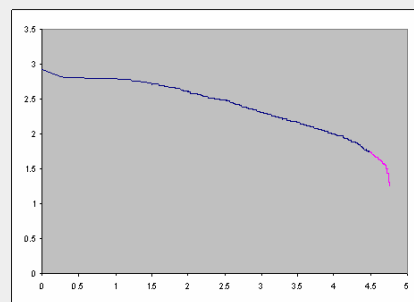
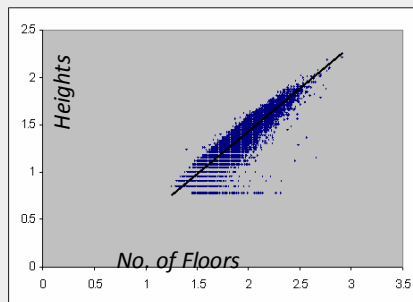
The World's Buildings

We can of course aggregate the data we have looked at into all buildings and we have done this – there are 57000 usable heights from 340K buildings giving you a crude idea of the accuracy and error in this data set.

There are 33314 usable stories which is less than heights



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We have not done the temporal scaling relations as yet



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<i>Regressions</i>	Min	Av	No	Intercept	Slope	r ²
<i>All buildings</i>	3.6714					
All heights	18	70	56999	3.8932	-0.4874	0.8898
All heights less long tail	72	113	21053	3.3029	-0.3290	0.9906
All heights from floors stories	4	72	33314	3.8533	-0.5043	0.7626
As above less long tail	73	117	11850	3.0857	-0.2849	0.9398
Heights com+mixed	13	81	15464	3.8037	-0.5240	0.8546
Heights residential	12	66	16075	3.4930	-0.4581	0.9081
Heights viz floorarea			8299	0.2000	0.3768	0.4222
Height rank			3445	3.1134	-0.3303	0.9611
Floor rank			4218	6.5103	-0.5641	0.9511



Glimpses of Allometry

I am fast running out of time but my ultimate purpose is to ask the fundamental question
“How Big is a City?” & “How Sustainable is It?”

This is a question that I do not believe can be answered any other way, in terms of population for example; it must be looked at with respect to how we use space and this relates to the size of buildings



From the data base, we have floor area; we do not have volume or surface area so we cannot get any detailed sense of how a building's volume changes as it gets bigger

Now this is not a talk on allometry per se but as a building gets larger in volume, then its surface area must increase faster than the usual Euclidean relation for buildings require access to natural light



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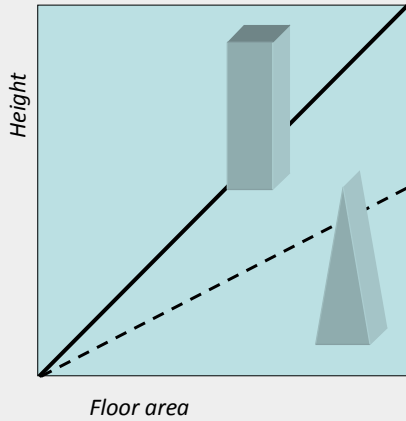
It has been shown that for building volumes, the building surface area scales as the power of $\frac{3}{4}$ of the volume, following Kleiber's Law, not as $\frac{2}{3}$ of the volume as the geometric relation would suggest.

We have done quite a bit of work on this and I will refer to the papers later, but all we have from this data set is floor area and we might suppose that floor area scales as height.



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These are the simplest theoretical relations but there are other shapes with plinths and so on ...

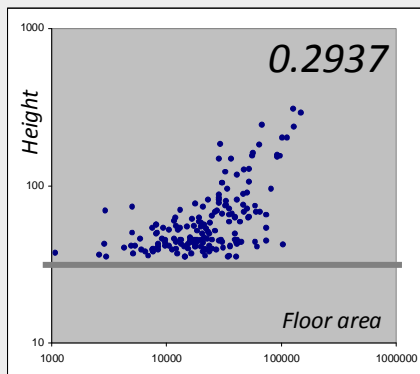
We can now quickly look at our data bases and these relations



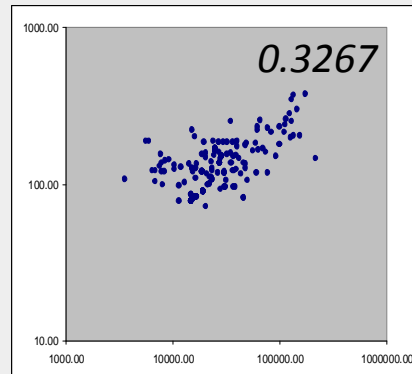
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Here we look at the relationship between Height and Usable (not Gross) Floor Area for London, HK, and the World's Buildings



London



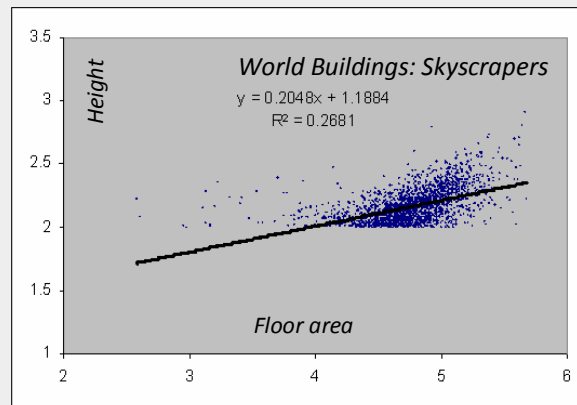
Hong Kong



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From this it looks like height scales more as $H^3 \sim F$ than $H^1 \sim F$



0.3259; for skyscrapers above, this is 0.2048



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Back to London: A Different Data Source

We have good data from LIDAR and vector building footprint and we are working hard to examine all the relations in this paper using our geometric database of London which has currently 3.6 million building blocks from which we can get surface area, volume etc.

Note that the problems of defining a building ...



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Scaling and allometry in the building geometries of Greater London

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Abstract. Many aggregate distributions of urban activities such as employment, retail, and residential can be used to approximate the size distributions of individual buildings which have been widely studied as rank-size and lognormal distributions and the Principle of Least Effort (Alderson-Wolsey, Cambridge University Press, 1991). We then extend the analysis of building heights from the Emporis database which suggests the data base for Greater London is then introduced from which we explore key allometric relationships illustrating how building shape changes according to size, and we extend the analysis of building geometries which supports our non-spatial analysis of scaling.

PACS. 89.65.Lm Urban planning and construction – 89.75.Da System structures and organization in complex systems

RESEARCH PAPER

Wall area, volume and plan depth in the building stock

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This research examines the volume of a building and its wall area in relation to its plan area and height. It shows that the relationship between wall area W and volume V can be expressed as $W \propto V^{2/3}$, and that the relationship between wall area W and plan area A can be expressed as $W \propto A^{1/3}$. The data base for Greater London is then introduced from which we explore key allometric relationships illustrating how building shape changes according to size, and we extend the analysis of building geometries which supports our non-spatial analysis of scaling.

Keywords. allometry, building geometry, building volume, building wall, building height, plan area, urban form, urban



Next Steps

We have a lot of issues and I will list these

1. It appears that storey height increases with the year of construction & also the ‘newer’ the city
2. Floor area increases with height and we ‘think’ from our London work that surface area does indeed increase at the $\frac{2}{3}$ power of volume
3. Building higher requires more artificial light



4. Essentially it looks like the higher we build, the more energy per unit volume, floor area, surface area we consume
5. We should be able to compute the difference between what might be required in artificial light & the actual light in each building block and use this as a measure of sustainability
6. We can add up these values for each city, determine how big it is and how much energy it uses



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*If there is time,
I will answer any*
Questions

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