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Building emergy analysis of Manhattan: Density parameters for high-density and high-rise developments

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ABSTRACT

To better understand how cities work, this study performs emergy (spelled with an "m") synthesis of buildings on Manhattan Island. Conventional emergy studies have focused on much larger unit of analysis; however, architects, urban designers, and policymakers are operating on a smaller scale of building, block, neighborhood, and district. This study contributes to overcoming the scale and resolution mismatch between the macro- and micro-levels. Overall emergy for entire buildings on Manhattan Island is computed by adopting square-foot-base building cost estimation technique to emergy synthesis. We found that high-density and high-rise developments can achieve their maximum empower at the range of 1–5 Floor Area Ratio (FAR; an indicator of development density computed as total building floor area divided by total parcel area) and building height under 40 stories.

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1. Introduction

With the increasing threats of climate change and steady increase in urban populations, sustainability has become a central focus of contemporary urban planning. Urban planners have emphasized a comprehensive approach in dealing with sustainability, including environmental durability, economic soundness, and social diversity (Berke, 2002, p. 30). However, actual policy interventions have focused on actionable solutions for discrete problems in building and transportation to conserve energy. A good example is the recent interest in autonomous electric cars. Instead of addressing a comprehensive change in systems to reorganize urban settlements for self-sufficiency, electric car initiatives intend to replace gasoline-fueled cars with electric cars that use electricity from renewable sources. This limited approach fails to address the underlying problems of dispersed settlement patterns and other urban issues of exclusion and class separation.

Urban issues are rarely isolated, wholly interconnected with each other (Odum, 2007; McHarg, 1969). For example, a community with higher density and mixed land use reduces the need for and the distance to travel (Jenks and Jones, 2010). As communities are connected with the city center and other communities, people have better access to public transit, further reducing transport energy (Cervero, 1998). With improved access and connectivity, the city center benefits from increased diversity and specialized labor that leads to economic growth through the agglomeration economy (Jacobs, 1961; Glaeser, 2011). Cities are complex ecological, economic, and social systems whose tendencies dramatically exceed the intentions of planners, politicians, and citizens. Therefore, a more comprehensive approach is necessary to understand the dynamics among density, land use, and transportation in cities.

What is an appropriate density, mix of land uses, and configuration of connectivity to minimize resource intake while continuing to be productive? What is an appropriate level of energy consumption per capita? This study seeks to answer these questions by analyzing the energy flow of buildings in Manhattan. We use the techniques of emergy (with an "m") analysis to understand the interaction among urban form matrices; the four urban form matrices include density, land use mix, connectivity, and accessibility. Different accounting methods such as exergy analysis, embodied energy analysis, and life cycle analysis (LCA) each have their place, and each considers different boundaries of analysis. Emergy analysis considers the entire upstream contributions of work, energy, and materials, including environmental energies, which are typically discounted or considered to be free (Buranakarn, 1998; Brown and Buranakarn, 2003). Emergy analysis is more than another sustainability metric to be compared to norms or established as a goal; it is a research methodology for understanding the structure and purpose of complex, self-organizing systems. By evaluating the total inputs, outputs, and potential environment impacts of a product or process (Srinivasan and Moe, 2015), this comprehensive energy accounting method helps us to understand the hierarchies and interactions that emerge as systems grow, develop, and adapt to changing circumstances. In this respect, emergy and life-cycle concept provide insight into the nature of urban form and the total resource flows used to sustain it.

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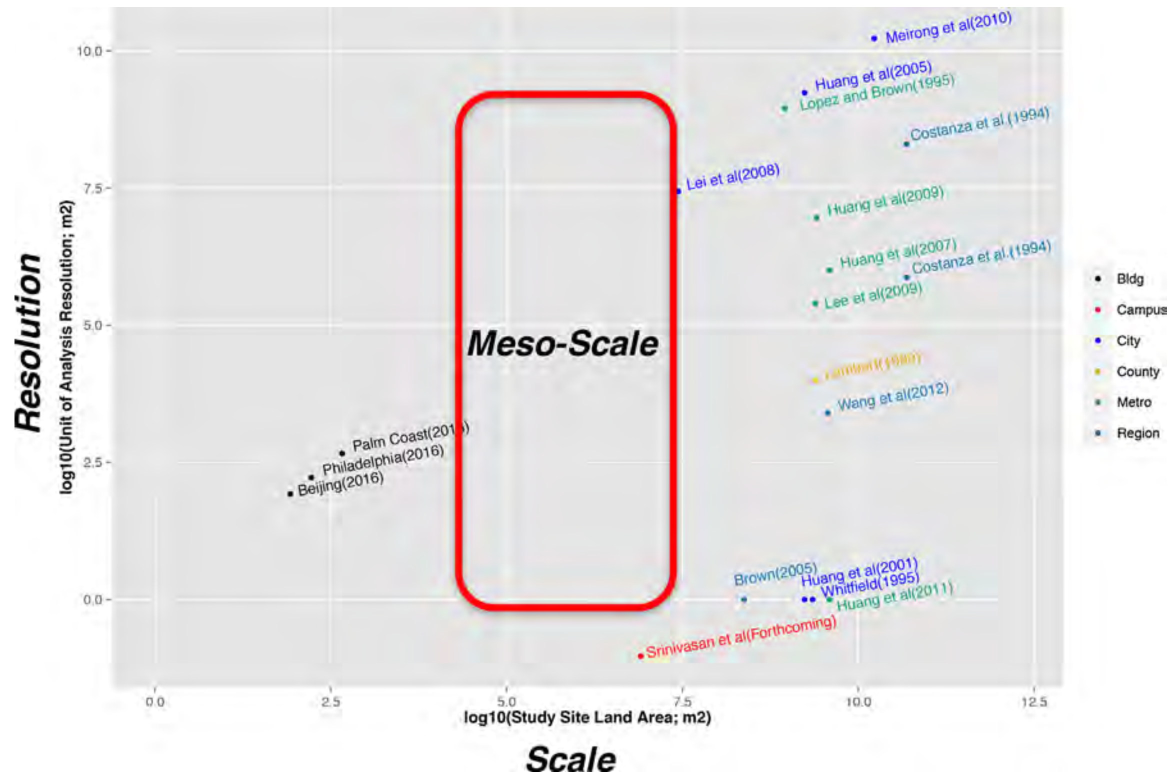


Fig. 1. Unit of Analysis and Resolution of Emergy Studies. While meso scale studies are relevant to understand sustainable urban form, most studies have done at micro or macro urban scale.

Emergy accounting is a top-down approach to account for inputs and outflows in a unit of analysis (Brown and Ulgiati, 2004, p. 331). It is an effective tool for understanding the relationships among urban elements and industries for large units, such as cities and regions; however, studies in smaller scale are less effective because of limited data and available information. This is a challenge for architects, planners, and urban designers who operate on a much smaller scale, buildings, blocks, neighborhoods, and districts. A new tool to overcome the gap in scale will help scholars and policymakers to assess and evaluate the effect of design and policy interventions. This study prepared an emergy synthesis of individual lots and block-level tracking of transportation, building operations, material, and monetary flow in New York City (Fig. 1).

2. Data and method

Emergy analysis is a useful tool for evaluating the overall sustainability of a system. Odum (1996) introduced the term emergy as a uniform measurement of energy and material flow. Formerly known as embodied energy (Huang et al., 1998; Brown and Ulgiati, 2004a; Brown and Ulgiati, 2004b), emergy is a cumulative accounting of available energy, a measure of the maximum useful work possible, captured and consumed in a process from its origin to its present state (Odum, 1996). That is, emergy synthesis of a building accounts for all energy spent to produce its raw materials, including wood, reinforced steel bars, concrete, and many others, as well as the energy taken to build its structure, labor, equipment use, and transport. Because emergy analysis uses a single unit of measurement—the solar emjoule (sej), or the amount of incoming available solar energy aggregated in raw materials—it allows for direct comparison of different processes and products (Srinivasan and Moe, 2015). In this respect, emergy synthesis is widely adopted to evaluate the sustainability of various industries, including agriculture (Odum, 1983; Sergio et al., 1994), trading (Odum, 1983; Brown, 2003), and tourism (Lei and Wang, 2008; Lei et al., 2011). Increasingly, environment impacts and policy effects are examined using emergy analysis (Almeida et al., 2007; Liu et al., 2011; Brown, 2014).

Emergy analysis has been extensively employed to study spatial organization and urban development pattern, mostly at the macro level: regional scale (Brown, 1980), state scale (Daniel and Ohrt, 2009; Campbell et al., 2004), metropolitan level (Huang et al., 1998), and city level (Odum et al., 1995; Lei et al., 2008; Ascione et al., 2009). At the micro level, emergy analysis became famous among architects and building systems engineers for expanding the boundary of life-cycle cost analysis (LCA) beyond the production and disposal phase of products (Brown and Buranakarn, 2003; Ravi et al., 2012; Srinivasan and Moe, 2015; Braham, 2015). Because finer resolution of emergy analysis introduces significant noise, a rigorous standardization would be helpful for emergy analysis of buildings (Braham and Benghi, 2016).

A few performance indicators have been developed to evaluate and compare systems (Odum, 1996; Brown and Ulgiati, 2004a; Brown and Ulgiati, 2004b; Brown, 2005; Brown and Vivas, 2007). These performance measures pay attention to the source of energy (renewable and nonrenewable) and to its location, inside or outside of system boundaries. Emergy yield ratio (EYR) is the ratio of total emergy input into a system, nonrenewable (N), renewable (R), and imported emergy (F), to the imported emergy: $EYR = (R + N + F)/F$. An EYR close to 1 indicates that few local resources were used in the system. Environmental loading ratio (ELR) is an indicator of potential pressure on the environment. The notion of ELR is evolving (Lu et al., 2014, 2017). The earlier notion of ELR was a ratio of imported resources, e.g. imported fossil fuel, spent over local renewable energy: $ELR = (N + F)/R$ (Brown and Ulgiati, 1997). The definitions of imported resources and local renewable energy are specified to cover resources that are related to the environment. Odum (1996) added imported materials (M_N) and imported ser-

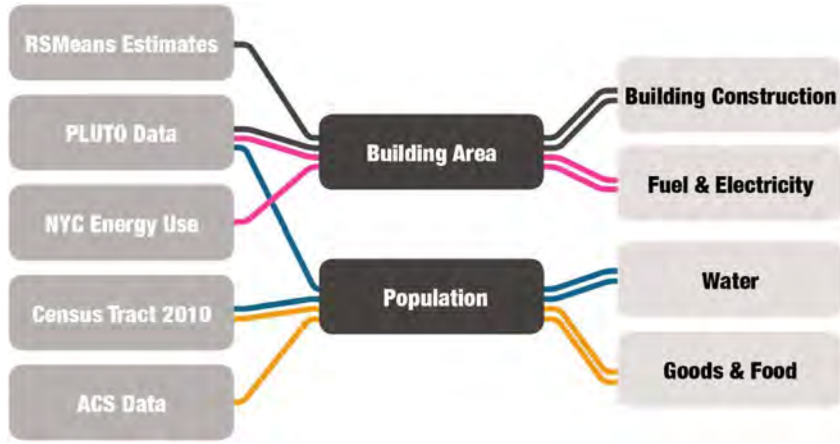


Fig. 2. Data Processing Flow Diagram. Multiple data sources are compiled to conduct emergy synthesis at building level.

vices (S_N) to replaced imported resources (F): ELR = (N + M_N + S_N)/R. Ortega et al. (2002) proposed matching the kinds of energy sources for both imported and local energy (R), M_N, S_N, local materials (M_R), and local services (S_R): ELR* = (N + M_N + S_N)/(R + M_R + S_R). The current definition of ELR is expanded to distinguish pre- from post-process distinguishing environmental load that is taken in the treatment system (foreground) and that is taken beyond the treatment process (background) on a larger scale. The Environmental Sustainability Index (ESI) is useful for measuring how a system changes its source of energy to sustain its economy. ESI is represented as EYR divided by the ELR: ESI = EYR/ELR, ESI* = EYR/ELR*. Both ESI and ESI* are useful indicators to show how societies became dependent on fossil fuel or imported materials and services over time.

Empower densities for a site area (ED-site, sej/yr/m^2), building area (ED-bldg, sej/yr/m^2), and per capita (EC, sej/yr/person) are more effective measurements for comparing similar urban systems. Urban blocks in Manhattan are almost identical in retaining the original grid plan of Manhattan (Reps, 1965); therefore, the renewable input of wind, rain, and sunlight are roughly the same. Furthermore, the renewable input is almost negligible to external energy input for each parcel. ED is a measurement for gauging spatial hierarchy; this is the ratio of total emergy use over the total area of the system. Cities show an empower density gradient from the center to the periphery; higher ED is in the center, and decreases as the distance increases from the center (Brown, 1980; Huang et al., 2001). Empower density is highly correlated with land use because zoning regulations follow the density gradient from the center as well.

Emergy synthesis at a finer resolution is not a new concept. Braham and Yi (2015) first introduced emergy synthesis at the building level by separating inputs into three scopes or scales of activities: site, shelter, and setting. Renewable emergy inputs such as sunlight, wind, and rainwater geo/chemical potential account for most of the site input. Researchers estimate the total weight of a building by examining the building plans, cross sections, and digital building information models (BIMs). Then the material quantity is multiplied by corresponding material unit emergy values (UEVs) to calculate the annual depreciation of a building's emergy or shelter. To estimate annual depreciation, individual building components are separately calculated using different expected lifespans. For interior finishes and mechanical and electrical systems, the expected lifespans are standardized. However, the lifespans of exterior walls and structural components are correlated with building age. When the age of a building exceeds its expected lifespan, the building age is used in place of the expected lifespan to calculate the annual depreciation of building structures.The setting is accounted for by estimating resource consumption, including water, food, durable goods, and utility based on demographic data with the depreciation of the building interior (Braham, 2016).

This study expands individual building emergy synthesis to multiple buildings, districts, and city-wide analysis. While emergy accounting of individual buildings provides greater accuracy and detail, accounting for over 40,000 buildings in the Manhattan borough in New York City is a time-consuming task, even with the help of advanced building digital models. Instead, we adopted a building cost-estimating practice to calculate the overall quantity of building materials, labor hours, and resources by individual buildings, using publicly available tax data, GIS shapefile, and RSMeans square foot cost data (see Appendix-A and Fig. 2). Similar to building emergy analysis the overall emergy value for each building is derived by multiplying corresponding UEVs by the estimated building material quantity.

Ravi Srinivasan and his team are developing a square-footage-based building emergy value.[1] Based on the data the team collected from emergy analysis of the University of Florida's campus buildings, a total of 93 building components were compiled, ranging from foundations, slabs, and steel columns to windows and doors. It is a comprehensive and easy-to-use platform for estimating building emergy value. However, the types and scale of buildings from the study are limited to educational campuses, dorms, classrooms, administrative offices, and recreational facilities in a suburban setting, while building of Manhattan Island are quite different from university campus; 39.8% less than three-floor walk-up row houses, 30% commercial office buildings, 27.5% mixed-use buildings, and only 1% educational buildings, including nurseries and K–12 schools.[2] The buildings in Manhattan Island has greater variance in building heights and number of floors than does the University of Florida campus; the highest building in Manhattan is the Freedom Tower (WTC1) at 104 floors, and the median number of floors for buildings is nine. This discrepancy leads us to expand the building types and scale of the University of Florida team's approach as relevant to the building types in New York City.

3. Data

The primary data is synthesized from multiple datasets, including the New York City Primary Land Use Tax Lot Output (PLUTO) published in 2010, New York City Building Footprint GIS shapefile, US Census 2010, American Community Survey (ACS) 2009, RSMeans Square Foot Building Cost Data, Census Transportation

[1] Build EM, http://buildem.herokuapp.com.
[2] Summarized from NYC PLUTO data.

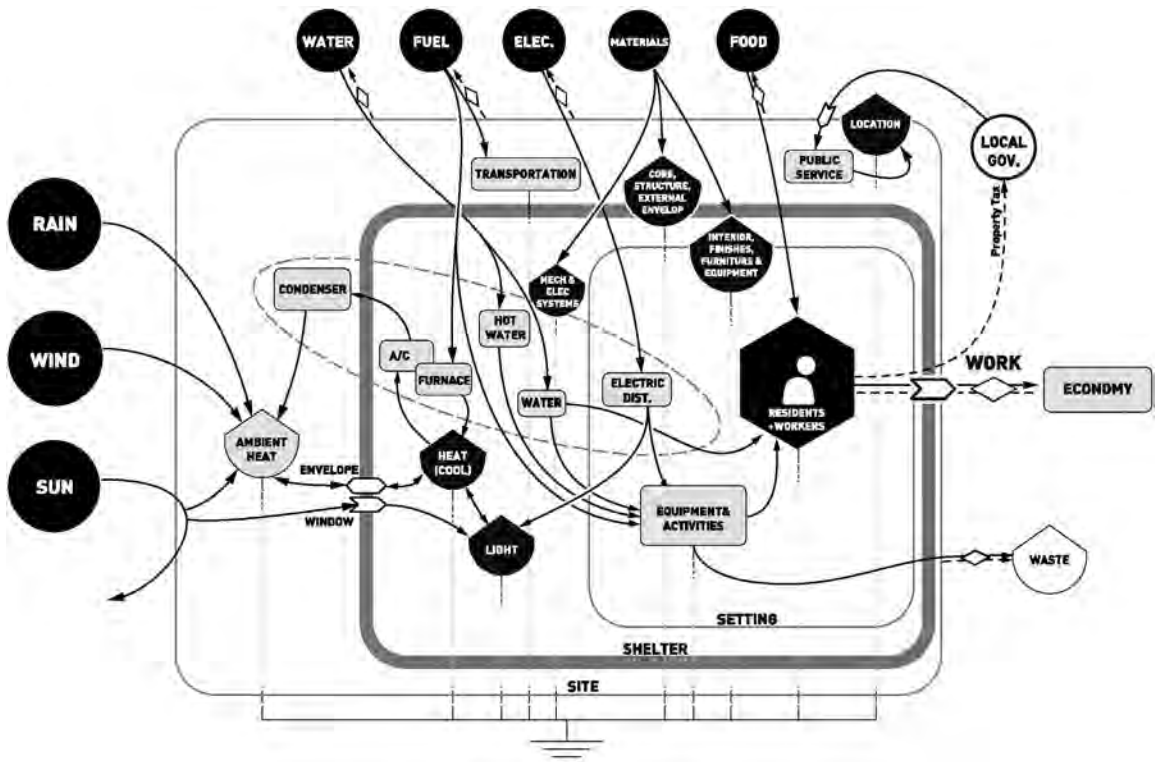


Fig. 3. Conceptual Emergy Diagram for Typical Building. Diagram shows the relationship among building components and input resources in the three divisions of the system, site, shelter, and setting.

Planning Product (CTPP) based on 2006 and 2010, and annual building energy use by zip code. PLUTO includes both parcel and building information such as dimensions of lots, total area for individual lots, total building floor area, floor area by use, built year, number of floors, and tax assessment, among many other detailed information related to individual buildings. Building construction quantities are estimated by synthesizing PLUTO, building footprint shapefile from GIS data, and RSMeans building assembly data. RSMeans provides an annual summary of building cost per square foot based on average construction data over the last few decades. The calculation formula is described in detail in the following section. The Census and ACS provide resident demographics, including median household income, transportation modes, average commute time, and total population. Then the demographic information is used to extrapolate the number of occupants and their socioeconomic characteristics at the block level, based on aggregate building area and number of units from PLUTO data. For worker demographics, CTPP provides information about the worker population and categories in terms of their occupations, modes of travel, and duration of their commutes. For energy use, each building is estimated by the annual energy use for New York City by square foot, which was developed by the Sustainable Engineering Lab in Columbia University.[3]

4. Building emergy synthesis: site, shelter, and setting

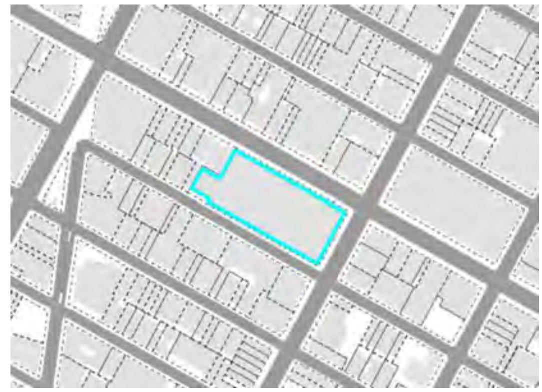
This study follows the emergy synthesis procedure for building, dividing the scope of activities into three nested systems: Site, Shelter, and Setting (Srinivasan and Moe, 2015; Braham, 2016). System boundaries and sources are identified in a conceptual emergy diagram in Fig. 3. The diagram describes partial relationships among building components and resource inputs. “Building-as-shelter” fulfills the primary purpose of building “modifying the local climate for human comfort,” temperature, humidity, and illumination, by constructing a shelter. The work and materials invested in constructing a building structure and mechanical and electrical systems are stored energy, depreciating over the lifespan of buildings. The concentrated energy, fuel, and electricity are necessary for heating, cooling, ventilating, and lighting, accounted as energy inflow. Building itself cannot facilitate the modern activities of production and recreation, or “building-as-setting.” Material services such as food, water, and concentrated forms of energy, fuel and electricity are required to facilitate activities such as living and working in buildings. “Building-as-site” reflects the locational characteristics of buildings. Unlike suburban tract houses, urban residential, office, and retail buildings organize themselves hierarchically based on the intensity of land usage. When demand for space exceeds supply, the land value increases. In turn, taller and higher-density buildings are built to offset development costs. Corporate headquarters and retail shops are concentrated at transportation nodes, creating a Central Business District or High Street. Therefore, the intensity of development and locational character is well reflected in the land value. To reflect the spatial hierarchy in development density and land use, we considered property tax as a reference to estimate the locational input for building emergy synthesis.

Table 1 shows the assumptions and calculations for the Empire State Building apportioned to three scopes of site, shelter, and setting. Renewable inputs, public service and commuting are added on site for locational inputs. Buildings alone cannot fully account for the locational properties of neighborhoods, districts, or cities in terms of distance to the city center, amenities, and level of public services. Local governments partially use property taxes to provide basic public service for residents and property managements (Braham, 2015). Therefore, we used annual property tax to esti-

[3] Howard et al., 2012. “Spatial Distribution of Urban Building Energy Consumption by End Use.” Energy and Buildings (http://sel-columbia.github.io/nycenergy/).

Table 1
Example emergy synthesis of empire state building.

Empire State Building	Data	Unit	Parcel Map
BBL	1008350041		
Building Identification Number (BIN)	101586		
Lot Area	93,151.0	sqft	
Building Area	2,812,739.0	sqft	
Residential	–	sqft	
Commerical	2,685,483.0	sqft	
Retail	127,256.0	sqft	
Floor Area Ratio	30.2		
Roof Height	1,238.8	ft	
Footprint	85,500.7	sqft	
Land Use	Commercial		
Zoning Designation	C5-3		
Population	20,900	person	
Residents	–	person	
Workers	20,900	person	



Note	Item	Data (Units)	Unit (Unit)	Unit Solar Emergy (sej/Unit)	Life Span (years)	Solar Emergy E+17 sej/yr	Solar Emergy E+17 sej/yr
Site							
Inflows							
1	Sunlight	4.47E+13	J/yr	1		0.0	
2	Rain (chemical potential)	1.85E+06	J/yr	2.35E+04		0.0	
3	Rain (geo potential)	5.73E+09	J/yr	1.31E+04		0.0	
4	Wind (kinetic energy)	9.67E+11	J/yr	1.90E+03		0.0	
13	Public Service	9.90E+07	$/yr	1.97E+12		15.6	
12	Fuel-Transportation	3.83E+13	J/yr	Appendix-E		167.2	
					Inflows, Building as Site		**182.8**
Shelter							
Inflows							
11	Fuel-Heating	4.78E+13	J/yr	1.43E+05		68.4	
11	Electricity-Cooling & Ventilation	1.03E+14	J/yr	2.18E+05		224.4	
Storage, Building Construction							
5	Structure (deprec.)	3.08E+06	kg/yr	Appendix-D	85	56.6	
5	External Envelope (deprec.)	4.72E+06	kg/yr	Appendix-D	85	34.1	
5	Mechanical System (deprec.; i.e. furnace)	5.91E+06	kg/yr	Appendix-D	25	34.9	
5	Electrical System (deprec.; i.e. AC, elec. dist.)	5.63E+06	kg/yr	Appendix-D	25	2.4	
					Inflows, Building as Shelter		**292.8**
					Outflows & Storage, Building as Shelter		**128.1**
Setting							
Inflows							
11	Fuel-Cooking & Water Heating	9.57E+12	J/yr	1.43E+05		13.7	
11	Electricity-Lighting & Electronics	1.54E+14	J/yr	2.18E+05		336.6	
6	Water	8.00E+08	L/yr	1.55E+09		12.4	
8	Food	5.69E+13	J/yr	9.53E+05		542.1	
9	Non-durable Materials	1.81E+07	$/yr	1.97E+12		356.0	
Outflows							
7	Wastewater	6.00E+08	L/yr	3.54E+09		21.2	
10	Solid Waste	1.21E+07	kg/yr	2.25E+11		27.2	
Storage, Building Construction							
5	Interior & Finishes (deprec.)	5.38E+06	kg/yr	Appendix-D	40	12.3	
5	Furniture, Fixture, Equipment (deprec.)	2.81E+06	kg/yr	Appendix-D	25	3.3	
5	Mechanical System (deprec.; i.e. plumbing)	3.58E+02	kg/yr	Appendix-D	25	0.7	
5	Electrical System (deprec.; i.e. communication)	3.24E+06	kg/yr	Appendix-D	25	12.4	
					Inflows, Building as Setting		**1,260.9**
					Outflows & Storage, Building as Setting		**77.1**

mate the level of public service for each building. Annual property tax is based on the property tax assessment data in PLUTO. Then, we multiply an average effective property tax rate of 0.8%.[4,5] For commuting, the American Community Survey and Census Transportation Planning Products surveys the modes and durations of travel for both residents and workers. The emergy value for commuting is calculated by tallying the total number of commuters by transportation modes and distance for the trip. Then, UEVs for different modes are multiplied to estimate total emergy for commutes.

Second, for building-as-setting, the total number of residents and workers are estimated using ACS, CTPP, and PLUTO data. The total number of residents was appropriated by comparing the number of housing units within a parcel to total housing units in a census tract. We assumed that the household size is the same within census tracts. The total number of office workers and retail shop attendants was calculated by the average floor area for a worker, approximately 100 square feet/worker for office and 300 square

[4] New York City Property Tax Calculator (https://smartasset.com/taxes/new-york-property-tax-calculator).

[5] On average, 57% of property tax is used for education, and rest are used for other public services including road maintenance, police, fire, and other basic administrative services. (http://www1.nyc.gov/site/finance/taxes/property-tax-rates.page).

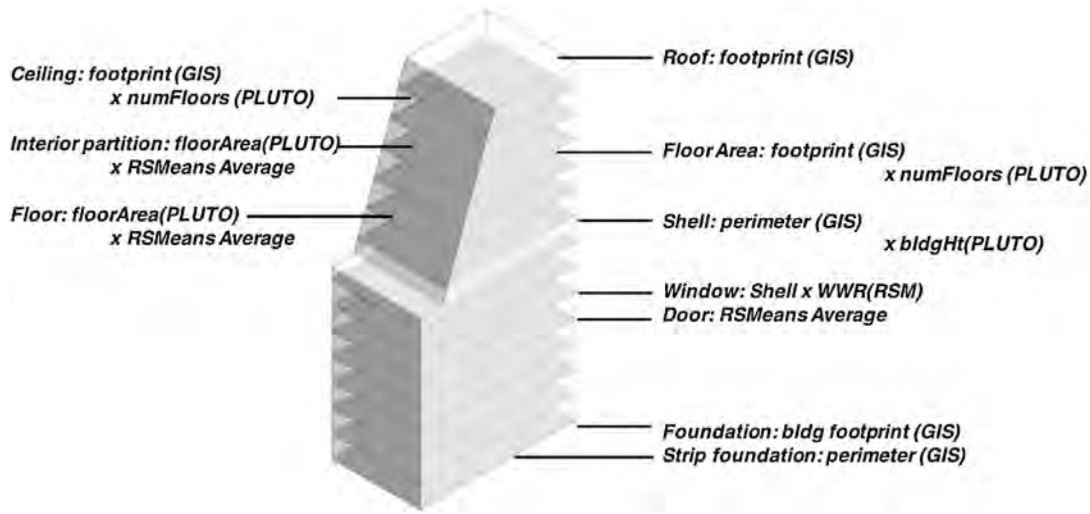


Fig. 4. Building Bulk Estimation. Individual building bulk is estimated mathematically using available building information from GIS and property tax data.

feet/worker for retail.[6] The floor area was adjusted to deduct the area for the central core (20% of gross floor area) and vacancy rate (5%). For example, the Empire State Building has 2,685,000 square feet of office area and 127,000 square feet of retail area. The number of workers is calculated as 20,727 people based on square foot estimate (for office $2,685,000 \times 80\% \times 95\%/100 = 20,406$; for retail $127,000 \times 80\% \times 95\%/300 = 321$). With this square-foot based method, we can predict 99% of the actual number of workers in the Empire State Building.

Another indicator to estimate the amount of materials used in building-as-setting is the level of economic contribution from residents and workers. Median annual household income for the census tract from ACS 2009 is multiplied to estimate the total economic contribution to buildings for residents. For workers, CTPP and CSI Market[7] report are joined to estimate corporate profit to calculate material services. CTPP provides the number of employees by industrial sector at the census tract level. The industry performance analysis from CSI Market report publishes the total sales and revenue per employee on a quarterly basis. The two datasets are multiplied and allocated to each building to estimate total business profit. The material use of office and retail buildings are estimated per capita. On average, office service venders estimate $200 per employee per year for corporate or $1000 for law firm. We used $300 per worker per year to calculate the amount of non-durable supplies.[8]

Lastly, for building-as-shelter, two major categories are the total amount of building construction materials including exterior, interior, and mechanical and electrical equipment, and concentrated forms of energy to condition the space such as, heating, cooling, and ventilation. The total amounts of fuel, electricity, and other forms of energy are computed from the energy use by square foot (Howard et al., 2012). The method of quantifying building construction materials will be discussed in detail in the following section.

5. Mathematical reconstruction of building bulk and building material quantity estimate

While Building Information Modeling (BIM) of individual buildings could increase the accuracy of material quantity calculation at the urban block level, obtaining such detailed building construction information for all of Manhattan County is almost impossible. Instead, building material quantities are mathematically derived from PLUTO, GIS building footprint, and RSMeans square foot construction cost data. By synthesizing PLUTO and GIS shapefile, enough information is extracted to assess the overall energy flow of the city. The joined building attribute table provides detailed building data, including building footprint area, building periphery length, building height, number of floors, land use, building category, and floor area for residential, commercial, and retail spaces. With this information, building bulk is mathematically calculated (see Fig. 4); for example, the roof is the same area as building footprint, the exterior wall area is the result of perimeter multiplied by building height, and the total area for floor slab is obtained by multiplying the building footprint by the number of building level. To account for all building components, building bulk is subdivided and itemized as shell, structure, interior, and electrical and mechanical services, which are widely adopted in architectural and cost estimation procedures. The shell includes exterior walls, windows, doors, and canopy; the structure includes cores, vertical circulations, stairs, foundations, piles, slabs, columns, beams, and girders; the interior includes partitions, interior doors, and windows; electrical and mechanical services cover plumbing, electrical wiring, communication wiring, heating, ventilation, and air-conditioning equipment (see Appendix A).

Once we have the building bulk estimation, the second step is to calculate total quantity for raw material. The raw material quantity is calculated by multiplying the derived building bulk by the square foot material composition from the RSMeans.[9] RSMeans have collected and compiled building cost data for more than 70 years in North America. Its database analyzes the building material quantity of 45 different building types and provides average cost per square foot with reference to building material quantity. We converted the various forms of material quantity data to interchangeable units: kilogram and USD.

[6] International Code Council, 2006. Table 1607.1–Minimum Uniformly Distributed Live Loads (https://www2.iccsafe.org/states/newjersey/nj_building/pdfs/nj_bldg_chapter16.pdf).

[7] CSIMarket is a private company that provides financial information and reports to investment companies (http://csimarket.com/index.php).

[8] Office supply vender, LAC Group, estimated the average annual office supply costs as $200 to $1000 per employee per year. (https://lac-group.com/average-office-supply-costs-per-employee/).

[9] RSMeans, 2016. *RSMeans Estimating Handbook*. Kingston, MA: R. S. Means Company. (https://www.rsmeans.com).

Table 2
Sample building assembly-strip footing. RS means building assembly table shows the material quantity of each building components per square foot.

A10101102700					
Strip footing, concrete, reinforced, load 11.1KLF, soil bearing capacity 6 KSF, 12” deep x 24” wide					
Description	Quantity	Unit of Measure	Material Q&P	Installation Q&P	Total Q&P
C.I.P concrete forms, footing, continuous wall	2.000	SFCA	4.95	17.04	21.99
C.I.P concrete forms, footing, keyway, tapered	1.000	L.F.	0.33	2.18	2.52
Reinforcing steel, in place, footings, #4 to #7	3.000	Lb.	1.74	4.01	5.75
Reinforcing steel, in place, dowels, deformed, #2	2.000	Ea.	1.64	11.63	13.28
Structural concrete, ready mix, heavy weight, 300psi	0.074	C.Y.	9.38	0	9.38
Structural concrete, placing, continuous footing	0.074	C.Y.	0	3.16	3.16
Concrete finishing, fresh concrete flatwork, floor	2.000	S.F.	0	0.37	1.37
Excavating, trench or continuous footing, center	0.148	B.C.Y	0	1.61	1.61
Excavating, trench or continuous footing, side	2.000	S.F.	0	2.16	2.16
Backfill, trench, 6” to 12 lifts, dozer backfilling	0.074	E.C.Y.	0	0.33	0.33
		Total	**$18.04**	**$42.49**	**$61.55**

Building assembly used in this study is compiled in Appendix B. The table shows raw material weights used for each building assembly. Each building assembly has a unique identification number with the name of the assembly that indicates the hours of labor, amount of equipment, and amount of materials used for the assembly. For example, a square foot of brick wall with composite double width (B20101321201) requires $10.45 for materials and $22 for labor and equipment in 2016 US dollar. This exterior wall has an 80-year lifespan. In terms of detailed building material quantities, it requires 0.461 kg of steel, lintel, and anchors attaching masonry to the wall, 0.012 kg of aluminum sheet-metal flashing, 16.825 kg of cement brick, 21.532 kg of mortar for bonding, 0.002 kg of acrylic, and 0.053 kg of PVC for caulking and expansion joints (Table 2).

Rather than applying uniform construction to all buildings on Manhattan Island, we retain some level of variety in building construction based on building class designations from PLUTO data. New York City property assessors categorize each building into 198 building classes to better assess the type and quality of construction. The building class consists of a letter indicating primary use and a number for subcategories informing the scale of buildings and materials. For example, in building class “B1,” attached family housing is described as brick building; therefore, a brick building composition is attached, while another building class “B2” a wood-frame building, is attached with wood-siding exterior. Furthermore, different building types consist of particular groups of building assemblies. For example, wood-siding exterior wall for single-family housing almost always has a wood frame structure because of the compatibility of wood structure and wood siding exterior. It is highly uncommon to mix a wood-siding wall with a reinforced-concrete structure or steel-frame structure. The dataset presents a variety of estimates in building types (i.e., house, office, retail, school, hotel, and hospital), structural assemblies (i.e., wood frame, masonry, reinforced concrete, and steel frame structure), and in building façade assemblies, including wood siding, brick veneer, precast, and glass curtain wall.

Synthesizing building bulk and square foot building assembly, the total quantity of raw materials is computed for each building in kilograms. Then, the weight is converted into solar emergy joules by multiplying UEV for each material (see Appendix D).

6. Results

Of the 42,851 parcels from PLUTO data, 2703 parcels are missing necessary information, including building footprints, building identification numbers (BIN), parcel areas, or the number of floors. We exclude these parcels from the dataset. As seen in Fig. 5, total emergy for building construction varies by building use type. The total emergy increases as buildings get taller. Commercial buildings show greater emergy than residential buildings because commercial buildings such as corporate headquarters and shopping malls often have higher structural and egress requirements, and they require higher-intensity energy use for heating, ventilation, and air conditioning (Oldfield, 2009).

Building depreciation accounts for 20–30%, and energy use accounts for 30% of total. Food takes up to 10–17% of total emergy for residential and mixed-use residential land uses. The expense for durable goods in household supplies account for 30–34% of emergy investment. Renewable energy, sunlight, wind kinetic energy, and rainwater potential are meager compared to nonrenewable resources.

7. Discussion

High-density cities and high-rise buildings are praised widely as potential alternatives to low-density suburban developments. Many believe that increased intensity of land use will reduce vehicle use while promoting public transportation (Newman, 1989; Cervero, 1998). Public and civic amenities support many users and increase opportunities for casual contacts, which in turn promotes social integration (Jacobs, 1961; Gehl, 1987; William, 1980); the diversity of high-density cities creates innovation and promotes an agglomeration economy for more growth (Jacobs, 1961; Glaeser, 2011). In this respect, Manhattan, a quintessential example of a high-density and high-rise city, is considered a model for greener and more-efficient human settlements (Owen, 2010; Glaeser, 2011).

The virtue of high-rise buildings is that they can achieve high-density without degrading microclimate conditions, e.g., sunlight and natural ventilation (March and Trace, 1969; Philip, 1979). However, high-rise developments are also associated with higher construction costs (Oldfield, 2009). A taller building requires larger structural components such as columns and beams, and higher-quality mechanical and circulation services such as ventilation, additional mechanical floors, and elevators. Furthermore, high-rise buildings could be used as vehicles to house the affluent class in an urban core with amenities.

Among the emergy performance indicators, empower density (ED, sej/yr/m^2) by site, building, and empower density per capita (EC, sej/yr/person) are effective analytical indices for gauging the sustainability of buildings in Manhattan. The ED-site is total Emergy over parcel land area; often this is correlated with the intensity of land use. Fig. 6 shows a plot for ED-site against a building's number of floors. As a building gets taller, ED also increases. However, the slope diminishes as buildings become taller, thus creating a negative quadratic curve. To some degree, the ED-site curve is the evidence for pro-density arguments.

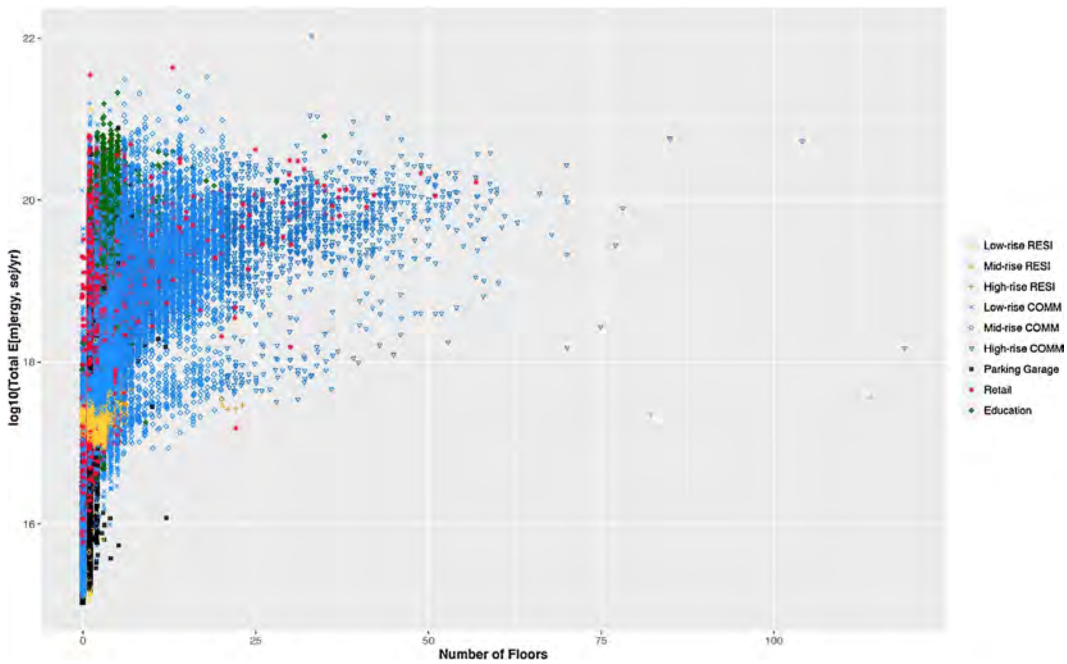


Fig. 5. Total Building Construction Emergy by Building Types and Number of Floors.

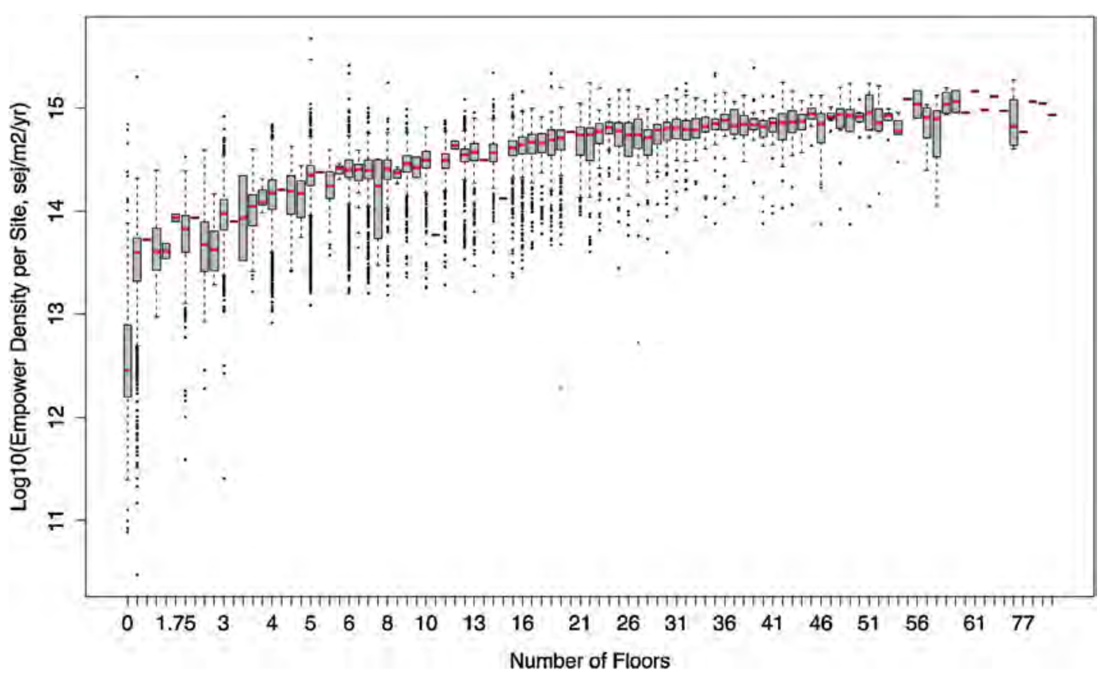


Fig. 6. Empower density – site (sej/yr/m2) by number of floors.

Table 3 is an ED-site comparison of Manhattan neighborhoods with previous emergy studies. When baseline is adjusted to relative to the baseline of 1.20 e + 25 sej/yr, an ED-site for Manhattan neighborhoods was higher than in other city districts. Overall, the ED-site for Manhattan Island is 2.28E + 15 sej/yr/m^2. Two central business districts in Midtown and Lower Manhattan show higher empower density than other parts of the city. Wall Street is higher than Midtown, mainly because of the concentration of large floor plate financial industry headquarters. Among residential neighborhoods, the Upper East shows higher ED-site than does Washington Heights, Soho, or Harlem. The ED-site hierarchy of residential neighborhoods correlates with the wealth of residents.

ED-building (sej/yr/m^2) also supports the argument for making cities more compact. When ED-building is plotted against Net FAR, ED-building gradually decreases as density increases (see Fig. 7). This decline indicates the economy of scale in building construction. For a high-rise building up to a certain level, the workmanship improves as workers continue to repeat the same tasks; duration of the tasks is reduced, and materials are saved. Therefore, the emergy per-square-foot building area decreases as the net FAR increases. However, the pace of the improvement slows down when the density increases further above 10 FAR. In this respect, high-density building communities can reduce the total resources spent for buildings.

Table 3
Emergy density per site comparison with previous studies.

	Emergy Density – Site (sej/m²/yr)	Note
Macao	6.09E + 14	Lei et al. (2008)
Taipei	6.76E + 13	Huang (1998)
San Juan	8.90E + 13	Odum et al. (1995)
Rome	8.11E + 13	Ascione (2009)
Single-Family Residential	1.36E + 12	Parker (1998)
Multi-Family Residential	9.70E + 13	Brown (1980)
High Intensity Commercial	9.60E + 13	Brown and Buranakarn (2003)
CBD (2 story)	1.22E + 14	Brown (1980)
CBD (4 story)	2.23E + 14	Brown (1980)
Manhattan Island (5.6 story)	2.28E + 15	*
Wall Street (9.9 story)	3.60E + 15	*
Midtown (11.7 story)	3.14E + 15	*
SOHO (5.2 story)	1.90E + 15	*
Upper East (6.3 story)	1.99E + 15	*
Washington Heights (4.4 story)	1.94E + 15	*
Harlem (4.4 story)	1.78E + 15	*

*Net empower density within lot area, this value excludes utility and other public right of way(ROW) including roads, sidewalks, and highways (these take up 15–25% of gross land area in average).
** values are adjusted to relative to the baseline of 1.20 e + 25 sej/yr

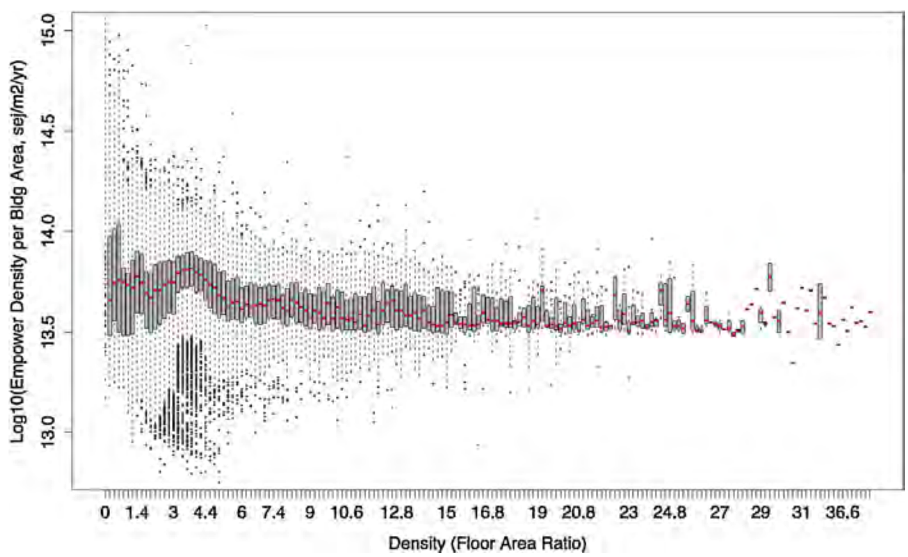


Fig. 7. Empower density – building (sej/yr/m2) by Net FAR.

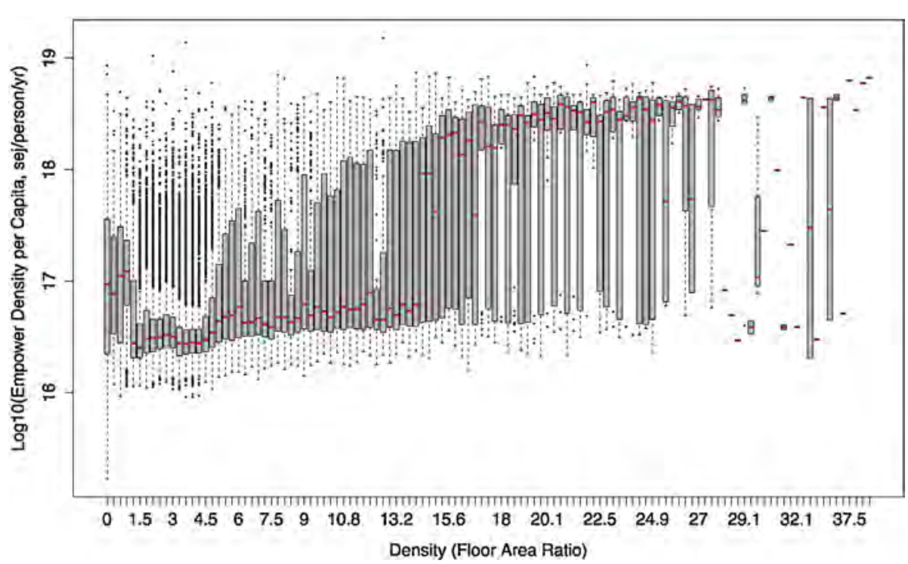


Fig. 8. Per capita Emergy used (sej/yr/person) by Net FAR.

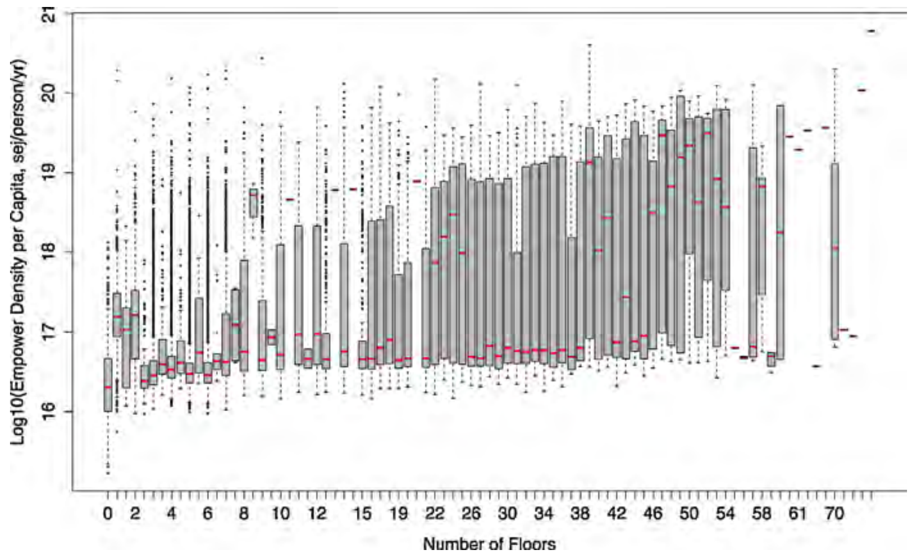


Fig. 9. Per capita Emergy used (sej/yr/person) by number of floors.

Table 4
Development density categories and its per capita emergy used performance.

	FAR	Per Capita Emergy Used	Average Number of Floors	Average Building Coverage
Unit		(sej/yr/person)	(floors)	(%)
Low-Density	Below 1	2.49E + 17	4.3	67.9%
Mid-Density	1–5	7.52E + 16	4.5	70.1%
High-Density	5–14	3.84E + 17	12.0	79.6%
Hyper-Density	Above 14	2.15E + 18	29.9	84.5%
Manhattan	4.4	1.72E + 17	6.0	72.4%

Both ED-site and ED-building of Manhattan blocks indicate that higher-density urban blocks are efficient forms for conserving resources. However, per capita emergy used (EC, sej/yr/person) of parcels presents conflicting evidence for the pro-density argument. High-density is relatively efficient in use of construction materials, fuels, and electricity per land area and building area, but not for per capita; there are apparent limits to high-density. EC is calculated by total emergy divided by total number of occupants. Often EC is considered an indicator of quality of life (Brown and Ulgiati, 2004a; Brown and Ulgiati, 2004b; Campbell, 2005; Daniel and Ohrt, 2009). Fig. 8 plots EC against Net FAR. There are several divisions of EC over-development density: buildings with FAR less than 1 show twice the EC as buildings with FAR 1–5. The majority of these low-density buildings are single-family or attached housing with less than 3 floors. This discrepancy tells us that low-density development enjoys higher-quality lifestyles or more lavish uses of energy and resources. Buildings with FAR from 1 to 5 shows the least per capita emergy used. Often these mid-density buildings from FAR 1–5 are similar to row houses in Brooklyn Heights or Washington Heights. Higher-density development from FAR 5–14 has slightly higher EC, with a larger variation than mid-density. The greatest shift takes place at FAR 14, where the average EC jumps from 3.84E + 17 sej/yr/person in high-density developments to over 2.15E + 18 sej/yr/person in hyper-density developments. Hyper-density developments greater than FAR 14 also show a jump in average number of floors to 30 stories from 12 in high-density developments. Despite the changes in EC and number of floors, there seem to be less change in the ratio of building footprint area to land area, or building coverage ratio. There is no outstanding difference in building coverage between high-density (FAR 5–14) and hyper-density (FAR 14 and up). The sudden increase of EC at FAR 14 resulted from the additional mechanical and electrical service that is necessary to support high-rise buildings (Oldfield, 2009).

High-rise buildings over 40 stories do not share the benefit of high-density. Fig. 9, EC against number of floors, shows that buildings over 40 stories have higher per capita emergy used. Several pieces of evidence explain this difference. We discussed that additional services are required to support high-rise towers. The second hypothesis is that buildings with over 40 stories have fewer occupants, leading to higher EC. This hypothesis is plausible. Often high-rise office buildings have a lower occupancy rate due to higher vacancy rate. Also, high-rise residential buildings have larger luxury units that capitalize on views of Manhattan Island. The average number of occupants for buildings with over 40 stories is 0.5 persons for every 1000 square feet, while buildings less than 40 stories reach over 200 persons. The inverse relationship between number of floors and average number of occupants is a contributing factor to the per capita energy used (Table 4).

8. Conclusions

The findings discussed above provide insights to urban planners in terms of rethinking high-density and high-rise development as sustainable urban forms. Based on the findings, high-density and high-rises are effective in conserving resources by improving efficiency in building construction. However, as Odum (2007) described the maximum empower theory, “efficiency” does not always guarantee the maximization of usable work. From the emergy synthesis of Manhattan’s buildings, there are parameters to achieve “maximum empower” development density and building height: Net FAR from 1–5 and buildings with less than 40 stories. Building types outside of this range need to be examined to achieve better building energy performance; low-density mansions, brownstones, and high-rise luxury condos do not contribute to improving overall citywide sustainability.

The density and building height parameters, Net FAR from 1–5 and buildings lower than 40 stories, demand a review of urban planning practices, especially in incentive zoning. The New York City government has provided a floor area bonus to real estate developers who comply with urban planning policies. For example, developers are allowed to have a 1-to-10 ratio of FAR bonus of what they provide as privately owned public space. With many incentives and transfer development rights, buildings in Manhattan often exceed the density of 10 FAR. These hyper-density developments seem to be efficient because these buildings cost less per square foot and are furnished with high-performance façades and equipment. However, hyper-density developments require more resources and emergy services per person than mid-density developments. Therefore, it is necessary to re-examine urban planning practices promoting excessive density and to pay close attention when designing and constructing tall buildings.

Emergy analysis on a smaller scale is a useful tool to study how urban form indices contribute to the economic, and social sustainability of cities. This study explores the feasibility of high-resolution emergy analysis. Urban planners and urban designers can use this method to analyze the performance and sustainability of current urban forms, as well as to test future proposals. For future research, we anticipate expanding the study to an entire city, five boroughs, and to a regional scale in order to understand the effect of other urban planning policies, including transit-oriented development, compact city, and potential for retrofitting suburban cities.

Appendix A. Building Bulk Calculation.

Shell

- Exterior Surface (sqft) = Building Perimeter * Building Height
- Exterior Window (sqft) = Exterior Surface * Window to Wall Ratio (RSMeans Average)
- Exterior Wall (sqft) = Exterior Surface * (1- Window to Wall Ratio)

Core

- Core Area (sqft) = Building Footprint * 20%
- Staircases = (Number of Floor −1) * RSMeans Average by Building Use and Size
- Elevators = RSMeans Average by Building Use and Size

Structure

- Linear Foundation (lnft) = Building Perimeter
- Mat Foundation (sqft) = Building Footprint
- Foundation Pile (each) = Building Footprint/Vary by Size and Height of Building
- Basement Wall (sqft) = Building Perimeter * Number of Basement Floor * 30 ft
- Basement Slab (sqff) = Number of Basement Floor * (Building Footprint – Core Area)
- Slab (sqft) = (Number of Floor −1) * (Building Footprint – Core Area)
- Roof (sqft) = Building Footprint
- Column (each) = {[round(Building Length/30 ft) −1] *2 + [round(Building Width/30 ft) −1]*2}]}*(Number of Floor + Basement Floor)
- Beam (lnft) = {Building Length * [round(Building Width/30 ft) −1] + Building Width *[round(Building Length/30 ft) −1]}*(Number of Floor + Basement Floor)

Interior

- Interior Partition (sqft) = Floor Area/RSmeans partition index * number of floor * floor to ceiling height – Interior Door *3ft*7 ft
- Interior Door (each) = Floor Area/RSmeans door index
- Ceiling (sqft) = (Number of Floor) * (Building Footprint – Core Area)
- Floor (sqft) = (Number of Floor) * (Building Footprint – Core Area).

Appendix B. Sample Raw Material Quantity for Building Construction Assembly (8 Story Office-R/C Structure-Stonewall Facade).

RSMeans Assembly Number	Unit	Assembly Specification	material($)	labor+equipment($)	Emergy	Life Span	Annual Emergy(sej/yr)	Plywood	Wood	Gypsum	Steel	Aluminum	Copper	Bronze	Cast Iron	Brass	Ready-Mixed Conc.	Concrete Block	Red Brick	Common Brick	Motar	Grout	Asphalt	Polyethylene	Polystyrene	Fiberglass	Fibermineral	Calcium Silicate	Stucco	Wall Texture Comp.	Paint	Acrylic	PVC	Vinyl	Glass	Carpet-Nylon	Resilient Flooring	Granite	Limestone	Aggregate	Ceramic Tile
			$/Unit	$/Unit	sej/Unit	year	sej/yr/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit	kg/Unit
8 Story Office - Reinforced Concrete Structure - Stonewall Envelope																																									
Site Work																																									
A10101103100	lnft	Strip footing, concrete, reinforced, load 14.8 KLF, soil bearing capacity 6 KSF, 12" deep x 32" wide	19.3	24.5	3.85E+14	80	4.82E+12	-	-	-	3.085	-	-	-	-	-	175.132	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A10102107700	ea	Spread footings, 3000 PSI concrete, load 200K, soil bearing capacity 6 KSF, 6' - 0" square x 20" deep	335	445	8.36E+15	80	1.05E+14	-	-	-	50.000	-	-	-	-	-	3,944.892	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A10201403780	ea	Steel H piles, 100' long, 800K load, end bearing, 12 pile cluster	58500	21200	2.64E+17	80	3.30E+15	-	-	-	42,117.978	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A10301202240	sqft	Slab on grade, 4" thick, non industrial, reinforced	2.17	3.01	7.54E+13	80	9.42E+11	-	-	-	0.549	-	-	-	-	-	21.228	-	-	-	-	-	0.073	0.000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.860	-
A20101106911	sqft	Excavate and fill, 100,000 SF, 4' deep, sand, gravel, or common earth, on site storage	0	0.1	1.97E+11	80	2.47E+09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A20201101560	lnft	Foundation wall, CIP, 4' wall height, direct chute, .148 CY/LF, 7.2 PLF, 12" thick	25	54	6.05E+14	80	7.56E+12	-	-	-	3.600	-	-	-	-	-	261.813	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Structure																																									
B10102049913	v lnft	Cast-in-place concrete column, 12", square, tied, minimum reinforcing, 150K load, 10'-14' story heig ht	13.45	55	2.46E+14	40	6.16E+12	-	0.167	-	3.329	-	-	-	-	-	65.453	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B10102049918	v lnft	Cast-in-place concrete column, 16", square, tied, minimum reinforcing, 300K load, 10'-14' story heig ht	21	72	3.88E+14	40	9.69E+12	-	0.167	-	5.924	-	-	-	-	-	116.755	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B10102205100	v lnft	Cast-in-place concrete beam and slab, 7.5" slab, two way, 12" column, 25'x25' bay, 40 PSF superimpos	6.05	11.2	1.16E+14	40	2.90E+12	-	-	-	1.238	-	-	-	-	-	47.763	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B10207257000	sqft	Roof, concrete, beam and slab, 25'x25' bay, 40 PSF superimposed load, 20" deep beam, 9" slab, 152 PS	7.2	13	1.34E+14	80	1.68E+12	-	-	-	1.717	-	-	-	-	-	54.503	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B20101321201	sqft	Brick wall, composite double wythe, standard face/CMU back-up, 8" thick, perlite core fill, 3" XPS	10.45	22	1.96E+14	80	2.44E+12	-	-	-	0.461	0.012	-	-	-	-	-	-	18.688	-	16.825	21.532	-	0.000	-	-	-	-	-	-	-	0.005	0.023	-	-	-	-	-	-	-	-
B20202102000	sqft	Aluminum flush tube frame, thermo-break frame, 2.25" x 4.5", 5'x6' opening, no intermediate horizor	16.9	11.75	3.53E+13	40	8.82E+11	-	-	-	-	0.728	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.028	-	-	-	-	-	-	-	-	-
B20202202000	sqft	Glazing panel, plate glass, 1/4" thick, clear	6.2	8.75	3.16E+13	40	7.91E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.436	-	-	-	-	-	-
B20301106550	openning	Door, aluminum & glass, without transom, full vision, double door, hardware, 6'-0" x 7'-0" opening	4400	2050	6.54E+15	40	1.64E+14	-	-	-	-	117.250	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	60.328	-	-	-	-	-	-
B20301107250	openning	Door, aluminum & glass, with transom, non-standard, double door, hardware, 6'-0" x 10'-0" opening	4550	2200	8.04E+15	40	2.01E+14	-	-	-	-	175.875	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	86.182	-	-	-	-	-	-
B30101203400	sqft	Roofing, single ply membrane, EPDM, 60 mils, loosely laid, stone ballast	1.09	0.5	8.51E+12	25	3.40E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.195	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.591	-
B30103202700	sqft	Insulation, rigid, roof deck, extruded polystyrene, 40 PSI compressive strength, 4" thick, R20	2.04	0.61	3.58E+12	25	1.43E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.272	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B30104300040	sqft	Flashing, aluminum, no backing sides, .019"	1.18	3.55	8.99E+12	40	2.25E+11	-	-	-	-	0.123	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B30106305100	sqft	Gravel stop, aluminum, extruded, 4", mill finish, .050" thick	6.6	4.49	1.06E+13	40	2.65E+11	-	-	-	-	0.108	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior																																									
C10101045500	sqft	Concrete block (CMU) partition, light weight, hollow, 6" thick, no finish (replacing C10101049000)	2.81	6.3	7.66E+13	80	9.58E+11	-	-	-	0.003	-	-	-	-	-	-	24.948	-	-	8.413	-	-	-	-	-	-	-	-	-	-	-	0.023	-	-	-	-	-	-	-	-
C10101265400	sqft	Metal partition, 5/8"fire rated gypsum board face, no base,3 -5/8" @ 24" OC framing, same opposite f	1.02	2.95	1.29E+13	80	1.61E+11	-	-	2.360	0.771	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C10101265425	sqft	Metal partition, 5/8"fire rated gypsum board face, no base,3 -5/8" @ 24" OC framing, same opposite f	1	2.95	1.02E+13	80	1.27E+11	-	-	0.123	0.771	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.017	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C10101280646	sqft	Furring 1 side only, steel channels, 3/4", 24" OC	0.23	1.33	2.91E+12	40	7.28E+10	-	-	-	0.054	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C10101280700	sqft	Gypsum board, 1 face only, exterior sheathing, fire resistant, 5/8"	0.32	0.55	2.59E+12	40	6.46E+10	-	-	1.180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C10101280700	sqft	Gypsum board, 1 face only, exterior sheathing, fire resistant, 5/8"	0.32	0.55	2.59E+12	40	6.46E+10	-	-	1.180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C10201205000	openning	Door, single leaf, wood frame, 3'-0" x 7'-0" x 1-3/8", birch, solid core	415	250	6.58E+14	40	1.65E+13	-	53.104	-	0.933	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.947	-	-	-	-	-	-	-	-	-	-
C10201201800	openning	Door, single leaf, wood frame, 3'-0" x 7'-0" x 1-3/8", birch, hollow core	320	244	5.67E+14	40	1.42E+13	20.194	9.342	-	0.933	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.947	-	-	-	-	-	-	-	-	-	-
C10301100420	unit	Toilet partitions, cubicles, ceiling hung, plastic laminate	605	277	5.51E+14	40	1.38E+13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.605	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C20101100590	flight	Stairs, CIP, w/ landing, 16 risers, w/o nosing (ref. G203003102560 4'w 2riser)	1800	4325	4.36E+16	40	1.09E+15	-	-	-	320.000	-	-	-	-	-	18,242.031	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C20101100740	flight	Stairs, steel, cement filled metal pan & picket rail, 16 risers, with landing	11900	2250	4.41E+16	40	1.10E+15	-	-	-	667.753	31.064	-	-	-	-	19,472.330	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C30102301940	sqft	Ceramic tile, thin set, 4-1/4" x 4-1/4"	2.43	4.58	2.04E+13	25	8.17E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.623	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.230
C30102300140	sqft	Painting, interior on plaster and drywall, walls & ceilings, roller work, primer & 2 coats	0.21	0.61	1.74E+12	10	1.74E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.028	-	-	-	-	-	-	-	-	-	-
C30204100080	sqft	Carpet tile, nylon, fusion bonded, 18" x 18" or 24" x 24", 35 oz	4.38	0.67	1.87E+12	25	7.48E+10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.038	-	-	-	0.012	-	-	-	-	-
C30204101600	sqft	Vinyl, composition tile, maximum	1.05	0.97	7.46E+12	25	2.99E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.038	-	0.635	-	-	-	-	-	-	-
C30204101720	sqft	Tile, ceramic natural clay	6.4	4.75	2.49E+13	25	9.96E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.623	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.296
C30302107400	sqft	Acoustic ceilings, 3/4"mineral fiber, 12" x 12" tile, concealed 2" bar & channel grid, suspended sup por	2.7	4.16	1.41E+13	80	1.77E+11	-	-	-	0.301	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.494	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mechanical Service																																									
D10101109300	ea	Traction, geared passenger, 3500 lb, 6 floors, 10' story height, 2 car group, 200 FPM	96000	46400	1.16E+17	25	4.65E+15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D20101102080	ea	Water closet, vitreous china, bowl only with flush valve, wall hung	1900	810	2.23E+15	25	8.93E+13	-	-	-	-	-	5.062	-	8.518	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D20102102000	ea	Urinal, vitreous china, wall hung	625	800	1.98E+15	25	7.94E+13	-	-	-	2.468	-	2.292	-	10.424	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D20103101560	ea	Lavatory w/trim, vanity top, PE on CI, 20" x 18"	800	715	1.75E+15	25	6.99E+13	-	-	-	0.057	-	3.328	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D20104404340	ea	Service sink w/trim, PE on CI,wall hung w/rim guard, 24" x 20"	2875	1175	3.60E+15	25	1.44E+14	-	-	-	-	-	9.013	-	95.254	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D20108201920	ea	Water cooler, electric, wall hung, wheelchair type, 7.5 GPH	1375	610	1.46E+15	25	5.85E+13	-	-	-	-	-	2.992	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D20202502140	ea	Gas fired water heater, commercial, 100< F rise, 300 MBH input, 278 GPH	13500	3275	1.34E+16	25	5.35E+14	-	-	-	-	-	31.208	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D20402104200	ea	Roof drain, CI, soil,single hub, 4" diam, 10' high	920	870	2.16E+15	80	2.70E+13	-	-	-	-	-	-	-	84.232	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D30201089010	ea	Plate heat exchanger, 1800 GPM	22200	3240	4.16E+16	25	1.66E+15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D30201089020	ea	Utility fan set system, belt drive, 7500 CFM	0	0	4.29E+15	25	1.72E+14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D30201361110	ea	Boiler, cast iron, gas & oil, hot water, 6000 MBH	1E+05	29200	1.65E+17	25	6.59E+15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D30203301050	ea	Pump, base mounted with motor, end-suction, 6" size, 25 HP, to 1550 GPM	27750	4050	1.18E+16	25	4.73E+14	-	-	-	10.306	-	-	-	1.529	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D30501553960	sqft	Rooftop, multizone, air conditioner, offices, 25000	9.05	8.2	1.62E+13	26	6.22E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D40104100620	sqft	Wet pipe sprinkler systems, steel, light hazard, 1 floor, 10,000 SF	1.62	1.89	4.36E+12	80	5.45E+10	-	-	-	0.084	-	-	0.000	0.013	0.001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D40104100740	sqft	Wet pipe sprinkler systems, steel, light hazard, each additional floor, 10,000 SF	0.9	1.72	4.03E+12	80	5.03E+10	-	-	-	0.084	-	-	0.000	0.013	0.001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D40203101580	floor	Wet standpipe risers, class III, steel, black, sch 40, 6" diam pipe, 1 floor	7725	5850	1.25E+16	80	1.56E+14	-	-	-	174.361	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D40203101600	floor	Wet standpipe risers, class III, steel, black, sch 40, 6" diam pipe, additional floors	1900	1650	3.26E+15	80	4.07E+13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D40204103630	floor	Fire pump, electric, with controller, 5" pump, 100 HP, 1000 GPM	25100	4650	1.27E+16	25	5.09E+14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D40204103700	floor	Fire pump, electric, for jockey pump system, add	2675	595	1.45E+15	25	5.78E+13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Electrical Service																																									
D50101301200	ea	Underground service installation, includes excavation, backfill, and compaction, 100' length, 4' depth,	26200	12800	5.08E+17	25	2.03E+16	-	-	-	-	7.620	948.810	0.290	-	-	18,291.563	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	49,027.105	-	-	-	-	-	-	-	-
D50102300200	lnft	Feeder installation 600 V, including RGS conduit and XHHW wire, 60 A	6.3	111.5	2.36E+14	80	2.95E+12	-	-	-	-	0.095	0.166	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50102300280	lnft	Feeder installation 600 V, including RGS conduit and XHHW wire, 200 A	28	22.5	1.27E+14	25	5.07E+12	-	-	-	-	0.318	0.894	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50102300480	lnft	Feeder installation 600 V, including RGS conduit and XHHW wire, 1200 A	207	148	4.52E+14	25	1.81E+13	-	-	-	-	0.485	1.754	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50102400580	ea	Switchgear installation, incl switchboard, panels & circuit breaker, 277/480 V, 1200 A	25700	7825	2.72E+16	25	1.09E+15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50201100640	sqft	Receptacles incl plate, box, conduit, wire, 16.5 per 1000 SF, 2.0 W per SF, with transformer	1.14	3.35	7.37E+12	25	2.95E+11	-	-	-	0.006	0.017	0.005	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.001	-	-	-	-	-
D50201350320	sqft	Miscellaneous power, 1.2 watts	0.08	0.25	5.59E+11	25	2.24E+10	-	-	-	-	0.002	0.000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50201400280	sqft	Central air conditioning power, 4 watts	0.18	0.43	1.32E+12	25	5.27E+10	-	-	-	-	0.004	0.005	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50201452080	ea	Motor installation, three phase, 460 V, 15 HP motor size	1225	1450	3.28E+15	25	1.31E+14	-	-	-	-	3.504	3.674	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50201700320	ea	Motor connections, three phase, 200/230/460/575 V, up to 5 HP	9.45	115	4.02E+14	25	1.61E+13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50201700560	ea	Motor connections, three phase, 200/230/460/575 V, up to 100 HP	200	420	5.86E+15	25	2.34E+14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50202100520	sqft	Fluorescent fixtures recess mounted in ceiling, 1.6 watt per SF, 40 FC, 10 fixtures @32watt per 1000 SI	1.63	3.62	7.97E+12	25	3.19E+11	-	-	-	0.004	0.017	0.005	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50309100454	ea	Communication and alarm systems, fire detection, addressable, 50 detectors, includes outlets, boxes,	17300	22000	4.57E+16	25	1.83E+15	-	-	-	-	136.078	0.000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50309100462	ea	Fire alarm command center, addressable with voice, excl. wire & conduit	10200	1725	6.96E+15	25	2.78E+14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50309200102	M.S.F	Internet wiring, 2 data/voice outlets per 1000 S.F.	179	465	9.42E+14	25	3.77E+13	-	-	-	1.490	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50303101010	sqft	Telephone wiring for offices & laboratories, 8 jacks/MSF (cost per MSF)	0.44	1.74	3.43E+12	25	1.37E+11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D50902200300	ea	Uninterruptible power supply with standard battery pack, 15 kVA/12.75 kW	2513	548.5	3.68E+15	25	1.47E+14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Other Service																																									
fixture	ea	e.g. washer, dryer, dishwasher, etc	0	0	2.70E+15	40	6.74E+13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Appendix C. Transformity.

Note: UEVs are relative to the baseline of 1.20 e + 25 sej/yr

Item	UEV	Unit	Referenced
USD	1.97E + 12	sej/$	NEAD (2008 2015)
Plywood	1.83E + 12	sej/kg	Buranakarn (1998)
Wood	2.67E + 12	sej/kg	Cabezas et al. (2010)
Gypsum	1.27E + 12	sej/kg	Odum (1996)
Steel	5.28E + 12	sej/kg	Buranakarn (1998)
Aluminum	1.61E + 13	sej/kg	Buranakarn (1998)
Copper	8.64E + 13	sej/kg	Brown et al. (1992)
Bronze	8.61E + 13	sej/kg	Odum et al. (1987)
Cast Iron	5.28E + 12	sej/kg	Buranakarn (1998)
Brass	8.61E + 13	sej/kg	Odum et al., 1987
Ready-Mixed Concrete	1.83E + 12	sej/kg	Buranakarn (1998)
Concrete Block	1.72E + 12	sej/kg	Haukoos (1995)
Red Brick	2.82E + 12	sej/kg	Buranakarn (1998)
Common Brick	2.82E + 12	sej/kg	Buranakarn (1998)
Motar	2.52E + 12	sej/kg	Buranakarn (1998) p. 142
Grout	2.52E + 12	sej/kg	Buranakarn (1998) p. 142
Asphalt	3.49E + 12	sej/kg	Cabezas et al. (2010)
Polyethylene	6.70E + 12	sej/kg	Buranakarn (1998)
Polystyrene	8.75E + 12	sej/kg	Meillaud et al. (2005)
Fiberglass	8.75E + 12	sej/kg	Meillaud et al. (2005)
Fiber Mineral	8.75E + 12	sej/kg	Meillaud et al. (2005)
Calcium Silicate	8.97E + 12	sej/kg	Buranakarn (1998)
Stucco	2.49E + 12	sej/kg	Meillaud et al. (2005)
Wall Texture Compound	2.49E + 12	sej/kg	Meillaud et al. (2005)
Paint	1.93E + 13	sej/kg	Buranakarn (1998)
Acrylic	1.18E + 13	sej/kg	Braham et al. (2015)
pvc	7.46E + 12	sej/kg	Buranakarn (1998)
Vinyl	8.03E + 12	sej/kg	Buranakarn (1998)
Glass	1.00E + 13	sej/kg	Buranakarn (1998)
Carpet-Nylon	8.03E + 12	sej/kg	Buranakarn (1998)
Resilient Flooring	8.03E + 12	sej/kg	Buranakarn (1998)
Granite	6.24E + 11	sej/kg	Odum (1996)
limestone	1.25E + 12	sej/kg	Odum (1996) and Campbell and Ohrt (2009)
Aggregate	1.73E + 12	sej/kg	Cabezas et al. (2010)
Ceramic Tile	3.89E + 12	sej/kg	Buranakarn (1998)

Appendix D. Emergy Calculation.

Note: UEVs are relative to the baseline of 1.20 e + 25 sej/yr.

1. Sunlight

Annual energy (J/yr) = (Average total annual insolation) * (Site area) = (Wh/yr/m2) * (3600 J/Wh) * (m2)

Source: GHI (global horizontal irradiance), TMY3 data sets, NREL, 2005

2. Rain (chemical)

Chemical potential energy of rain (J/yr) = (Annual rainfall rate) * (Site area) * (Gibbs' free energy of water) * (1-Runoff coefficient) = (m/yr) * (m2) * (106 g/m3) * (4.72 J/g) * (1-Runoff coefficient)

Transformity = 2.35E + 4 sej/JFormula for Gibbs' free energy of rain, Lu et al., 2007

3. Rain (geopotential)

Geopotential energy of rain (J/yr) = (Annual rainfall rate) * (Footprint) * (Runoff rate) * (Density of water) * (Average elevation) * (Gravity) = (m/yr) * (m2) * (%) * (1000 kg/m3) * (m) * (9.8 m/s2) Annual rainfall rate (m/yr) from TMY3 data, NREL, 2005

Transformity = 1.31E + 4 sej/J, Campbell and Ohrt, 2009

4. Wind (kinetic energy)

Kinetic energy of wind (J/yr) = (Site area) * (Air density) * (Drag coefficient) * (Geostrophic velocity)3 * (Seconds per year) = (m2) * (1.25 kg/m3) * (Drag coefficient) * (m/s)3 * (31,700,000 s/yr)Drag coefficient, Garrat, 1977

Transformity = 1.90E + 3 sej/J, Odum, 1996

5. Building construction (depreciated)

Building annual depreciation (sej/yr) = (Weight of material) * (UEV)/(Lifespan) = (kg) * (sej/kg)/(yrs)

6. Water

Annual consumption of water (L/yr) = (Number of people) * (Days per year) * (Liters of water per person each day) = (# people) * (365 days/yr) * (L/day per capita)

Transformity = 2.05E + 9 sej/L, Buenfil 2000Annual consumption of water – AWWARF, 1999

7. Wastewater

Volume wastewater (L/yr) = (Annual consumption of water) * (Percent of water used indoors) = (L/yr) * (%)

Transformity = 3.54E + 9 sej/L, Bjorklund et al., 2001

8. Food

Food consumption (J/yr) = (Number of people) * (Calories consumed each day per capita) * (Days per year) * (Joules per calorie) = (# people) * (2500 Cal/day/person) * (365 days/yr) * (4187 J/Cal)

Transformity = 9.53E + 5 sej/J, Susanne et al., 2000

9. Non-durable Supplies

Annual consumption ($/yr) = (0.96 * Household income) * (Percent of income for non-durables) = (0.96 * $) * (%)

Transformity = 1.97E + 12 sej/$, NEAD, 2012 Average% income spent on non-durable goods – Bureau of Labor Statistics 2013

10. Solid waste

Solid waste (kg/yr) = (Number of people) * (Annual waste per capita) = (# people) * (kg/person/yr)

Transformity = 2.25E + 11 sej/kg, Brown, 2000

11. Utilities

Utility breakdown based on End Uses Survey

Transformity Fuels

Natural Gas = 1.41E + 05 SeJ/J; Oil, Diesel = 1.43E + 05; Gasoline = 1.48E + 05, Brown et al., 2011

US Electricity Fuel Mix.

% Mix	Sej/J	Note	
Coal	47.42%	2.17E + 05	Brown et al. (2012)
Natural Gas	19.40%	2.16E + 05	Hayha (2011); Brown et al. (2012)
Oil	0.95%	4.31E + 05	Brown et al. (2012)
Nuclear	20.83%	4.81E + 04	Campbell and Ohrt (2009)
Hydro	6.27%	8.49E + 04	Hayha (2011); Brown et al. (2004)
Wind	2.28%	8.34E + 04	Hayha (2011); Brown et al. (2004)
Wind	2.28%	8.34E + 04	Hayha (2011); Brown et al. (2004)
Wood	0.86%	2.43E + 05	Odum (1996)
Biomass	0.69%	6.18E + 05	Odum (1996)
Solar PV	0.03%	9.08E + 04	Brown et al. (2012)
Other	0.90%	2.29E + 05	Braham et al. (2016)
US Electric Mix	100%		

* % Mix 2010 EIA Annual Energy Report.

12. Transportation.

Transportation (sej/j) = (Number of Commuters) * (Mode of Transportation) * (Duration of Trip) * 2(round trip).

Transformity Based on Federici et al., 2003.

Passenger Car: 1.66E + 11 Sej/P.km.

Bus: 6.00E + 10 Sej/P.km.

Rail: 7.40E + 10 Sej/P.km.

New York City Average Speed by Mode of Transportation.

Subway: 17.4 mile/hr (http://www.nyctransitforums.com/forums/topic/17313-subway-system-average-speed-by-line/).

Bus: 9.35 mile/hr (http://www.wnyc.org/story/traffic-speeds-slow-nyc-wants-curb-car-service-growth/).

Passenger Car: 9.35 mile/hr (assumed to be the same as the average speed of bus).

13. Annual Property Tax.

Annual Property Tax ($/yr) = {(Assessment Land) + (Assessment Building) – (Tax Exemption)} * (Average Effective Property Tax Rate).

Average Effective Property Tax Rate: 0.08%, New York City Property Tax Calculator (https://smartasset.com/taxes/new-york-property-tax-calculator).

Transformity = 1.97E + 12 sej/$, NEAD, 2012.

14. Annual Household Income.

Annual Household Income ($/yr) = (Median Household Income by Census Tract) * (Number of Residential Unit).

Transformity = 1.97E + 12 sej/$, NEAD, 2012.

15. Annual Corporate Profit.

Annual Corporate Profit ($/yr) = (Number of Employees by Industry) * (Revenue per Employees by Industry).

Transformity = 1.97E + 12 sej/$, NEAD, 2012.

16. Number of Occupants

Number of Occupants = Number of Residents + Number of Office Workers + Number of Retail Workers

Residents = (Number of Housing Units within A Block) * (Total Number of Housing Units by Census Tract)/(Total Number of Population by Census Tract)

Office Workers = (Total Floor Area of Office, sqft) * (80%, floor area efficiency for leasable area) * (5%, vacancy rate)/(100 sqft/worker, live load estimate for structural engineering)

Retail = (Total Floor Area of Retail, sqft) * (80%, floor area efficiency for leasable area) * (1–5%, vacancy rate)/(300 sqft/worker, live load estimate for structural engineering).

References

AWWARF, American Water Works Associations Research Foundation, 1999. Residential End Uses of Water. AWWARF, Denver, CO.

Almeida, C.M.V.B., Barrella, F.A., Giannetti, B.F., 2007. Emergetic ternary diagrams: five examples for application in environmental accounting for decision-Making. J. Clean. Prod. 15, 63–74.

Ascione, Marco, Campanella, Luigi, Cherubini, Francesco, Ulgiati, Sergio, 2009. Environmental driving forces of urban growth and development: an emergy-based assessment of the city of rome, Italy. Landscape Urban Plann. 93 (3–4), 238–249, http://dx.doi.org/10.1016/j.landurbplan.2009.07.011.

Philip, Philip R., 2002. Does sustainable development offer a new direction for planning? Challenges for the twenty-first century. J. Plann. Lit. 17 (1), 21–36.

Bjorklund, Johanna, Geber, Ulrika, Rydberg, Torbjorn, 2001. Emergy analysis of municipal wastewater treatment and generation of electricity by digestion of sewage sludge. Resour. Conserv. Recycl. 31, 293–316.

Braham, William W., Benghi, N., 2016. The Varieties of Building Emergy Intensity. https://niccolobenghiarchitect.files.wordpress.com/2016/12/benghi_braham_buildingvariety_paper_rev1.pdf.

Braham, William W., Yi, H., 2015. Hierarchies of production in a contemporary residence. emergy synthesis 8. In: Proceedings of the 8th Biennial Emergy Conference, University of Florida, Gainseville.

Braham, William W., 2016. Architecture and Systems Ecology: Thermodynamic Principles of Environmental Building Design, in Three Parts.

Brown, M.T., Buranakarn, Vorasun, 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resour. Conserv. Recycl. 38 (1), 1–22.

Brown, M.T., Ulgiati, Sergio, 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9 (1), 51–69, http://dx.doi.org/10.1016/S0925-8574(97)00033-5.

Brown, Mark T., Ulgiati, Sergio, 2004a. Emergy analysis and environmental accounting. In: Cutler, J. (Ed.), Encyclopedia of Energy. Elsevier.

Brown, Mark T., Ulgiati, S., 2004b. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecodinamic 178 (1–2), 201–213, http://dx.doi.org/10.1016/j.ecolmodel.2004.03.002, Through the MACROSCOPE: The Legacy of H.T. Odum.

Brown, Mark T., Vivas, B., 2007. Landscape development intensity index. In: Emergy Synthesis 4: Theory and Application of the Emergy Methodology The Center for Environmental Policy. University of Florida, Gainsville. FL.

Brown, Mark T., Protano, Gaetano, Ulgiati, Sergio, 2011. Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas. Ecol. Modell. 222, 879–887.

Brown, Mark T., 1980. Energy Basis for Hierarchies in Urban and Regional Landscapes. PhD Dissertation. University of Florida, Florida http://www.cep.ees.ufl.edu/emergy/documents/dissertations_theses/Brown_EnergyBasisfor%20Hierarchies.pdf.

Brown, Mark T., 2005. Landscape development intensity index. In: Emergy Synthesis 3: Theory and Application of the Emergy Methodology Center for Environmental Policy. University of Florida, Gainsville. FL.

Buranakarn, Vorasun., 1998. Evaluation of Recycling and Reuse of Building Materials Using the Emergy Analysis Method.

Cabezas, H.D., Campbell, T., Eason, A.S., Garmestani, M.T., Herberling, M.E., Hopton, J., 2010. In: Heberling, M.T., Hopton, M.E. (Eds.), Templeton, and M. Zanowick. 2010. San Luis Basin Sustainability Metrics Project: A Methodology for Evaluating Regional Sustainability. United States Environmental Protection Agency (US EPA), pp. 119–136.

Daniel, Campbell, Ohrt, Andrew, 2009. Environmental Accounting Using Emergy: Evaluation of Minnesota. EPA/600/R-09/002. US Environmental Protection Agency, Narragansett, RI.

Campbell, Daniel M., DeMoss, Meisch T., Pompinio, J., Bradley, P., 2004. Keeping the books for the environment: an emergy analysis of minnesota. Environ. Monit. Assess. 94, 217–230.

Cervero, Robert, 1998. The Transit Metropolis: A Global Inquiry. Island Press, Washington, D.C.

Daniel, C., Ohrt, A., 2009. Environmental Accounting Using Emergy: Evaluation of Minnesota. EPA/600/R-09/002. US Environmental Protection Agency, Narragansett, RI.

Federici, M., Ulgiati, S., Verdesca, D., Basosi, R., 2003. Efficiency and sustainability indicators for passenger and commodities transportation systems: the case of siena, Italy. Ecol. Indic. 3 (3), 155–169, http://dx.doi.org/10.1016/S1470-160X(03)00040-2.

Gehl, Jan, 1987. Life Between Buildings: Using Public Space. Van Nostrand Reinhold, New York.

Glaeser, Edward L., 2011. Triumph of the City: How Our Greatest Invention Makes Us Richer, Smarter, Greener, Healthier, and Happier. Penguin press, New York.

Haukoos, D.S., 1995. Sustainable Architecture and Its Relationship to Industrial Building. University of Florida.

Howard, B., Parshall, L., Thompson, J., Hammer, S., Dickinson, J., Modi, V., 2012. Spatial distribution of urban building energy consumption by end use. Energy Build. http://sel-columbia.github.io/nycenergy/.

Huang, Shu-Li, Lai, Hsiao-Yin, Chia-Lun, Lee., 2001. Energy hierarchy and urban landscape system. Landscape Urban Plann. 53, 145–161.

Huang, Shu-Li., 1998. Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. J. Environ. Manage. 52 (1), 39–51, http://dx.doi.org/10.1006/jema.1997.0157.

Jacobs, Jane., 1961. The Death and Life of Great American Cities. Random House, New York.

Jenks, Mike, Jones, Colin, 2010. Dimensions of the Sustainable City (Future City 2). Springer.

Lei, Kampeng, Wang, Zhishi, ShanShin, Ton., 2008. Holistic emergy analysis of Macao. Ecol. Eng. 32 (1), 30–43, http://dx.doi.org/10.1016/j.ecoleng.2007.08.008.

Liu, G., Chen, B., Zhang, L., 2011. Analysis of resource and emission impacts: an emergy-based multiple spatial scale framework for urban ecological and economic evaluation. Entropy 13, 720–743.

Lu, Hongfang, Campbell, Daniel E., Chen, Jie, Qin, Pei, Hai, Ren., 2007. Conservation and economic vitality of nature reserves: an emergy evaluation of the yancheng biosphere reserve. Biol. Conserv. 139, 415–438.
Lu, Hongfang, Yuan, Yaguang, Campbell, Daniel E., Qin, Pei, Lijuan, Cui., 2014. Integrated water quality, emergy and economic evaluation of three bioremediation treatment systems for eutrophic water. Ecol. Eng. 69 (August), 244–254, http://dx.doi.org/10.1016/j.ecoleng.2014.04.024.
March, L., Trace, M., 1969. The Land Use Performance of Selected Arrays of Built Forms. Cambridge University Press, Cambridge, UK.
McHarg, Ian., 1969. Design with Nature. Doubleday/Natural History Press, New York.
Meillaud, F., Gay, J.-B., Brown, M.T., 2005. Evaluation of a building using the emergy method. CISBAT '03: Innov. Build. Envel. Environ. Syst. 79 (2), 204–212, http://dx.doi.org/10.1016/j.solener.2004.11.003.
NEAD, National Environmental Accounting Database, 2012. Center for Environmental Policy, University of Florida, Gainesville, FL www.cep.ees.ufl.edu/nead/.
NREL, National Renewable Energy Laboratory, 2005. National Solar Radiation Data Base, 1991–2005 Update: Typical Meteorological Year 3. rredc.nrel.gov/tmy3/.
Newman, Peter W.G., 1989. Cities and Automobile Dependence: A Sourcebook. Gower Technical, Aldershot, Hants, England.
Odum, Howard T., Brown, Mark T, Whitfield, D.F., Lopez, S., Woithe, R., Doherty, S., 1995. Zonal Organization of Cities and Environment – A Study of Energy Systems Basis for Urban Society Center for Environmental Policy. University of Florida, Gainesville, Florida.
Odum, Howard T., 1983. Systems Ecology: An Introduction. Wiley, New York.
Odum, Howard T., 1996. Environmental Accounting: EMERGY and Environmental Decision Making. Wiley, New York.
Odum, Howard T., 2007. Environment, Power, and Societ. Columbia University Press, New York.
Oldfield, Philip, 2009. Five energy generations of tall buildings: an historical analysis of energy consumption in high-rise buildings. J. Archit. 14 (5), 591–613.
Ortega, E., Anami, M.H., Diniz, G., 2002. Certification of food products using emergy analysis. In: Ulgiati, S., Brown, M.T., Giampetro, M., Herendeen, R.A., Mayumi, K. (Eds.), 3rd Biennial International Workshop. Advances in Energy Studies, Reconsidering the Importance of Energy, Servizi Grafici Editoriali, Padova, Italy, pp. 227–237.
Owen, David., 2010. The Efficiency Dilemma: If Our Machines Use Less Energy, Will We Just Use Them More? The New Yorker.
Philip, Steadman, 1979. The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts. Cambridge University Press, Cambridge.
RSMeans, 2016. Estimating Handbook, 3rd ed. R. S. Means Company, Kingston, MA.
Ravi, Srinivasan, Braham, William W., Campbell, Daniel E., Curcija, Charlie D., 2012. Re(De)fining net zero energy: renewable emergy balance in environmental building design. Int. Workshop Vent. Comfort Health Transp. Veh., 300–315, http://dx.doi.org/10.1016/j.buildenv.2011.07.010.
Reps, John., 1965. The Making of Urban America: A History of City Planning in the United States. Princeton University Press, Princeton.
Sergio, Ulgiati, Odum, Howard T., Bastianoni, S., 1994. Emergy use, environmental loading and sustainability. An emergy analysis of Italy. Ecol. Modell. 73, 215–268.
Srinivasan, Ravi, Moe, Kiel, 2015. The Hierarchy of Energy in Architecture Energy Analysis. Routledge, Abingdon, Oxon; New York, NY.
Susanne, J., Doherty, S., Rydberg, T., 2000. Sweden food system analysis. In: EMERGY SYNTHESIS 1: Theory and Applications of the Emergy Methodology.
William, W., 1980. The Social Life of Small Urban Spaces. Project for Public Spaces, New York.