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BEYOND COMPACT CITY:

A spatial configuration model for carbon emission reduction

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Abstract

This paper proposes, in the context of sustainable urban form, a GIS-based quantitative model to estimate carbon emission amount primarily affected by the spatial configuration of street layouts and building masses. The model is composed of the two parts: carbon emission directly caused by horizontal vehicular movements between buildings and that which is transformed from electricity consumption by vertical elevator movements within buildings. The performativity of various hypothetical urban forms is examined with this model, particularly in their local height and grid intensification conditions. The simulated results are then compared with those from a case study of New Town Projects in Seoul. Taking carbon emission amount as a single currency, we aim through this study to make comparative morphological studies possible and also to locate what is often overlooked in the current discourse on compact city.

Keywords: *Carbon Dioxide Emission, Sustainable Urban Form, Spatial Configuration, Compact City*

Theme: *Green Urbanism and Sustainable Developments*

1. Introduction

The relationship between sustainable development and urban form has been extensively discussed in the age of global warming. There seems to be an unequivocal agreement that relentless urbanisation is a primary cause behind this accumulating environmental crisis, and consequently urban planners and designers together have actively been seeking for a more sustainable way of developing our cities over the generations. But such a consensus starts to break down as soon as we ask what exactly 'sustainability' means for cities. Duany (2010), for instance, has pointed out at least three different contending ideas of sustainable urbanism, but his own suggestion for it seems to remain less than compelling.[1] Moreover, what is meant by 'urban form' when researchers and practitioners argue that 'compact city', in opposition to 'urban sprawl', is an alternative form of sustainable development? Population density has more than often been employed to represent compact or sprawled urban form, but this umbrella measure remains far short of being successful in producing consistent evidence for the connection between compactness and sustainability (Neuman, 2005). As Neuman points out, "Surprisingly, [they] have only recently begun to rigorously define the compact city apart from density."

In line with these recent efforts, Hillier (2009) has suggested an idea of *spatial sustainability*, by which he means that the geometric and configurational ordering of space in a city is in itself an important evidence to reflect its sustainability. This is because the spatial form of a city is already the product of interaction between environmental, economic and social factors, namely, the three pillars of sustainability. In particular, a city can be made more sustainable by the reorganisation of its street network, through the process called 'local grid intensification' in the centre, since, as he argues, it is capable of enhancing the 'general accessibility' within the city and thus reducing the energy consumption required for vehicular movements.[2] In another context, Ratti et al. (2005) have tried to show that the spatial form of cities alone (apart from building design, system efficiency and occupant lifestyle) may account for up to two times variation in energy consumption, if not by reducing movements by cars, but by increasing naturally-lit-and-ventilated zones in individual buildings. At the heart of their work lies the idea that the production of such 'passive zones' should also be seen as a matter of urban geometry and configuration through the spatial arrangement of building masses, or the idea of spatial sustainability in short.

To some extents, this paper is an attempt to consolidate the idea of spatial sustainability, *by combining the configuration both of street network and building masses*. Many have already tried, since the much-cited work by Rickaby (1987), to explain energy consumption in terms both of accessibility at the urban level ('between-place energy') and of utility at the building level ('within-place energy'). However, there has rarely been an attempt to integrate the two types of energy consumption variation not only from a technological (e.g. solar heating, insulation, electric vehicles) but also from a configurational viewpoint. We will assume that configurational effects

1 They are first 'Old (or Traditional) Urbanism' which values high density at the expense of nature in cities, 'New Urbanism' which attempts a sort of hybrid compromise between city and nature, and 'Landscape Urbanism' which seeks for an active introduction of nature in city. Duany (2010) tries to generalise his own idea of 'Sustainable Urbanism' by retaining the best aspects of these three urbanism while improving at the same time the green performance of suburb areas that have been neglected by all of them.

2 To be more precise, 'local grid intensification' refers to a process by which blocks in the central area of a city get more dense and smaller in size, and it can be observed as such in almost any of self-organised cities around the world (see also Hillier, 1999). In Space Syntax, the process is understood as being based on the principles of minimising 'universal distance', that is, mean distance from all points to all others in a spatial network.

exist if the mass and location of buildings can bring differences to the amount of energy required for movements in a street network. This may lead us to ask, for instance, how a high-rise building located at the centre of a city is different from the same building at the periphery with regard to city-wide energy consumption. On the other hand, we do not yet fully understand how the process of 'local grid intensification' can be related to the arrangement of building masses in the grid. It might also induce 'local height intensification' in the centre, but such a typical image of high-density and high-rise compact city has been rejected by some researchers (Owen, 1992; Hui, 2001) as it will increase electricity consumption through heavy elevator uses at the building level.

In this paper, we develop these ideas further by introducing a configurational model in which two types of movements are combined: movements by elevators *within* buildings and movements by private cars *between* buildings. By assuming that these movements occur in proportion to building masses and also under the constraints of street network, the model measures height and distance travelled to estimate the *total amount of carbon emission* in a city area. This model is therefore seen different not only from the conventional traffic model in that it refers directly to physical urban components, but also from the conventional space syntax model in that it deals explicitly with movements (or trips). It is not yet our purpose to make our model perform a diagnostic function by estimating the exact amount of carbon emission. Rather, we aim specifically to make comparative morphological studies possible by taking the amount of carbon emission as a single currency. For this purpose, we first apply the model to the simulation of various theoretical urban arrangements and validate its performance. The findings will then be re-evaluated in the real context of 'New Town Project' in Seoul, which have pursued in themselves for the objective of sustainable developments. In so doing, we will pay our special attention to discuss how 'local grid intensification' can be related to 'local height intensification' in the course of minimising carbon emission, and in the end, to reveal what has been so far overlooked in the discourse on compact city and by the measure of population density.

2. Model Construction for Carbon Emission Estimation

2.1. Carbon emission associated with movements

First of all, we assume a simple path connecting two places *i* and *j* and a virtual movement or trip realsing this path once in a day. The movement is not continuous but shall consist of three different parts: *horizontal movement* by a private car between the two places and *vertical movement* by an elevator within each place. So the amount of carbon emission c_{ij} [gCO2] associated with a single movement can be defined as:

$$c_{ij} = r_i h_i + t_{ij} d_{ij} + r_j h_j$$

where r_i (or r_j) stands for the unit amount of carbon emission, through electricity consumption, by an elevator [gCO2/km]; t_{ij} for the unit amount of carbon emission by a car [gCO2/km]; h_i (or h_j) for height travelled by an elevator [km]; and d_{ij} for distance travelled by a car [km].

While the unit amounts of carbon emission r_i and t_{ij} may vary independently of their relative locations, both distance d_{ij} and height h_i are spatial in nature and supposed to have configurational effects in their own rights. For the sake of simplicity, we will assume throughout this paper that r_i and t_{ij} are global parameters remaining invariant for all places and all types of elevators and cars (i.e. $r_i = r_j = r$ and $t_{ij} = t$). On the other hand, d_{ij} and h_i are variables directly measured from a given spatial condition: 'shortest path distance' in a street network where cars travel and the 'effective height' of buildings through which elevators move. Here the 'effective height' is a kind of average distance which an elevator travels in a single movement. Considering vertical distance above the third floor in a building, it is defined as the half of that distance plus the height of three floors, such that $h_i = 0.5(f_i + 3)\delta$, where f_i is the number of floors and δ is the standard floor-to-floor height. For d_{ij}, we measure shortest path distance between the two points on streets which are closest, along the shortest perpendicular connection, to the centroids of building footprints (Figure 1).[3]

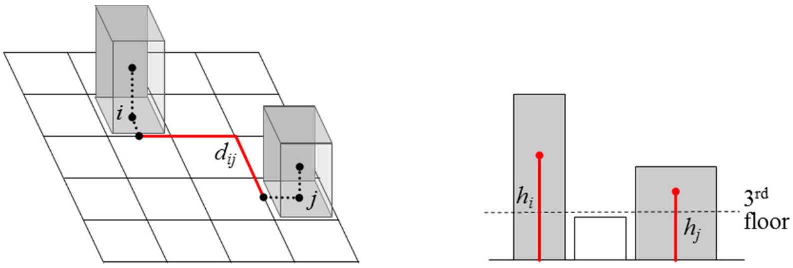

Figure 1: Distance travelled by cars in a street network (Left) and effective height travelled by elevators in individual buildings (Right)

Secondly, the same path is repeated in a day by multiple movements m_{ij} that occur in proportion to the population p_i of an origin and the total floor space (i.e. attraction) s_j of a destination.[4] If we also assume, following the basic postulate of trip generation model (Hutchinson, 1974), that population p_i of an origin is proportional to its total floor space s_i, then we have:

$$m_{ij} = p_i \cdot \frac{s_j}{\sum_i s_i} = ks_i \cdot \frac{s_j}{\sum_i s_i} = k' s_i s_j$$

where $k = p_i/s_i$ is a proportionality constant that can be estimated by $P/S = \sum_i p_i / \sum_i s_i$ (the ratio of total population to the sum of total floor space in an area) and thus $k' = P/S^2$. This result confirms that movements are symmetrical (i.e. $m_{ij} = m_{ji}$), not necessarily distinguishing origins and destinations.

Hence, the total amount of carbon emission C_{ij} produced by those multiple movements between two places becomes:

$$C_{ij} = c_{ij} m_{ij} = k' s_i s_j \left(rh_i + td_{ij} + rh_j \right)$$

[3] This algorithm has been implemented in UNA (Urban Network Analysis), an open-source toolbox for spatial network analysis in ArcGIS, by Sevtsuk and Mekonnen (2012).

[4] Or, it is equivalent to the assumption of completely mixed-use development, so that the ratio of non-residential use (destination) to residential use (origin) remains the same for all buildings in a city.

2.2. Place-specific values and whole-map values

Now consider the sum of C_{ij} over all the other places *j* than a root place *i*. This will represent the total amount of carbon emission resulting from all the movements ending in that specific place.[5] We will call such an amount the *carbon emission potential* of a place and define precisely as:

$$C_i = \sum_j C_{ij} = krs_ih_i + k's_i\left(r\sum_j s_jh_j + t\sum_j s_jd_{ij}\right)$$

In turn, the total amount C of carbon emission in a whole area of interest can be considered simply as the sum of the carbon emission potential over all places, that is:

$$C = \sum_i C_i = 2kr\sum_i s_ih_i + k't\sum_i\sum_j s_is_jd_{ij}$$

Note that the first term in this equation refers to the amount C_V of carbon emission by vertical movements and the second term to the corresponding amount C_H by horizontal movements. The ratio C_V/C_H is then a whole-map value representing the relative weighting of vertical movements over horizontal movements in an area and can be employed as such to grade its 'compactness' in certain conditions. Dividing C by total population $P = k'S^2$, we can also have as another whole-map value the average amount of carbon emission per person in an area. Such a per-capita value C/P is especially useful when comparing the configurational effects of different areas independently of their population sizes.

2.3. Model parameter estimation

There are three model parameters that need to be estimated empirically in order to operate our model: the unit amounts of carbon emission r and t and the standard floor-to-floor height δ. Reflecting the types of vehicles, their component ratio, building construction techniques, lifestyles and so on, their values may well be different depending on local contexts to which the model is applied. In this paper we refer to the Korean context, for which the three parameter values have been estimated as shown in the following table.

Table 1: Basic units for carbon emission estimation

r (by elevators)	t (by cars)	δ (floor-to-floor height)
611 gCO2/km	239 gCO2/km	0.003 km (3 m)

Following basically a previous study by Yang and Choi (2011), we have combined the electricity power consumption by elevator-type (Korea Elevator Safety Institute, 2013) with the CO2 emission coefficient per electricity energy of 424.81 gCO2/kwh (Korea Energy Economics Institute, 2013) to estimate r. For the estimation of t, we have referred to the data on CO2 emission by

5 We note at this point that a place can be represented not only by a building but also by a block in which the properties of buildings located within it are all aggregated.

car-type (Korea Energy Management Corporation, 2013) and employed their median value to take into account the high skewness of the data. But here we note briefly that the parameters can be also classified to reflect the various types of cars and elevators.

3. Simulation #1: Varying Population Density

Our first simulation is run on a technical setting where the total floor space S and population P remain constant, but only population density ρ is allowed to vary with built area *A*. In addition, we assume a regular grid pattern of streets and a uniform building height *f* over the entire area. This is an obvious idealization of real cities, but intended as such to filter out the effects of urban envelope on carbon emissions with bringing configurational effects to the minimum. Since $P = kS$ in our model, population density $\rho = kS/A = kf$ is found to be a function of uniform height only, which is in turn inversely proportional to area. It is also assumed that density may vary from the extreme 'urban sprawl' case in which no vertical part of carbon emission C_V exists to the opposite 'compact city' case in which no horizontal part of carbon emission C_H exists. It is therefore the case that we are given with an all-or-nothing situation, highly unrealistic in itself, but deemed sufficient to embody most of the discourses on 'compact city', in which population density dominates as a proxy of urban form.

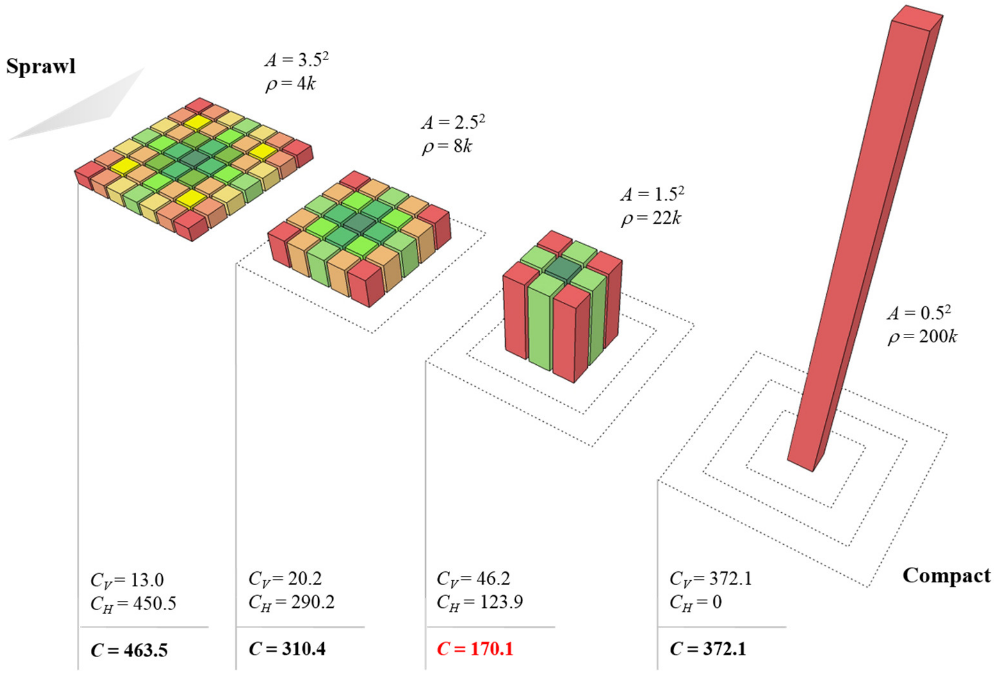

Figure 2: Total amount of carbon emission (per capita) changing with population density. The variation of colour represents carbon emission potential for individual buildings (Red: high, Green: low)

Figure 2 above illustrates then a particular case with the constant of $S = 50$. Population *P* do not need to be specified, but we can see that population density ρ increases discretely from 4*k* to 200*k* as area decreases from 3.5^2 (7×7 grid) to 0.5^2 (1×1 grid) with the fixed shape of square. Such an enforcement of compactness will of course cause the vertical part of carbon emission C_V to increase, while the horizontal part C_H to decrease. However, the total amount of carbon emission *C*, as the sum of those two parts, does not change in such a monotonous way, but rather it reaches a minimum at certain density ρ^* (Figure 3 left). This is a kind of 'optimal density' beyond which compactness will not bring any further reduction in carbon emission, mainly due to high energy consumption through heavy elevator uses. In other words, it is desirable to achieve urban compactness as it will reduce travelling distance by cars, but only to a certain extent; we should not go too far in this way.

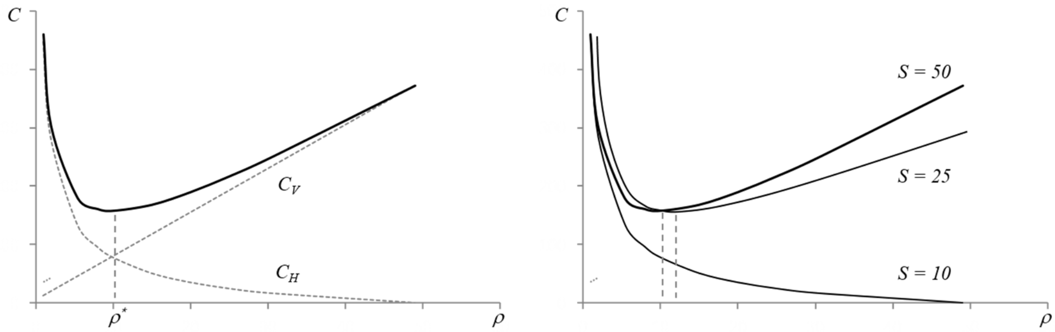

Figure 3: The minimum total amount of carbon emission at an optimal density (left) and the non-existence of minimum points in the case of small population (right). Density has been relativised for comparison in the latter

However, we can also note other particular cases where such an optimal density does not exist. If we suppose total floor space *S*, and thus population *P*, are much smaller, say *S* = 10, than our initial conditions, then density will get lower accordingly over the same areal condition. Yet, in this case, compactness will never make buildings high enough to produce vertical carbon emission to the extent comparable to its horizontal counterpart and thus there will be no lower bound for total carbon emission (Figure 3 right). It is in this case that the arguments for 'compact city' regain most of its power, that is, when population a city needs to accommodate is relatively small. For cities with large population though, we have already seen that compactness with high density may have to pay its cost. These results together seem to highlight a divergence in our strategic approaches to reduce carbon emission: when to foster compactness through high-rise and high-density buildings at the city-wide level or when to improve energy efficiency at the individual building level. There seems to be no cure-all even in this little domain of entire urban carbon emission scenarios.

4. Simulation #2: Varying Spatial Configuration

For our second simulation, it will be assumed that the total floor space and population are constant again, but their spatial arrangements are allowed to change within a city of the fixed area. More specifically, starting from the non-optimal state with the same extensional condition of $\rho = 8k$ (*S* = 50, *A* = 2.5^2) as in the first simulation, we ask how much total carbon emission can be reduced further by modifying only the configuration of street layout and building height. Street layout may get dense or loose around the centre, while building height may rise up or down exponentially toward the centre, independently of street layout. In this way we suppose the nine moments in the matrix of 'local height intensification' (**C-to-A axis**) and 'local grid intensification' (**1-to-3 axis**) (Figure 4). Note that the uniform arrangement **B2** is that which has come from the first simulation and sets itself now as a datum to evaluate the performances of the other non-uniform arrangements. Table 2 shows for the whole map values of each arrangement i) the total amount of carbon emission per capita, C/P, as the sum of vertical and horizontal parts; ii) the C_V/C_H ratio, and iii) the change amount of carbon emission relative to the uniform **B2**.

Table 2: The comparison of total carbon emission amount as the sum of its vertical and horizontal parts (top), C_V/C_H ratio (middle) and the change rate relative to the uniform arrangement B2 (bottom)

	1	2	3
A	28.6 + 162.2 = 190.8 17.65% (▼38.5%)	36.4 + 188.7 = 225.1 19.28% (▼27.5%)	46.5 + 227.5 = 274.0 20.44% (▼11.7%)
B	20.2 + 293.0 = 313.2 6.88% (▲0.9%)	20.2 + 290.2 = 310.4 6.95% (0%)	20.2 + 305.8 = 326.0 6.59% (▲5.0%)
C	24.0 + 365.3 = 389.3 6.58% (▲25.4%)	22.9 + 330.4 = 353.3 6.92% (▲13.8%)	21.4 + 324.1 = 345.5 6.62% (▲11.3%)

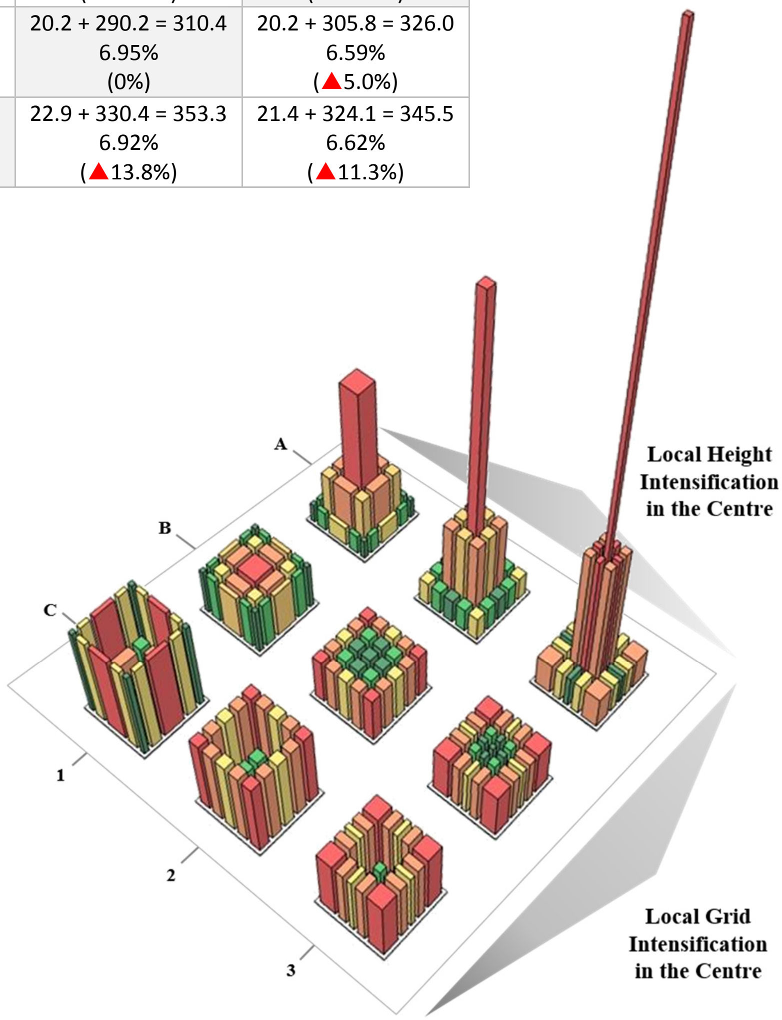

Figure 4: Carbon emission potential of individual buildings changing with their mass and location (Red: high, Green: low)

We first focus on height variations and find that the horizontal part of carbon emission tends to decrease as height intensifies toward the centre (C-to-A), irrespective of local grid conditions, which leads to the reduction of total carbon emission amount in general. Due to the presence of high-rise buildings, the vertical part tends to increase in any ways other than the arrangements of uniform height. But the C_V/C_H ratio itself reaches maxima only with the cases of local height intensification in the centre (**AX** arrangements). This is because, in the case where height intensifies toward the periphery, both the vertical and horizontal parts of carbon emission tend to increase. Such a case of local height intensification in the periphery would be hard to find for real cities anyway. It is therefore local height intensification in the centre that seems to be a right configuration to reduce the amount of carbon emission. In particular, the arrangement **A1** reduces carbon emission by the greatest amount (38.5%) compared to the uniform **B2** and comes almost to a rival to the optimal arrangement with higher density in Figure 2.

However, no such clear tendencies can be found with grid variations. The horizontal part of carbon emission may increase in the case of **AX** arrangements or decrease in the case of **CX** arrangement as street layouts get denser in the centre. In the case of **BX** arrangements, where building heights are uniform, any types of local grid intensification tend to increase the horizontal part. These results seem to be at odds with those found by Hillier (1999, 2009), in which he has shown that local grid intensification in the centre reduces the 'universal distance' of street networks (i.e. $\sum_i \sum_j d_{ij}$) and this reduction of 'universal distance' is a crucial condition for spatial sustainability. A crucial difference of course lies in that we are here dealing explicitly with movements, rather than paths, and therefore 'universal distance' involved in our model through horizontal movements has been weighted by the total floor space of individual buildings. If not weighted, or speaking more technically, if total floor space is the same for all individual buildings, then we should be able to verify what Hillier found. Indeed, such an effect of unweighted or equally weighted 'universal distance' can be identified in our simulation, particularly when we follow the diagonal series of **C1**-**B2**-**A3** in the matrix of arrangements (marked in grey). If we note first that taller buildings must have smaller building footprints, and vice versa, in order to maintain the same total floor space and also that it is only those three moments which can be so arranged, their series can be seen to represent the proper effects of local grid intensification in the centre through carbon emission reduction by horizontal movements.

After all, Hillier in his papers has not taken explicitly into account what will fill in street layouts. In the course of combining the effects of local height intensification with those of local grid intensification, we have been able at least to make it explicit and thus to visualise a three dimensional image of local grid intensification in the centre. However, in doing so, we have also realised that local grid intensification in the centre may not be the only process for sustainable urban form as well as for centrality. As shown, the arrangement **A1**, where buildings are higher but grid is sparser in the centre, seems to have much superior performativity in terms of carbon emission reduction than **A3** in which both height and grid intensify in the centre. In effect, it seems to be the case, mainly due to the simple fact that the total floor space of the most central building in **A1** is much greater than that in **A3**, so that most horizontal movements are allowed to arise only in the central area. It remains therefore as a question, considering together with the variations of building mass, why and how local grid intensification in the centre can be so frequently observed in real cities.

Finally, if it is the case that the arrangement **A1** performs best in reducing carbon emission, we may need to clarify its implications for real cities. What should be noted first and foremost is that this arrangement requires, irrespective of population density, a massive as well as tall building (or a large block with high-rise buildings) at the centre of a city, so that most citizens can live and work in it without a need to move around by private cars. This may imply further two things in regard to urban design and planning processes. First, a relatively large portion of area in the centre would have to be designated as 'car-free zone' or made accessible only by public transport.

In this way may we also reduce traffic congestion problems in the central area which can be expected in such an arrangement as **A3**. Second, the relatively high value of C_V/C_H ratio indicates that technical innovation at the level of individual buildings (e.g. energy efficient building systems) may induce most dramatic consequences at the level of whole city. By comparison, the same technological innovation applied to **A2** or **A3** may bring relatively small effects at the city-wide scale and further it may cost too much to make those skyscrapers energy-efficient sufficiently. Also, no prior places can be assigned to apply such technical innovations in the case of **BX** arrangements, or low energy buildings in the periphery would produce only minor effects in the case of **CX** arrangements. There is perhaps nothing novel in these ideas; but at least, our configurational model seems to succeed in making these ideas replete with spatial definition, in probing the right place for right technology. The so-called 'ruralisation' of an entire city, which Landscape Urbanists do not hesitate to advocate, could be given no real values in this perspective.

5. Case Study: 'New Town' Developments in Seoul

Now we apply our configurational model to real cases and see how it works. Cases selected for this purpose are five New Town Project Areas in Seoul. Initiated by the Seoul Metropolitan Government in 2002, New Town Projects denote large-scale urban redevelopments which aim to "systematically reorganise outdated residential quarters and to foster urban core in the underdeveloped areas towards a more balanced development (Kang, 2012)." They are thus 'town within town', rather than new towns in suburbs, and being currently implemented as a key means of re-engaging public sector with urban redevelopments that have been mostly dominated by private sectors. In terms of their physical form, New Towns can be typically envisaged as an estate of high-rise mixed-use buildings that will replace a blighted area of low-rise residential buildings, allowing for more green areas such as parks and other well-being facilities (Figure 5). Total floor area is planned to increase after developments, while the number of buildings will naturally decrease (Table 2).

Table 3 Comparisons of before and after New Town developments. All numerical values are those characteristic of the 2 Km-radius catchment area of each New Town and carbon emission amounts are estimated per capita**.**

Areas		C_H	C_V	*C* (gCO2)	change rate *C*	C_V/C_H ratio	# of Bldg	*S* (km2)	change rate *S*
CH	Before	588.4	22.7	611.1	+0.6%	3.86%	21,410	15.74	+1.4%
	After	591.0	23.6	614.6		4.00%	20,141	15.97	
GR	Before	499.3	22.7	522.0	+0.1%	4.56%	22,483	16.34	+3.9%
	After	498.3	24.1	522.4		4.84%	21,206	16.98	
DE	Before	500.6	9.8	510.3	-0.2%	1.95%	23,932	15.36	+2.1%
	After	481.2	28.2	509.3		5.85%	23,209	15.69	
YD	Before	559.4	28.1	587.5	-0.8%	5.02%	19,361	14.14	+3.8%
	After	553.8	29.2	583.0		5.27%	18,845	14.68	
WS	Before	539.4	21.3	560.7	-2.2%	3.95%	35,185	14.67	+6.4%
	After	525.4	22.8	548.1		4.34%	34,568	15.61	

Since New Towns are not self-contained entities as those in the previous simulations, their catchment areas must be delineated in the first place for analysis. We have drawn a circle of 4 km diameter in such a way that a New Town lie in its geometrical centre. This size does not seem to be sufficiently large when considering vehicular movements, but it has been so chosen as to compromise with the practical limitation of computational time. Note that distance travelled by vehicles cannot but increase with the size of catchment area, so the absolute values of carbon emission and C_V/C_H ratio themselves should not be taken much seriously, if not for comparison purpose. In comparing before and after developments, we also have to employ per-capita value C/P to take into account differences in total floor area and population induced by New Town developments. In effect, we may regard this analytical setting as emulating local height intensification in the centre, with varying local grid conditions and population densities. Due to this height intensification, carbon emission by vertical elevator movements will of course increase in all of five New Town areas after developments.

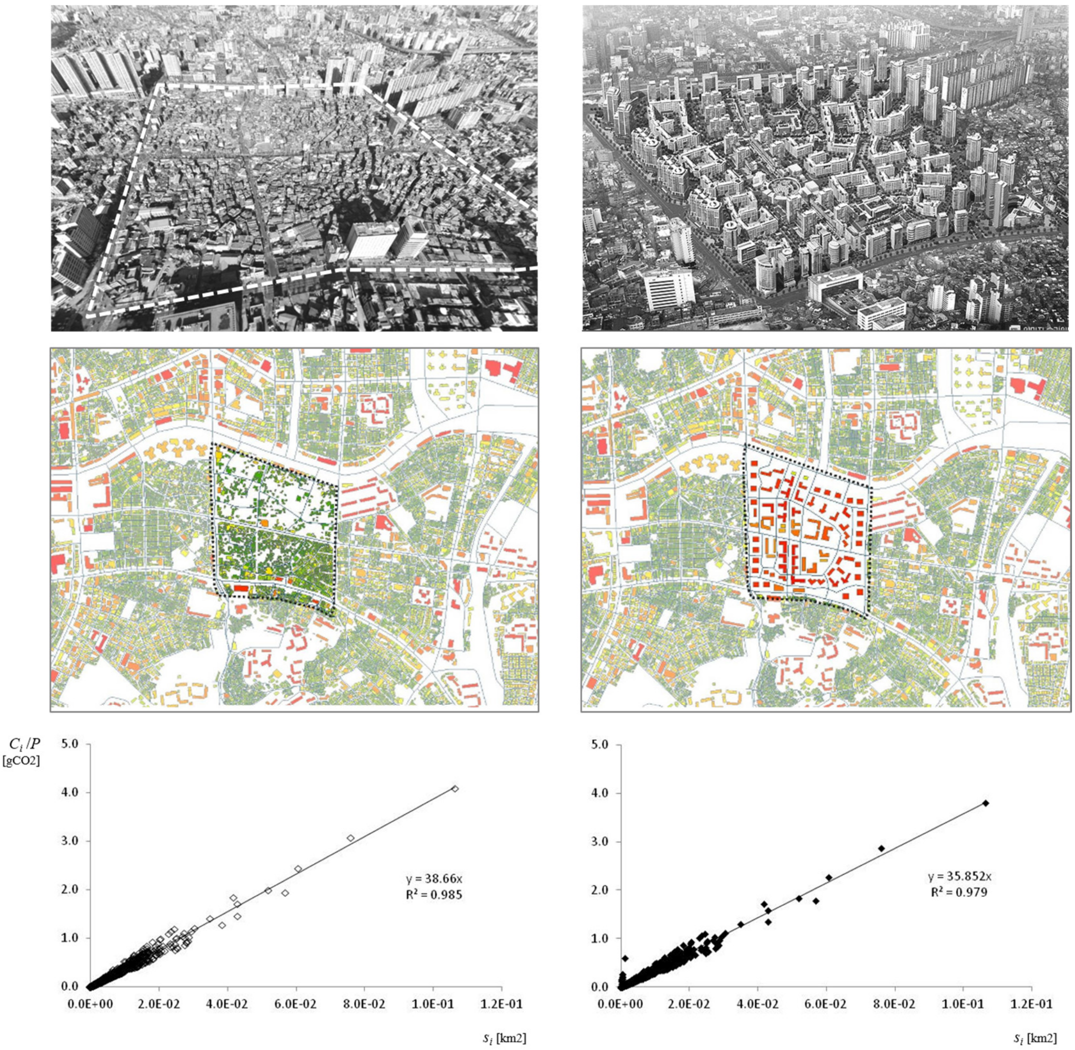

Figure 5: Wangsimni (**WS**) New Town development (currently under construction) showing the spatial distribution of carbon emission potential for individual buildings and the regression of carbon emission potential on the total floor area of individual buildings (image source: Daum Map)

However, the total amount *C* of carbon emission may decrease or increase due to the combined effects, which are configurational in nature, of horizontal and vertical movements (Figure 6). In Chun Ho (**CH**) area, for instance, the total carbon emission amount increase by 0.6% and this seems to be mainly because the area is located on the riverside and thus realise the contrary effects of attracting movements toward the periphery. The total carbon emission amount for Gari Bong (**GB**) area also increases by 0.1% and we can see for this case that the effects of local height intensification in the centre tend to be diffused by massive high-rise buildings in the surroundings. On the other hand, in all the other three New Town areas, we can expect the reduction of total carbon emission amount after developments, which is mainly due to the reduction of carbon emission by horizontal vehicular movements. In particular, Wangsimni (**WS**) area, for which total carbon emission amount is expected to decrease by 2.2%, seems to illustrate the effects of local height intensification in the centre typically well.

a) Chun Ho (CH)

b) Don Eui (DE)

c) Young Deungpo (YD)

d) Gari Bong (GB)

Figure 6: The spatial distribution of carbon emission potential for individual buildings before and after New Town developments

Underlying these variations, we report one final property that is common to all the five New Town areas, which is that carbon emission potential for individual buildings is directly proportional to their total floor area (see Figure 5 for the example of **WS** area). The relationship between the two variables can be thus expressed by the simple equation as in the following:

$$C_i = \mu\, s_i \qquad \text{or} \qquad C = \mu\, S$$

where μ is a proportionality constant. What this simple equation tells us is that the increase in the sum of total floor area in an area will result in the increase in the total amount of carbon emission. However, as we have shown, the total amount of carbon emission may decrease while the sum of total floor area increase after developments. This is possible only because the parameter μ changes along with developments (from 38.7 to 35.9 in **WS** case) and it is by nature characteristic of the spatial configuration of building masses and street layouts. It is thus true to argue that carbon emission potential by individual buildings will be simply proportional to their total floor area, but at the same time that it is their spatial configuration in street layouts that determines the total amount of carbon emission in an area. No removal of one building can be considered to reduce that much of carbon emission potential without affecting other buildings' carbon emission potential through space configurational effects.

6. Discussion and Conclusion

Based on the space configurational model to estimate carbon emission, this paper has located what can be discussed further within the current discourse on compact city. We have first shown that there can be a trade-off between height intensification and building energy consumption in the course of driving a compact city, while to achieve an optimality in the trade is also dependent on the given level of population density. However, we may also consider an alternative way of achieving such an optimality than directly controlling population density, which is to re-organise the spatial configuration of building masses and street layouts. It has been illustrated through the simulation that the best performativity in reducing carbon emission amount can be expected for the case of local height intensification in the centre that is large enough to accommodate most urban activities without being dependent on private cars. We have also shown that such configurational effects can be succinctly summarised by a parameter in the linear relationship between the total amount of carbon emission and the sum of total floor areas of individual buildings in an area. It can be argued that this finding seems to support well our common-sense knowledge, while at the same time providing a new perspective in understanding the external effects of spatial configuration in relation to the internal properties of those urban components which are spatially configured.

The model also has several shortcomings. In future researches, the model can be made sophisticated further by taking into account building uses, vehicle types, everyday lifestyle and so on. It will be also crucial to develop a way to calibrate carbon emission amount which this model estimates relative to real amount observed with vehicular and elevator movements. To overcome computation cost is also important, particularly when we analyse and compare whole city areas rather than their local parts. For this we may try to employ an urban block, rather than a building, as a basic unit of analysis, in which the properties of buildings within it are all aggregated. However, there are some technical points involved in this procedure, such as scale dependency and the significance of aggregated statistics. At its current status, nonetheless, we expect the model structure proposed in this paper to stand as a basis for all those future developments.

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