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"The study showed that wind load per building is much less than for the same buildings without ETFE atria and multi-level skybridges, requiring up to 10% less structural material."

The concept of cities as self-contained megastructures has fascinated architects and urban theorists for decades. The idea received much attention in the 1960s and 70s, resulting in some experimental built works. With today's renewed interest in sustainability and compact living, along with advances in computerized architectural optimization, there is now an opportunity to revisit this concept. This paper examines the potential for the nearest modern analogue – the college town – to be incorporated in such a self-contained structure, which is nevertheless connected to the world.

Introduction

People love their cars, but what is the cost of this love affair? The average American family spends 17% of its income on transportation (US BLS 2015). The ratio of the number of traffic fatalities to the total number of deaths each year reveals that about one out of 79 dies in a car crash (US NHTSA 2015; US CDC 2015). Air pollution from vehicles causes the premature death of about one out of 49 Americans (Caiazzo et al. 2013). Car use contributes to the pandemic of physical inactivity, which causes about one out of 10 deaths worldwide (Kohl et al. 2012). Congested traffic is a source of wasted time, noise, and stress. The American lifestyle is so dominated by car usage that most people choose to ignore the dangers and costs.

Is it realistic to build car-free cities? The past century has seen the development of high-density ground-access-skyscraper (GAS) cities throughout the world. Such urban intensification has been called the "Paradox of Intensification," which states, "*Ceteris paribus,* urban intensification which increases population density will reduce per capita car use, with benefits to the global environment, but will also increase concentrations of motor traffic, worsening the local environment in those locations where it occurs" (Melia, Parkhurst & Barton 2012). One reason high-density GAS cities are congested with vehicles is that in many cases the horizontal distance between origin and destination is too far to walk. Studies show that people are willing to walk about 800 meters before taking a motorized vehicle (Guerra, Cervero & Tischler 2012). This article examines car-free cities where all daily origins and destinations are located within an 800-meter horizontal walking distance.

Evolution of the Self-Contained City

A city that includes all daily origins and destinations for all its residents will be referred to hereafter as a "self-contained" city, for which there is a significant theoretical precedent. Buckminster Fuller contemplated such cities in conjunction with his famous geodesic dome designs in the 1950s. These ideas influenced the London-based architectural group, Archigram, which was committed to a high-tech, lightweight, infrastructural approach. Metabolism was a post-war Japanese architectural movement that combined ideas from architectural megastructures with organic biological growth in the 1960s. In 1970, construction began on Arcosanti in Arizona, a hyperdense city designed by Paolo Soleri to maximize interaction of its 5,000 inhabitants as an example of architecture coherent with ecology, or "arcology." These ideas are again becoming popular as sustainability becomes a priority. In 2012 Ken King established Vertical City, a not-for-profit organization that aims to ignite a worldwide conversation about vertical cities as a solution to a more sustainable future. In recent years, massive self-contained "hyperstructures" have been proposed, including the X-Seed 4000 in Japan, 1995; Crystal Island in Russia, 2007; and Ziggurat in Dubai, 2008.

How much floor space is needed for a self-contained city, and what is a logical population for a city encompassing residences, workplaces, offices, schools, stores, hospitals, restaurants, churches, and entertainment? Everyone who lives in the self-contained city works there. Some of the best contemporary examples of self-contained cities are college towns. The following five college towns in the USA were considered: Auburn, Alabama; Lafayette, Indiana; College Station, Texas; State College, Pennsylvania; and Ames, Iowa. Based on the 2010 US Census, the analysis of the demographics and land use of these five cities revealed that the average population of these cities, including students, is about 100,000 (US Census 2010), and the average total floor area is about seven million square meters.

One blunt-force approach to accommodating the above would be to construct a single mega-building with a floor area of 7 million square meters. If the mega-building has a square 800-meter-by-800-meter footprint, it would require 11 stories. Alternatively, if the mega-building has 100 stories, it would require a square 265-meter-by-265-meter footprint. People would not want to live in an uninspiring mega-building such as this because it lacks architectural diversity and limits natural light penetration and exterior views.

A team of students and faculty from a variety of engineering, management, and social science disciplines designed a car-free University City for 100,000 people including 33,000 students with the same floor space and outer dimensions as the "mega-building," but which instead consists of 46 diverse buildings ranging from 15 to 44 stories (see Figure 1). This University City is an example of an urban paradigm that will be referred to herein by the name "greenplex." At the CTBUH World Conference 2011, the notion of the greenplex was introduced and research needs were outlined (Balling 2011). This article presents research results garnered over the past five years and further refines the greenplex as a "car-free polycentric urban paradigm."

Space Use and Multi-Level Skybridges

The team addressed the optimum allocation of space use throughout the University City by considering results from an optimization study on a simpler city with 25 buildings. This city was divided into 344 zones, in which each zone consisted of three consecutive floors in one of the buildings. Space was optimized with a genetic algorithm that represented a particular design as a chromosome with 344 genes – one for each zone. The value of each gene was an integer between 1 and 16, corresponding to 16 specific residential, commercial, educational, and recreational space uses. The algorithm's objective was the minimization of the average travel time of all trips during the evening peak period. A three-step transportation model was developed: 1) trip generation, 2) trip distribution, and 3) trip assignment.

Four optimization problems were solved (see Table 1). In scenarios 1 and 3, skybridges were located between every building at four equally-spaced levels. In scenarios 2 and 4, there were no skybridges. In scenarios 1 and 3, each building was equipped with one multi-car circulating elevator loop (Hitachi 2006) that stopped at every story and one express multi-car circulating elevator loop that stopped only at skybridge levels. In scenarios

Figure 1. The University City plan.

2 and 4, each building had three express and three standard elevator loops. The average travel time was the same for scenarios 1 and 3, 19% longer for scenario 2, and 134% longer for scenario 4.

These results clearly show the value of skybridges in reducing travel time. The fact that increasing the number of elevator loops did not shorten the travel time suggests that pedestrian movement is predominantly horizontal rather than vertical when skybridges are present. When skybridges are present, the optimum location of high-attraction uses such as shopping centers, supermarkets, food & beverage, and athletic clubs was at skybridge levels, while the optimum location of low-attraction uses, such as offices, medical centers, schools, and churches was at non-skybridge levels. Optimization distributed all uses vertically throughout the city. These results suggest that the presence of multi-level skybridges leads to the creation of "multi-level communities" in the optimum design, where people spend most of their time within a few levels of their residence.

The team used these results to design the space use for the 100,000-resident University City (see Figure 2). Recall that the 46 buildings range from 15 to 44 stories. Note that the mixed-use buildings are highly-connected with skybridges every seven stories, and that high-attraction retail space

Optimization problem	Skybridges present	Elev. loops	Average travel time (s)	Longest trip time (s)
1	Yes	3X	168.6	594.2
2	No	3X	196.5	706.2
3	Yes	1X	168.8	594.2
4	No	1X	267.5	1390.3

Table 1. Travel times for optimum designs of generic city.

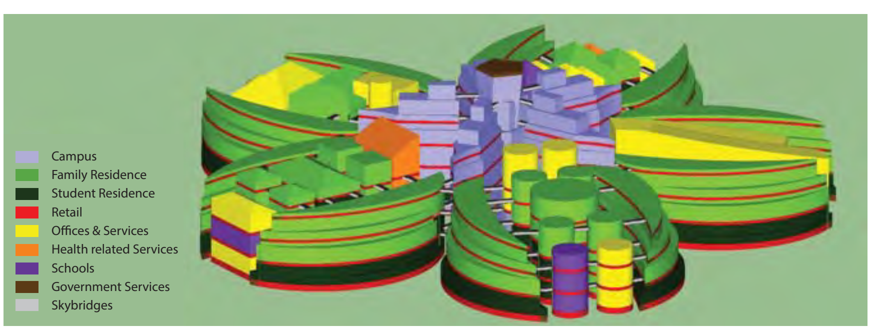

Figure 2. Facility configurations for the University City.

is located on the skybridge levels of the multi-level city. The university campus is located in the stem of the city and residences, offices, hospitals, and schools are located in the five leaves that surround it. The family residences are located mostly in the banana-shaped buildings on the exterior of each leaf, and consist of spacious and soundproof homes with terraced balconies with an average floor space of 251 square meters for a family of four. Student residences consist of dorms with an average floor space of 93 square meters for four students.

Multi-level skybridges relieve ground-level congestion and transform ground-access buildings into multi-level access buildings (see Figures 1 and 2). This design protects the city from fire and terrorist attack, because the multi-level skybridges are fireproof and provide multiple escape routes from every building (Wood 2003). A fire/police station is located on each skybridge level of the city so that emergency responders need only ascend/descend three flights of stairs to reach any point in the city if elevators are inoperable.

ETFE Atria and Thermal/Structural Response

Since the car-free city is free from vehicle emissions, the University City includes enclosed atria between all the buildings. This was accomplished by spanning building roofs and exterior building sides with the Ethylene tetrafluoroethylene (ETFE) structural material. ETFE has the following remarkable properties: it is lightweight, transparent, flexible, easy-to-repair, self-cleaning, noncombustible, recyclable, inexpensive, and has low embodied energy (LeCuyer 2008). ETFE cushions between buildings can be supported by a lightweight, flexible, cable-spring truss system as shown in Figure 3 (Balling & Bessey 2015).

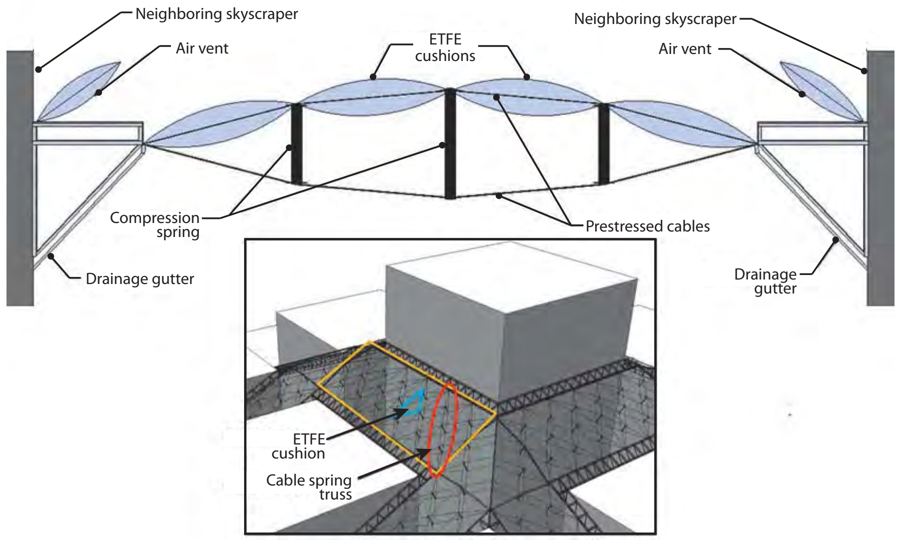

Figure 3. Cable-spring support for ETFE cushions.

The ETFE atria between buildings fully protect people from rain, snow, wind, dust, extreme heat, and extreme cold while allowing the penetration of natural light. This makes it possible for people to move comfortably between buildings year-round, regardless of the weather outside.

It also reduces the total exposed surface area of the city, which reduces the energy required for heating, ventilation, and air-conditioning (HVAC). Even though the ETFE atria increased the indoor volume of the University City by 48%, the exposed surface area was reduced by 52%. The University City was analyzed for three cases over a year long period: 1) conditioned ETFE atria between buildings, 2) unconditioned ETFE atria between buildings, and 3) no atria between buildings (see Figure 4). For the year, the conditioned-atria case used 36% less energy than the no-atria case, and the unconditioned-atria case used 40% less energy than the no-atria case. The outside temperature ranged from a low of -18°C to a high of 38°C. The temperature of the conditioned atria was in the same range as the buildings' interior temperature, between 18.3°C to 23.9°C. The unconditioned atria temperature, meanwhile, ranged from 8°C to 30°C.

One example of a small system of buildings interconnected with multi-level skybridges and ETFE atria is the Parkview Green in Beijing, which received a LEED Platinum

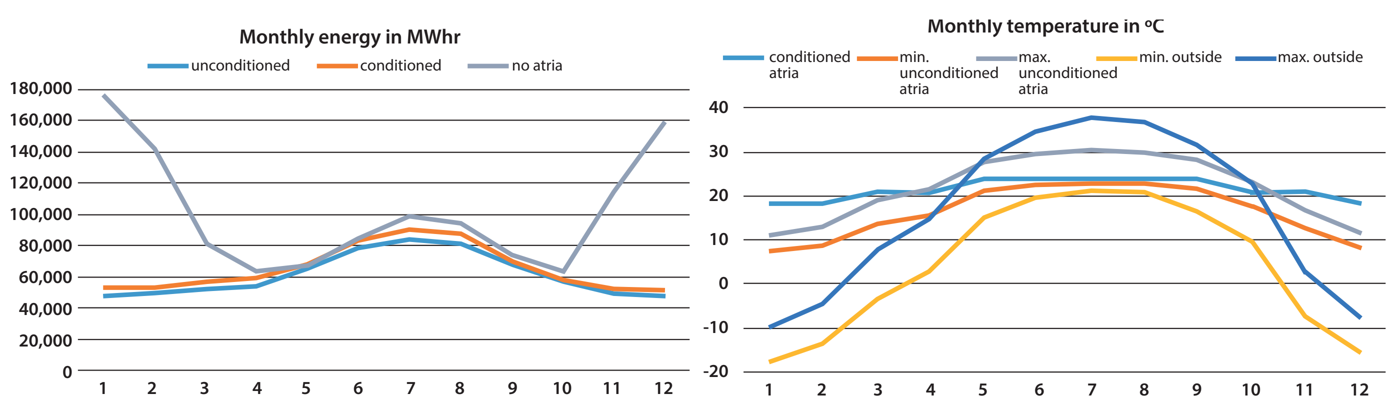

Figure 4. Energy consumption and temperature in University City.

Figure 5. Parkview Green, Beijing serves as a useful smaller-scale built precursor of an ETFE city.

Figure 6. Linked Hybrid, Beijing, provides a precursor built example of a multi-building complex linked by skybridges. © StevenHollArchitects/Shu He

rating in 2009 (see Figure 5). Parkview Green consists of two 18-story and two 9-story mixed-use buildings within a quarter pyramid with an ETFE roof and glass sides. Skybridges between buildings are located at multiple levels. The unconditioned atria temperatures are much milder than the outside temperatures.

Fossil fuel consumption for HVAC can also be reduced by utilizing ground-source heat pumps and hydronic heating/cooling. These technologies were used in the Linked Hybrid in Beijing, which received the CTBUH Best Tall Building Worldwide Award in 2009 (see Figure 6). The Linked Hybrid consists of nine 21-story buildings that sit atop 660 100-meter-deep wells that harness cool ground temperature in summer and warm ground temperature in winter. Water from these wells is circulated up through the floor slabs of the buildings to provide radiant hydronic heating/cooling that eliminates the space needed for the ducts and noisy fans of a forced-air system. These technologies shoulder 70% of the heating/cooling load for the complex.

Structural analysis and optimization methods were used to study the structural design of tall buildings interconnected with multi-level skybridges and ETFE atria subjected to gravity, wind, and seismic loads. The study controlled for factors such as number of buildings, equal-height vs. variable-height buildings, type of skybridge connection, site seismicity, and wind intensity, and presence vs. absence of skybridges and atria. If skybridges are connected to the buildings with sliders, then the buildings can sway independently under lateral wind and seismic load. The study showed that it is advantageous to construct hinge connections between the skybridges and the buildings. The axial stiffness of hinge-connected skybridges constrain the buildings to horizontally sway in unison under lateral loading (see Figure 7).

The long natural period of the system leads to a low seismic response. Response to wind loading is often more critical for tall buildings. The ETFE envelope between building roofs and exterior building sides creates an aerodynamic shape, such that the total wind load on the system is significantly less than the total load due to wind blowing in and around buildings without the envelope. The hinge-connected skybridges utilize the lateral stiffness of both interior and exterior buildings

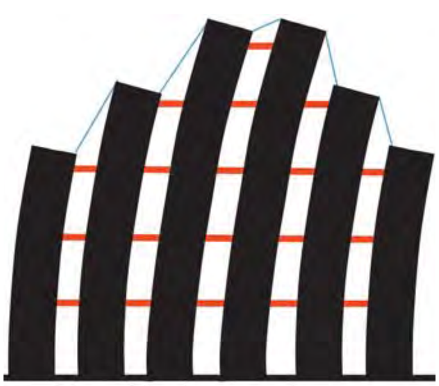

Figure 7. Buildings with hinged-skybridges and ETFE Atria.

to resist wind load. The study showed that wind load per building is much less than for the same buildings without ETFE atria and multi-level skybridges, requiring up to 10% less structural material.

Polycentric Greenplex Urban Paradigm: Expansion Potential

The University City is an example of a general urban paradigm, the "greenplex." The characteristics of the greenplex are summarized below:

1. Car-free with a walkable footprint diameter less than 800 meters.
2. Self-contained, with origins and destinations for about 100,000 people.
3. Inspiring form, with many architecturally diverse, multi-story buildings.
4. Multi-level city, with multiple retail levels in mixed-use buildings.
5. Highly-connected, with multi-level skybridges.
6. Fully-weather-protected, with ETFE atria between buildings.
7. Near net-zero fossil fuel and water consumption with green technologies such as ground-source heat pumps, hydronic heating/cooling, reduced exposed surface area, multi-car circulating elevators, wind turbines, solar panels, on-site wastewater treatment, natural lighting, and natural ventilation.

Can the greenplex urban paradigm be extended to large metropolitan areas? The Wasatch Front Metropolitan Area (WFMA) is an urban area in the United States that includes Salt Lake City, Utah. The projected population of the high-growth WFMA is 3.5 million for the year 2040 (Davidson 2012). Like many metropolitan areas in the USA, the current urban form of the WFMA is car-oriented, low-density sprawl.

The projected population of the WFMA could be accommodated with 35 greenplexes of about 100,000 people each. The University Greenplex would be economically catalyzed by the university at its core. Each of the 35 greenplexes in the WFMA would have different economic catalysts, such as a biomedical research park, a software development campus, a financial services cluster, or a food processing center. The architectural form and function would vary significantly among greenplexes. The WFMA would become a polycentric metropolitan area, which has been recognized as a sustainable urban form (Jenks & Dempsey 2005).

The WFMA greenplexes would be interconnected with high-speed trains, and each greenplex would have an underground train station at its center. Since the maximum footprint diameter of each greenplex is 800 meters, all origins and destinations are within 400 meters walking distance from train stations. This short walking distance makes mass transit between greenplexes the desirable mode of transportation.


Figure 8. Comfortable "talkable" environment, year-round.

Trucks and trains would also be used to transport food and freight to an off-site distribution center for each greenplex, with underground conveyance to the freight elevators of the greenplex. Transport links between the greenplex and the off-site distribution center are underground so that the outdoor surface space immediately around the greenplex can be used for public spaces and cultivation, rather than highway infrastructure.

Currently 7% of vehicle miles of travel (VMT) in the WFMA is for recreation and rural trips (Utah DOT 2012), and 10% of VMT is for truck freight trips (US FHA 2010). It is possible that all other VMT could be eliminated in the polycentric greenplex WFMA. This implies that it may be possible to reduce car accidents by as much as 83%.

Sustainability Impact

The sustainability of the polycentric greenplex urban paradigm can be examined in the context of its impact on people, planet, and prosperity. The greenplex environment is walkable by design. People walk to school and work, and to stores with their shopping carts. Electric forklifts are available to transport heavy loads. Walkability leads to "talkability" – social interaction – at a level not achievable in car-centric communities. As shown in Figure 8, the atria provide a comfortable, talkable environment year-round. People can interact, and multi-level communities can develop.

The greenplex environment is accessible. Parents can take children to a variety of recreational options within walking distance. Disabled people are no longer trapped in their residences and dependent on others to drive them around. The greenplex environment is safe. There are no dangerous vehicular streets. People are fully protected from bad weather. Increased sense of community and police proximity lead to lower crime (Cook 2008). Skybridges provide multiple emergency escape routes. Without cars the air is clean and noise is diminished. Exercise increases and stress decreases.

The potential impact of the polycentric greenplex urban paradigm on the planet is truly staggering. The projected developed land use for the WFMA in 2040 is about 1,000 square kilometers (Envision Utah 2005). The 35 greenplexes needed for the projected 2040 population would occupy about 90 square kilometers, including the off-site toy boxes and distribution centers. This represents a 91% reduction in land consumption.

Utah is a dry place. About 57% of the water consumed is used for outside sprinkler systems for lawns and gardens. Assuming that outdoor sprinkler consumption is reduced in accordance with the 91% reduction in land consumption, and that indoor water consumption is reduced by 50% due to recycling and green technologies, total water consumption could be reduced by 73%.

In the United States, about 41% of energy is consumed in residential and commercial buildings, 30% is consumed in industry, and 29% is consumed in transportation (US DOE 2012). In buildings, 61% is consumed in air and water heating/cooling, and 39% is consumed in lighting/electrical. Assuming heating/cooling energy consumption is reduced by 40% due to the lower exposed surface area, and assuming 70% of the remaining heating/cooling energy comes from ground source heat pumps – as was the case for the Linked Hybrid – the heating/cooling fossil fuel consumption could be reduced by 82%. Assuming that the lighting/electrical fossil fuel consumption could be reduced by 40% due to green technologies, the fossil-fuel consumption in buildings would be reduced by 66%. In transportation, assume that the 83% reduction in VMT translates to a 70% reduction in fossil fuel consumption, since fossil fuel would still likely be used to power trains. In total, the reduction in fossil fuel consumption would be 47%. This calculation does not include further reductions in the industrial sector.

Since cars and trucks account for 57% of Utah's air pollution (Utah Foundation 2008), the 83% reduction in VMT would reduce air pollution by 47%. The reduction would be even greater due to reduced fossil fuel consumption for heating/cooling and power generation. Utah occasionally has the worst air in the nation during winter temperature inversions.

The benefits to prosperity of the polycentric greenplex urban paradigm are significant. High-density greenplexes catalyze productivity. Productivity is further enhanced when people are healthy and comfortable, and wasted time in traffic is eliminated. Utility and transportation costs are dramatically lower. By exploiting prefabrication, modularization, and replication, the construction costs of greenplexes can be brought down to competitive levels.

Implementation

Transition from the current sprawl paradigm to the polycentric greenplex urban paradigm is a major economic issue. Fortunately, greenplexes can be constructed incrementally rather than all at once. For example, the first phase of the University Greenplex could consist of the university core or "stem," along with one of the five surrounding "leaves." Then, as demand for car-free living increases, the other four leaves could be added in succession. Greenplexes do not require large amounts of land, and are ideal for urban areas that need revitalization. In some cases, the value of the land that is freed up in the transition from sprawl to greenplex could be used to help finance greenplex construction. Demand for mixed-use, walkable, high-density living is increasing throughout the world (Cech 2012). The polycentric greenplex urban paradigm is out in front of this trend. ■

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