BioComplexity, Systems Thinking, and Multi-Scale Dynamic Simulation: Foundations of Geodesign

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Abstract

Landscape Architecture and Planning have long used visual simulations for design ideation and communication, but the complex demands of the twenty-first century will require more than simply visual simulations; dynamic simulations across a spectrum of scientific, social and perceptual issues will be key to effective design in the future. The new science and art of 'geodesign' promises to harness digital and computational technologies, from Geographic Information Sciences (GIS) and remote sensing to software engineering and algorithmic design, in the service of imagining, designing, simulating, implementing, and evaluating better environments, worldwide, enabling collaborative design informed by scientific knowledge. Landscape ecology, engineering, and other disciplines have contributed non-visual, and sometimes non-static, analyses to the repertoire of impact assessment in natural systems management, transportation, energy, and urbanization projects, etc., but these additions are mostly still of limited scope and complexity. The interrelated nature of natural systems at all scales is still only becoming apparent to us and to the scientific community, as the recent interest in 'biocomplexity' and 'systems thinking' demonstrates (e.g. NSF Biocomplexity initiative). Increasingly, geodesign projects will need to incorporate systems thinking across all aspects of the process, be informed by the findings of biocomplexity research, and make maximum use of multi-scale dynamic simulations in the process of evaluating impacts of proposed designs.

1 Introduction

Landscape architecture has long been understood to be not just a decorative art, but to depend upon function as one determinant of form; and to require an understanding of dynamic behaviors – of water, soil, plants, animals, including people, et al. – for sustainable success. Plants grow and die; water runs downhill; people respond to perceptual cues, both subtle and obvious. Good landscape architects, and their plans and designs at all scales, whether for gardens or for cities, must take all this into account.

Landscape architecture and planning have, likewise, long depended upon a rich repertoire of representation tools, methods, and conventions. Most of these representations have been, and still are, formal and visual. Drawings, sections, eye-level and aerial views – today often presented as artful composites, or 'photomontage' – dominate the practice and education of landscape architects, and the sophistication of representational skill is constantly growing. "That's a beautiful presentation" is regularly heard at design reviews, especially of student work, as high praise – and "presentation" is a term that covers a broad and expending range

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of media, including “drawings”, both hand-made and machine-aided, digital animations, spreadsheets, maps, physical models, and others. Such media, primarily visual, are often inadequate for conveying dynamic behaviors, or functions. In spite of constant advances in the expressive power and ease of use of digital animation technology, as a profession we have little good understanding of how to represent, analyze, evaluate, predict, or even describe dynamic behavior in the landscape – whether of plants, water, people, or cities. Yet, increasingly, that is precisely what is urgently needed. For we know that not only do plants and animals grow and move, and human settlements evolve and change, but also that they interact as systems in complex and important ways, some of which are slowly becoming better understood.

For landscape architecture, and equally for architecture and engineering, understanding 'systems' – not just the definition of the term as “a group of interacting, interrelated, or interdependent elements forming a complex whole”, but what MEADOWS (2008) has called “Thinking in Systems” – is fundamental, and we need new digital tools, not just drawings, photomontages, or pre-canned animations, in order to inform tomorrow’s plans and designs. Embedding information-based, scientifically informed simulations into both the conception, and evaluation – or what SIMON (1996) called both the 'generate’ and the 'test' phases – of design is among the pressing challenges, and opportunities, for the evolution of landscape architecture and geodesign in this century.

Imagine being able to sketch or diagram (that is: represent, quickly and in simple terms, graphic or otherwise), a design, in its geographic context, and have its behavior over time, across many dimensions – ecological, economic, visual, and others – simulated and displayed, as an integral part of the iterative process of design. Imagine having one or more ‘key indicators’ (carbon footprint, square meters of parking, volume of water flow, etc.) against which designs in progress are continually evaluated, with a facility for keeping track of design alternatives and variants, and comparing them against one another, in the course of a multi-iteration design process… That is the promise of the approach that has been called 'geodesign', and it will depend both upon the discipline of systems thinking, and upon harnessing the technologies of simulation in new and exciting ways. And when that technology is in hand, in usable geodesign systems with real-time feedback based upon data-driven simulations, landscape architecture will then have a way to address the findings and concerns of the emergent scientific field called 'biocomplexity', which are essential to the development of sustainable landscapes on our planet – what YU (2006) has called “The Art of Survival”.

2 Geodesign

The term 'geodesign' has been used (STEINITZ 2012) (figure 1) to describe the emerging discipline of using Geographical Information Systems (GIS), Computer Aided Design (CAD), and other digital and communication tools to enhance the ability designers and their collaborators to engage scientific knowledge and embed real-time feedback of impact assessments into their design processes. Simply defined as “changing geography by design”, a somewhat fuller definition is:

“Geodesign is environmental design usually involving large areas, complex issues, and multi-person teams, that leverages the powers of digital computing, algorithmic processes, and communications technologies to foster collaborative, information-based design projects, and that depends upon timely feedback about impacts and implications of proposed designs, based on dynamic modeling and simulation, and informed by systems thinking. Systems thinking means that multiple interconnected systems are considered, and that the models and simulations evaluate impacts over a larger area, greater complexity, and longer time-frame than any immediate design proposal."

This definition requires that digital data, information processing, computing and algorithmic processes are involved (i.e. not just intuition and training); that the efforts are collaborative (not purely individual); that simulations and evaluations are timely, (and not only visual); and that the geographic and temporal scope of impacts considered is broad (broader than the 'immediate design proposal'). And 'environmental' design (not 'landscape design') means not just that it happens in the natural and built world, but that the ethics and attitudes of environmentalism are engaged in the process. Finally, requiring 'systems thinking' recognizes the dynamic and interconnected nature of the world we live in, and the necessity for identifying and understanding connections and systems (e.g. ecosystems, transportation systems, energy systems, and others.) Thus, geodesign projects will be aimed at improved environmental health and resilience, not just economic growth or transport efficiency; at sustainability, minimum impact, and concern for ecological structure and function, as well as for human communities and concerns.

So, the design of a dam, or a wildlife refuge, 'eco-city', or transportation-oriented development, in the 21st century, would all be 'geodesign', as they would surely leverage GIS, CAD, remote-sensing, and other digital data and computational tools, and teams of specialists; the design of a sculpture garden, or even a 100-hectare master plan, by a virtuoso solo landscape architect with a 2B pencil, would not qualify.

All landscape architecture and planning is not geodesign, by these criteria: some isn't digital, some isn't collaborative, some isn't of sufficient scale or sufficiently informed by impact simulations or systems thinking – but some is, and a growing percentage. This is good news for the planet, and the future of the profession.

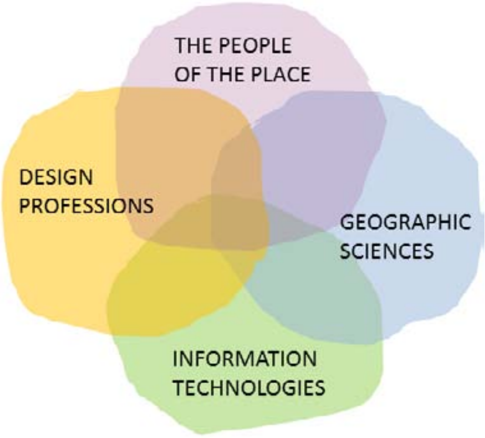

Fig. 1:
Cover from A Framework for Geodesign: Changing Geography by Design (STEINITZ 2012), showing the four necessary components of geodesign. Used with permission.

3 BioComplexity

The above discussion suggests that geodesign approaches are required for the 'large, complex' problems of our century. Size is one thing, and large projects are common throughout the world. Computers with access to mass storage, satellites with sensors that encompass large swaths of the earth’s surface, and fast algorithms for searching, finding, and managing large quantities of data, are all obviously helpful. But complexity is another thing altogether – orthogonal to size, for as we know, very small things can be complex, and very large things sometimes rather simple. Complexity of design problems and projects is hard to define or quantify. However, in several important realms, considerable scientific effort is being devoted to just this question (NSF 2013; Michener 2001). In the recently identified field of 'biocomplexity', scientists are focusing on the interconnected behavioral, biological, social, chemical, and physical interactions of living organisms – from cells to organisms and communities – with their environment (figure 2). Studies of landscape ecology and biodiversity are subsumed under the study of 'biocomplexity'.

In 2007, at the founding of MIT’s Center For Complex Engineering Systems (CCES), then President Vest said: ”Innovation and success [in macroscopic engineering – the domain of larger and larger and more and more complex systems for energy, the environment, communications, health care, manufacturing, and logistics –] will be essential for meeting the daunting challenges of a world with a burgeoning population, limited resources, and justified demands for a better quality of life and more economic opportunity.” The study of complex engineering systems, and of biocomplexity from the molecular to the planetary scale, is desperately needed to better inform landscape architects using geodesign approaches.

Living organisms are not the only objects of concern to geodesign projects – rocks, water, and atmosphere are also important – but plants of all sizes and genera, and animals, including people, are perhaps the most complex, because their living dynamics. So the practice of geodesign will depend heavily on the work of the biocomplexity and engineering research community in the future. Biocomplexity also reminds us of the essential role of systems thinking, in the recognition of the interdependent “web of life” (Capra 1997.)

Fig. 2:
Depiction of multileveled complexity of organisms in their environments from the U.S. National Science Foundation.
http://commons.wikimedia.org/wiki/File:Biocomplexity_spiral.jpg

For some specific examples of bio-complexity thinking and impacts on geodesign, consider two fundamental landscape contexts: the forest, and the city:

Forests consist of multiple organisms (trees, e.g.), each of which depends on very localized microbial action and nutrient, sunlight, and available water conditions. Changes in these local conditions, at sufficient scale, are enough to have impacts on individual organism health, and then on up the biocomplexity chain, to stands, groves, and whole regional forests – thereby affecting regional microclimates, soil conditions, and nutrient cycling. Conversely, changes in macro weather conditions, or climate, or forest harvesting regimes trickle back down, to local conditions, individual plants, and individual microbes. To change forest conditions, for whatever reason, we may choose to intervene at the macro scale – cloud seeding, say, or modified harvest practices; or we could perhaps engage in genetic engineering, introducing a new strain, or a virus, to affect individuals first. Of course the spectre of genetic-engineering gone bad is a vivid one – not because the principle is wrong, but because we don't yet know enough about how it all works! (People were killed in the early years of bridge engineering, until the science of cast-iron structures was further along.) A better understanding of the chain (or spiral) of biocomplexity will enable greater choice, and more variety of actions, in geodesign projects involving vegetation.

Cities, similarly, are systems made up of individual parts, including vehicles, buildings, and people. Each of these, likewise, has smaller component systems – engines, trusses, organs and cells. It's well known that cities and their environments can be stressors on humans, through all kinds of pollution, and other stimuli. As we continue to build cities in extreme environments, we know we have building-scale elements with which to work: plazas, covered walkways, bridges. And we also know that larger-scale systems, of transportation, of energy distribution, and education or health-care, also have specific impacts, not just on people, but on physical conditions (and thence, to urban forests, and other organisms, plant and animal...). But we can also imagine working at the microscopic level – designing nano-scale interventions (tools? organisms? processes?) that may also help humans and others not just survive, but thrive, in changing urban environments.

Just as by the study of 'biomimicry' (BENYUS 2002) scientists have learned about techniques in the natural world for building, lubricating, cooling, and other organisms' strategies for survival, so will a better and continually evolving understanding of bio-complexity inform our strategies for building sustainable and sustaining human settlements in tune with natural systems and processes.

4 Cross-scale Dynamic Simulation

Designers use a range of representations – often drawings and photographs – to inform simulations, formal and informal, so that evaluations of design impacts can be made prior to actual construction. Drawings enable a wide range of evaluations based on 'instantaneous simulations' in the viewer's brain – from "Is it ugly? Or beautiful?" to "Can a visitor see point X from point Y?" (SHEPPARD 1989). Drawings and photographs can also serve to engage more deductive analyses, to answer questions about structural ("Will it stand up?") or geometric ("How many people will it hold?") or other ("How easily navigable will it be?") properties, by using graphical methods and tools (compass, straight-edge, ruler, e.g.). These approaches have served environmental and spatial design quite well, for centuries. Only more recently have complex, statically indeterminate structures required finite element analysis and other more advanced simulations in their design. MALKAWI &

AUGENBROE (2004) describe advances in applications of physical simulations to buildings, and suggest the next challenge is to integrate simulation with design processes. Buildings themselves are becoming more dynamic, as they open and close – and perhaps even re-position themselves – to admit air, light, inhabitants, pleasing views (or exclude strong light, foul smells, unwelcome visitors...). More recently, also, landscape architects have concerned themselves with systems of natural fluid flow and the resultant forces and forms in waterways, and landscape ecologists with the spatial implications of biological processes of plant and animal communities, across scales (JOHNSON 2012).

Cities have always been even more dynamic than their constituent buildings (SPIRN 1985), and simulations of growth patterns, traffic flows, energy, waste and water distribution more essential (ROBINSON 2011). Gardens, watersheds, hydrologic systems are even all the more dynamic, calling for even more complex and astute simulations, and far exceeding the analytic power of drawings alone. Traffic simulations, structural simulations, energy demand simulations, structural analyses, fluid-flow and wind-tunnel simulations are all familiar in environmental design (figure 3.). PAEGELOW & CAMACHO OLMEDO (2008) have shown the value of scientifically informed dynamic simulations to begin to capture the complex interrelated behaviors of ecosystems. For example, the Spatial Modeling Environment ('SME') (COSTANZA & VIONOV 2004) has effectively been used to create, run, analyze, and present spatial models of ecosystems, watersheds, populations, and landscapes, at different scales of spatial and temporal resolution.

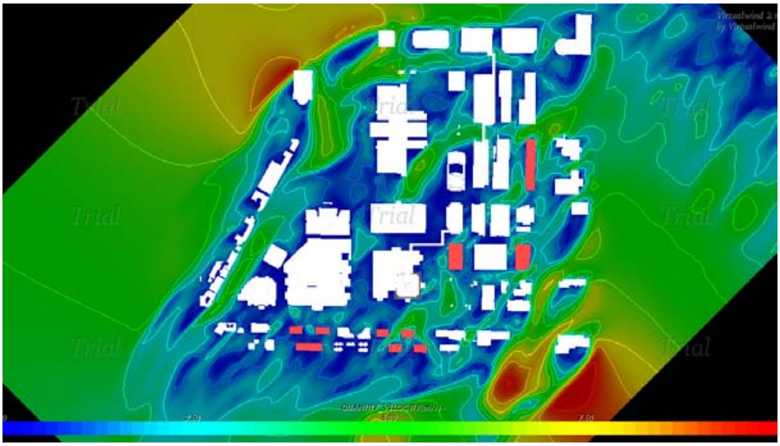

Fig. 3: Illustration of simulation of airflow over a landscape with buildings, using CFD software. Professor Wu, HIT, used with permission.

Effective geodesign simulations will need to cover a wide range of topics and technologies, from hydrological and traffic flow, to energy life-cycle costing and macroeconomics, to human perception and social network analysis, in order to overcome overly simplistic, static, and single-scale evaluations that have characterized much of the last several decades' efforts at GIS-based impact assessment. Too often, to date, these simulations, no matter how powerful or useful, are de-coupled from each other, require input in different and incompatible forms, and produce output in different and incompatible formats. A major challenge to the scientific, engineering, and computation communities is to help reduce this friction, so that more and better simulation models can be linked together and run from the same input, generating compatible output, especially in real-time. These are not trivial problems, and simulations will doubtless be forever candidates for improvement and recalibration – but the returns will be better, more informed, more reliable impact assessments, which, coupled with a design process that takes impact assessments seriously as a part of the design process, rather than only conceiving of them as a final by-product, will result in better design – and geodesign.

Visual simulations will continue to play a central role in geodesign, to be sure, but they alone are insufficient to the challenges. Simulations need to be dynamic too, to overcome the limitations of static drawings. Informed by the sciences of physics, ecology, biology, et al. and the insights of sociology and psychology (not to mention the even less predictable politics and economics!), these simulations need to be available to designers and planners as part of every geodesign project. The results of simulations, run based on proposed design conditions, need to be summarized and fed-back to designers in a timely fashion (real-time is ideal) so that the efficacy and impact of design proposals can be better understood. In iterative design processes, it is valuable to try a range of possibilities, and to compare, rank, and choose among them based on predicted impacts. Of course impact assessments can be inaccurate, and often competing goals are mutually incommensurable; but one touchstone of design is the ability to find propitious arrangements that do satisfy multiple goals; and some evidence, based on some data and knowledge, is usually better than none. This at least is a basic assumption in geodesign.

Simulations and models also must be understood across scales. Landscape ecological research has demonstrated the need for multi-scale analyses (TURNER 1989) that take into consideration the scale and resolution of their inputs, and of the processes being evaluated. As biocomplexity recognizes the interaction of organisms and environments from microscopic to planetary and beyond, the need for scientific knowledge of these interacttions, and their embodiment into dynamic digital models and simulations, is ever more pressing for geodesign approaches.

An essential aspect of working with simulations is verification – understanding and quantifying the accuracies and limits of models and simulations, by 'field-truthing' and calibration. In order to verify digital simulations of real world processes, we need sensors of the real world. Sensors are a necessary and growing component of geodesign, much more central than surveying has been to traditional landscape design. Sensors may be 'remote', as with aerial photographs and satellite images, or, increasingly, 'intimate', at closer scales, as with soil temperature or humidity probes, traffic cameras, and others.

(FRAGUADA et al. 2013) have reported on techniques and technologies for collecting and managing "large scale landscape site data" using a variety of sensors. Remote-sensing has been tightly coupled with the development of GIS in the last decades, and intimate sensing, and augmented reality techniques, as with 'Google Glass' and other developments, will surely influence the next decades of landscape and, increasingly, urban design.

Ready access to data from an array of sensors is part of the infrastructure necessary for geodesign. One example in the U.S. is the 'National Ecological Observation Network, (NEON) (figure 4) sponsored by the National Science Foundation. From their on-line literature: "The NEON Education mission is to enable society and the scientific community to use ecological information and forecasts to understand and effectively address critical ecological questions and issues…. NEON manipulative experiments are designed so that ecological forecast models can be developed that accurately anticipate future conditions."

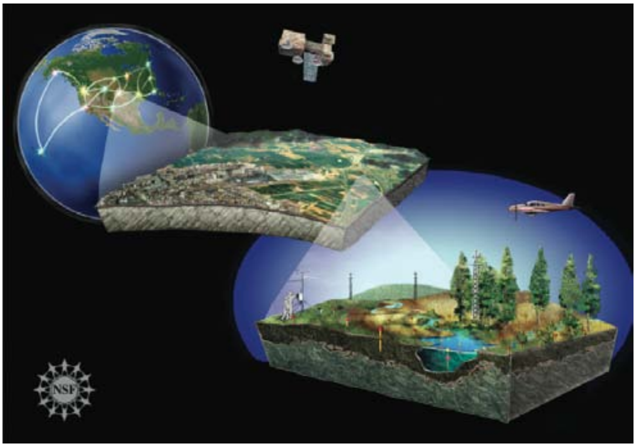

Fig. 4: Illustration of nested scales of ecological observation, from the National Ecological Observatory Network; http://www.neoninc.org/sites/default/files/NeonScienceStrategySept09.pdf

Integrating sensors and real-time data with simulations, in the service of better-informed design and evaluation, is an exciting, albeit complex, development in simulation and modeling. DAREMA (2004) describes a framework and method for "Dynamic Data Driven Modeling", a technique intended to "improve modeling methods" and "improve the efficiency of simulations" by incorporating real time measurements in running simulations. As geodesign projects may be anticipated to extend over longer periods of time than simpler projects, the idea of simulation only as an after-the-design evaluation needs to be replaced with the idea of ongoing-geodesign-projects-with-integrated-ongoing-simulation(s)!

5 Conclusion

ERVIN (2012) describes a specification for a 'System for Geodesign' in which are identified 15 essential categories of tools, helpers, and techniques (figure 5). The ideas above are represented in this short list in a number of the named categories in that system specification. The category called 'Simulation', closely related to 'Models and Scripts', is toward the end of the list. The idea that the outputs of designs ('change models' in Steinitz's terms) can be the inputs to simulations (Steinitz's 'process' models), and the outputs from simulations the inputs to 'Dashboards', (or 'status monitors'), and thence either serve as inputs to cyclical design iteration, or to a decision process, is key to the promise of geodesign – what FLAXMAN (2009) called "tightly coupl[ing] the creation of a design proposal with impact simulations". Some models, and scripts, may not be simulations of existing or proposed systems, but used to generate forms de-novo, in the ‘algorithmic design’ approach. ‘Objects’, ‘Configurations’, and ‘Constraints’ represent the building blocks of design, upon which the models and simulations depend, including objects, configurations, and constraints specified across a range of interconnected scales, from the micro to the macro. Thus, the object called ‘bosque’ will involve smaller objects called ‘trees’, and together they operate with different impacts in different domains (nutrient cycling and psychological, e.g.) across scales. Geodesign projects must involve every scale, across a continuum of biocomplexity, and our analyses and evaluations need to be calibrated for this range. The category ‘Abstraction’ captures the idea of trans-scale representations and models, and their range of content and application, from highly abstract diagrams, or conceptual models, to working drawings, schematics, or genetic codes, etc., for proposed designs and changes to the environment.

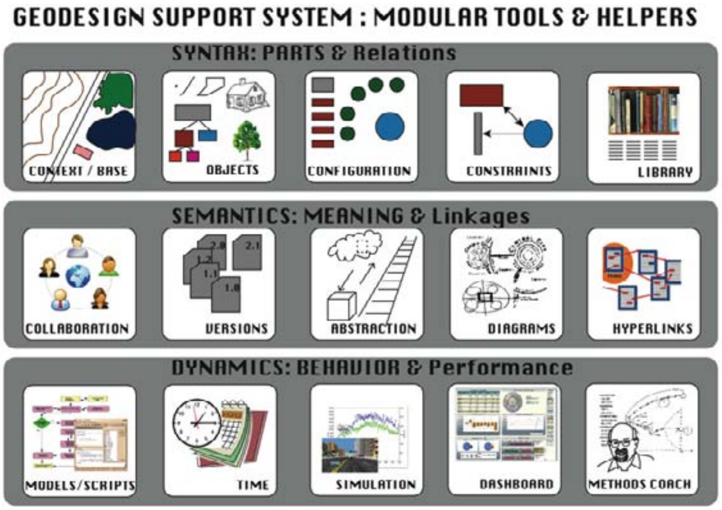

Fig. 5: The 15 components of a ‘System for Geodesign” (from Ervin 2012)

I am aware of the concern that over-dependence on simulation may separate the designer too much from the real-world, human-perceptual qualities of design (Gleiniger & Vrachliotis 2008). Some may also say that emphasis on simulation and measurable quantities, instead of immeasurable qualities, is too much in the ‘science’ camp; that landscape design is more essentially an ‘art’. This is one reason to have the new word ‘geodesign’ – an unabashedly data-driven design discipline, dependent upon science for its art. It needs to respond to the timeless qualities of human perceptual experience, to engage both expression and impression, like any art, and learn from the study of visual form and human psychological/behavioral function. But equally pressing is the study of organismic, community, and ecosystem behavior, on up through regional systems, to planetary function, into which we have only the barest beginnings of understanding, and upon the better understanding of which, so much rests.

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