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Geo-spatial Mapping as a Catalyst for Creative and Engaged Design in Engineering Education

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GEO-SPATIAL MAPPING AS A CATALYST FOR CREATIVE AND ENGAGED DESIGN IN ENGINEERING EDUCATION

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GEO-SPATIAL MAPPING AS A CATALYST FOR CREATIVE AND ENGAGED

DESIGN IN ENGINEERING EDUCATION

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Exploiting the technology of geo-spatial mapping student designers can develop deep understandings of the rich and layered data of a spatial context, a situational understanding essential to responsible civic design. However the actions inherent in the construction of spatial data armatures can simultaneously be harnessed as creative strategies, in which mapping processes become the context for generative spatial play. The ambition of this study is to propose efficient pedagogic structures to help prepare civil and environmental student engineers to be not only strong participants, but leaders, in the design of the built environment. The interpretation of site data, mapped as a series of connected functions, is here described as a design potential, hidden in the discourse of landscape and articulated through mapping. This paper will explore tactics by which the agency of geo-spatial mapping can assist student-designers to uncover new research directions, develop embedded understandings of site and community, and search out imaginative interdisciplinary overlaps and new patterns of place-making.

Keywords

Design, geo-spatial data, civil & environmental engineering, infrastructure design, geographic information systems (GIS), creativity, engineering education, qualitative research, mapping, divergent thinking, design thinking, innovation, project-based learning (PBL), engagement, problem-design.

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Dedicated to my father

Ian Harley Marshall (1933-2016)

A soundboard for my early idea explorations and a master editor of those drafts,

he is greatly missed for his strong support, his sharp criticism and his keen eye for design.

Chapter 1

Introduction

Data

Imagine a map-layer dataset in which the intensity of sound is made visible in color such that the powerful roar of highway noise is a dark red zone seen in contrast to the pale green near an empty closed warehouse. Imagine another dataset in which all the sidewalks in a neighborhood are drawn but only those lines on the page; there are gaps, spaces where there is no line, no movement connection. The lost feeling of walking without safety across an open, unprotected territory is made visible in the empty space of the page.

Imagine these layers overlapped, brought into three dimensional integration so that the perceptual landscape of the neighborhood, its sounds, experiences and histories, becomes a new context for re-envisioning urban construction. The new mapped vision with its differences and overlaps creates a represented landscape which may not have been apparent at first visit. It is a site for innovative re-reading. The data itself is merely the medium for this new vision, like the material for a sculpture it becomes the content through which the site is able to be re-imagined. The power of that new imaginative vision is that it can engender new inquiries, new approaches and alternative site design solutions.

Design

Conventional solutions often follow from repeated visits to similar problem sets; such repetition is confident, comfortable and familiar. Creative solutions unfold instead from re-thinking, from stepping bravely outside a known solution set to imagine alternative visions. Design-thinking approaches innovation through the practice of tactics which enable the re-framing of problems and the new inquiry of old questions. In a spatial context such problem re-framing is most powerful if it takes place visually, constructed through specific engagement and manipulation of formal data. Rather than isolation from the site, pertinent questions develop from engagement strategies; the data becomes the medium for the new vision rather than the result of it.

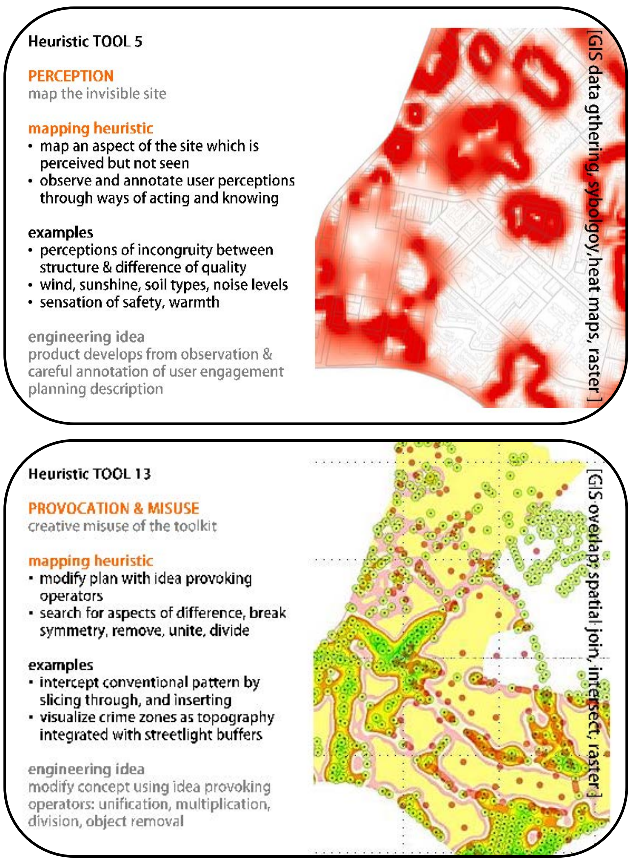
Landscape

The urban landscape is a deep archive of interconnected data; physical, experiential, social, political and historical, each element accessed and documented through opinionated observation. (Jackson, 1984; Stilgoe, 1999). The primary threads ordering this spatial structure are its infrastructure networks. The first marks made onto the field of a site, the first urban land decision, is made by a civil or environmental engineer. Engineering site-design brings together systems of infrastructure, movement, and the environmental resources and patterns of the land. The design of infrastructure is the marking of place; those constructed bones of infrastructure set up the ways we dwell in our landscape. The nature of a site can be revealed through a deep study of the landscape; in Texas this is seen in the vast horizontality of its land, the iterative waves of its agricultural infrastructures. Mapping such elements makes apparent the patterns of the given ground in which social and ecological factors are dynamically and efficiently integrated into a functional spatial vision (Ahern, 2007).

In North Texas as throughout our fast-developing world, population growth and income inequality imposed upon the fragility of climate change, impose enormous responsibility upon the designers of our built environment. Teams of engineers and planners, politicians, developers and designers are writing the marks onto the existing data-rich landscape that will describe its future sustainable livability, its shared efficiency and its beauty. Such work takes not only knowledge and skill but the ability to envision creative solutions. Preparing engineering students to approach site-design work with skills, courage, and confidence in creative design practices requires a new approach to site-design teaching in the academic context.

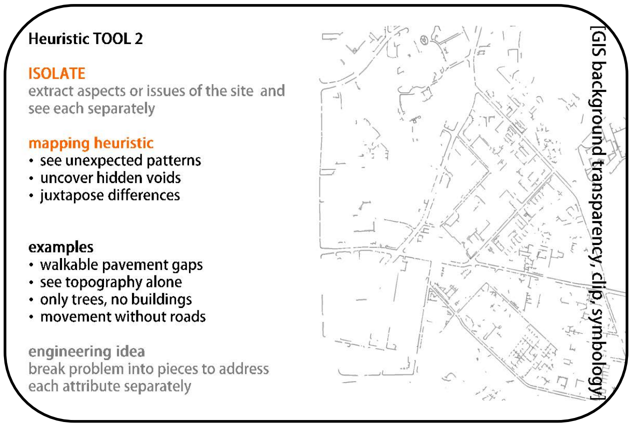
Geo-design Cards

The research goal of this study is to identify opportunities within the processes of geo-spatial mapping in which a tactical engagement with site-specific spatial data can open opportunities for creative design-thinking for infrastructure engineering students, and assist them to build confidence in strategic approaches to design. By developing and testing specific teaching methodologies and heuristic tools using Geographic Information Systems (GIS), the research seeks to measure the extent to which a geo-spatial structure can serve as a fruitful design context, impacting student innovation and creativity-learning in the classroom.



1.1 Samples Geo-Design Cards # 5 and 13

A support structure for creative site-design work, a deck of Geo-Design Cards has been designed, created and tested. The double-sided cards are intended to function, for student designers, as tools for inspiration or design-heuristics, a helpful support or rule-of-thumb to fall back on in a moment dry of ideas. Like a musician who is able to draw from a series of chord-changes, or groups of note-motifs, the tactical instructions on these cards provide a direction for play, a way of opening up options or generating possibilities; questions rather than solutions. An open spatial exploration tactic rather than a sequential design-thinking process, a card-tool selected from the deck might encourage a strategic approach to re-thinking that site or its histories or offer a jumping-off point for open-ended exploration and play with form, data or time-sequence. Illustrated with previous students' site-design map explorations and coded or linked to specific GIS mapping tools, each card describes a way of interacting with one or several spatial datasets in what might be an unexpected way. A handful of examples of where such of exploration might lead are given, as well as an abstract verbal description isolated from site, which opens up the potential for the transfer of this methodology beyond the spatial design context.



1-2 Sample Geo-Design Card #2

Heuristic Tool 2, for example, suggests trying to isolate, or 'break a problem into pieces to address each attribute separately'. It is illustrated with fragmented sidewalk paths, and coded with GIS tools 'transparency, clip, symbology'. It invites designers to extract site issues by isolating them to reveal patterns, and uncover voids to juxtapose difference. In visual terms, the creative opportunity is made by extracting particular vector layers and making those lines or dots into a visible structure without a context, a technique which can reveal surprising gaps and forms that might not have been seen within the complexity of the multi-layered data set.

Developed over several years of design teaching, the deck of geo-design cards is neither complete nor conclusive but is a step towards developing a vocabulary of applied spatial design-thinking tactics for student engineers and designers, tied to specific GIS tools. The research will attempt to critically assess the extent to which geospatial-data practices, supported by the deck of Geo-Design Cards and integrated into a project-based course context, can support site-design teaching and impact students' creativity-learning in the classroom.

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Chapter 2

Creativity and Engineering Education

Students of engineering are not, traditionally, taught to create (Baillie, 2002). Engineering schools understand the importance of creative work but don't have strategic approaches to facilitate or teach it. While some, like Olin College or Stanford's d-school, have developed independent structures to teach design processes, most remain more focused on 'engineering thinking' than design thinking, making it hard to increase the innovative or 'amorphous' thinking students are able to apply to scientific research (Lande & Leifer, 2009). The US Accreditation Board for Engineering and Technology (ABET) specifies creative learning and innovation as integral parts of an engineer's education, with an innovation award honoring the breaking of new ground in the program development, and for teaching methodologies designed to improve the creative dimension of education (ABET, 2015). Nevertheless creative skills remain undervalued in engineering education. A study measuring the self-efficacy of the primary skills of engineering students, for example, tested their confidence in math and science, business, teamwork and communication skills, but did not investigate design (Sheppard, Winters, Matusovich, Brunhaver, & Chen, 2013). Final year engineering students found that they had been given few opportunities for innovative thinking or discussion on creative learning, within the classroom (K. A. Davis & Amelink, 2016; N. Davis, Winnemöller, Dontcheva, & Do, 2013). While researchers increasingly refute those skeptics who argue that design skills emerge naturally, there remains pushback to the dedication of time to teaching creative skills and their connection to engineering (Törnkvist, 1998). Systemic educational change is difficult to make; within the academic resistance to curriculum change (Baillie & Walker, 1998).

Engineering programs since the 1950s have followed a traditional pattern in which two years of foundation in 'engineering science' precede two of analysis in which scientific principles are applied to technological problems, a pattern across all engineering areas including civil and environmental, at least partly due to the

ABET structure. Such a pattern not only leaves little opportunity for design thinking; it actively teaches students to isolate math from analysis, and analysis from creativity, separating each strand and upholding the traditional bias of engineering as problem solving (Dym, 1999; O. Eris, Dym, Agogino, Frey, & Leifer, 2005). While the design process is described by professionals as a rich layering of collaboration and divergence, much engineering education still teaches it as a single block flow model (Mosborg et al., 2005).

Different kinds of learning build on different kinds of input; sensory, auditory, deductive, sequential or active. Passive, lecture-based learning method which, in spite of the consensus on creative instruction, remain the most common in schools of engineering, support neither the active experimenter nor the reflective observer learner type (Felder, 1988; Felder & Silverman, 1988). Investigations even argue that through the imposed constraints of the curriculum, not only is creativity not taught, but innovation capabilities of engineering students are typically reduced between the first and final year (Genco, Hölttä-Otto, & Seepersad, 2012). Even when exposed to creative learning many engineering students are not comfortable with the non-deterministic trajectory of an open-ended design process. More familiar with problem solving focused towards an end, engineering students receive training and practice within a pattern of learning in which a preliminary set of directions is inevitably narrowed as emergent work is checked against a target. Little wonder that many engineering students find it difficult to negotiate the inherent uncertainty of creative processes (Fantauzzacoffin, Rogers, & Bolter, 2011).

Conversations about the need for a new type of engineering education better suited to training a modern, creative engineer have moved from education conferences into popular books and conversations. There is solid agreement in the academy on the need for more open-minded ways of teaching emphasizing creative approaches (ABET, 2015; Goldberg & Somerville, 2015). Described as a key component for future engineering education and practice, the ability to innovate is seen as essential, in combination with other untraditional skills such as communications and sustainability. The issue is not relevance but method; how can one improve teaching and learning practices of such open-ended processes in engineering education (Jamieson & Lohmann, 2012; Killgore PE, 2014; Kober & others, 2015), and how can one assess and measure such change?

Creativity

Once re-defined as a normative capacity of cognition, rather than a specialized characteristic of the gifted, psychological questions about creativity moved their focus away from the exceptional nature of genius to focus on the processes of this specific cognitive function (Teresa M. Amabile, 1982; Finke, Ward, & Smith, 1996; Sawyer, 2012). Described as 'applied imagination', cognitive psychology hoped that an outcome, such as brainstorming, which could be identified in certain problem solving processes, could then be stimulated in individuals and taught as a practice (A. F. Osborn, 1963). Rather than merely describing creative personalities, a culture that was able to enhance such skills could powerfully increase the creatively active proportion of working individuals. (Gowan, 1977). Divergent production, the generation of multiple alternatives, is a primary structure and first stage in the conception of creative thinking (Guilford, 1950, 1973, 1984). Regardless of quality, a wider range of ideas yields more chance of one unusual one. However it is necessarily followed by a convergent stage of intelligent criticism, or testing, within the limits of a domain of study, often with a stage for incubation in between (Teresa M. Amabile, 1982; Gowan, 1977; Guilford, 1950; Sawyer, 2012).

Processes from the divergent phase provide useful categories for thinking about skill development: these include memory retrieval, association, mental transformation, analogical transfer and categorical reduction; followed by the exploratory processes of attribute finding, conceptual interpretation, functional inference, contextual shifting, hypothesis testing, and limitation discovery. Motivation, environment and level of risk all have an impact on this stage of creative action (Sternberg, 2006). Mental representations such as visual patterns, forms of objects, and category examples all support these processes, and interestingly can do so through both ambiguity and implicit meaningfulness, properties which seem to be in conflict (Shah, 1998; Sternberg, 2006). There is extensive interchange between generative and exploratory processes such that interaction between the open-ended and the constraint limited is cyclical and iterative (Finke et al., 1996; Cross, 2004; S. Daly, Yilmaz, Seifert, & Gonzalez, 2010).

Believing creativity to be the result of specific problem-solving aspects of the intellect, Osborne identified factors such as age, gender and effort which affect creative activity, but also variables such as habit, outside encouragement and, interestingly, education, which could impact or cramp it. Based on his assertion that ideation and creativity can be stimulated and taught, Osborne's creative training model, brainstorming, remains the most well-known and well-used creativity strategy to attack or 'storm' a creative problem. (Gowan, Demos, & Torrance, 1967; A. Osborn, 1948; A. F. Osborn, 1963). An early and passionate advocate for the idea that all children could be taught to think creatively, Torrance assessed 142 experiments which explored methods to teach creative thinking to children. He argued for deliberate teaching, with methods including both cognitive structure and creative practice (Torrance, 1972). From 1960 to 1964 Torrance undertook a systematic assessment of children, developing the Torrance Tests of Creative Thinking (TTCT), which scored students on divergent thinking and abilities to solve problems in unexpected ways. His categories remain influential in contemporary creativity measures, including *Fluency*, (quantity of ideas), *Flexibility* (solution or idea range), *Originalit*y (statistical rarity) and *Elaboration* (detail).

Critical of limiting attention to individual cognition, Teresa Amabile refined the definition of creativity to focus on the assessment of the creative product, rather than the creator, proposing that the value of the product could only be determined in the context of the creative practice by domain specialists. Her consensual definition of creativity serves as a baseline for most contemporary work in education. (Teresa M. Amabile, 1982, 1983; T. M. Amabile, Conti, Coon, Lazenby, & Herron, 1996; Sawyer, 2012). Thus, creativity is regarded as the quality of products judged to be creative by appropriate observers, and the process by which something so judged is produced (Teresa M. Amabile, 1982).

Measurement systems for assessing creative problem solving (CPS) in the classroom, using both qualitative and quantitative data, emerged from Treffinger's work in the 1990s. Studying a range of interactions between individuals, the social context and the outcomes, his work did remain focused on assessment of the gifted individual, rather than creative processes (Gowan, 1977; Gowan et al., 1967; Lucas, Claxton, & Spencer, 2012; Treffinger, 2009; Treffinger, Young, Selby, & Shepardson, 2002). However most early exploration into cognitive measurement of creativity build on his studies. Particularly interesting are the importance he gives to meta-cognitive qualities, such as having the courage to listen to one's own inner voice (Charyton, Jagacinski, Merrill, Clifton, & DeDios, 2011). In creativity, research support methods multiplied, each tool seeking to widen a students' potential solution set. While specific techniques are debated, the notion that strategic methods can assist in creative exploration has become familiar and accepted, and multiple creativity support tools, such as CompendiumLD (a mind-mapping software) (Charyton et al., 2011) continue to be developed to support educational instruction, in addition to familiar teaching approaches such as project-based, or interdisciplinary learning. Interested in the notion that both method and teaching strategy impact learning, Mumford assessed almost two hundred creativity programs and identified key instructional methods and components which had strong positive outcomes on students' divergent thinking. He found that greatest effectiveness came from those focused on the development of skill-based heuristics, especially when tied to practice in the domain. (Mumford, Scott, & Leritz, 2004).

Teaching Creativity

Under increasing pressure to train students to confidently approach creative work, few engineering instructors know how to teach creativity. Traditionally, ideation in engineering took the form of an academic literature search or context analysis using analogies of existing systems, with primary effort focused on technical problem-solving, measurement and analysis (Pahl & Beitz, 1996). Recommendations from early researchers in this area were somewhat vague, focusing on the need for repetition and practice, and an encouragement for the posing of unanswerable questions (Felder, 1988; A. F. Osborn, 1963). Engineering instructors and students, however, tend to like clear and specific strategies even for something as complex as idea-generation, with precise directions for specific problem-solving environments (Ahmed, Wallace, & Blessing, 2003; Kramer, Daly, Yilmaz, & Seifert, 2014). This can be illustrated by the international following for Al'tshuller's methodology, TRIZ, which was built on his strategic approach and heuristic strategies, each a way to 'look at the problem from a different angle, for greater inventiveness' (Al′tshuller, 1996). Yet his method begins at convergence where the problem is already narrowing. Further, one good idea may not be enough; engineering students tend to struggle with design fixation, a tendency to stick with an early concept, and be unwilling to stretch beyond to divergent exploration (Jansson & Smith, 1991; Kramer et al., 2014).

Creativity requires divergent thinking, and divergent thinking requires improvisation, supported by techniques and practice. Training can help students open up their creative potential, stimulating their confidence in divergent thinking (de Vries, 2014). The complex environment of design inquiry, learning and iterative collaboration is a multilayered experience. Far from being an extra add-on to the curriculum, "Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints." (O. Eris et al., 2005).

Problem based learning

It is argued that creativity teaching provides not so much strategies as stimulators for creativity, ways to help students un-block their approach and a context where free-wheeling work can take place. Building on visualization skills or the ability to associate ideas, external conditions can support creativity; a strong team, communication, and both intrinsic and extrinsic motivation (Baillie, 2002). Merely exposure practice for first-year engineers on active team-based projects, for example, reveals some change in cognitive creativity and behavior traits. (Aboukinane, Moriasi, Kenimer, Dooley, & Linder, 2013).

Learning can be designed to encourage risk; tactics such as requiring interaction between students, generation of several solutions or specific creative training tasks (Baillie & Walker, 1998). Even the metacognition of self-analysis that comes through participation in an education study or creativity counselling session can be shown to achieve measurable improved outcomes in creative production (Fosmire, Wertz, Ross, Purzer, & Cardella, 2011; Fosmire, Johnson, & Mentzer, 2016; Cropley & Cropley, 2000). The purposeful development of a design language in engineering reflection can shape students processes (Atman, Kilgore, & McKenna, 2008). Teaching can be facilitated by posing creative work as a phenomenon rather than knowledge. In an environment which allows creative flow, freedom for learning is prioritized as much as processes of invention are supported (Baillie & Walker, 1998).

Problem-based learning (PBL) empowers students to bring together theoretical knowledge with practical understanding in the service of better-informed decisions. Through such practices students develop a range of less tangible skills such as adaptability, persistence, and ethical behavior in addition to research and communication skills, technical competence and practice in the stages of evaluation and execution (Savery, 2006). Positioning project-work within a complex social context, for example, introduces engineering students to ideas of human-centered social justice, aspects with which they might otherwise not grapple until dropped into the turmoil's of practice (Kabo & Baillie, 2009; Titus, Zoltowski, & Oakes, 2011). Among other aspects, an increase in creativity has been measured by researchers after project-based immersions, perhaps due to interdisciplinary context for the project (Gerhart & Carpenter, 2012), and taking problems out of the lab into a project-based context is often proposed as creativity teaching strategy; with the hope that the dynamic environment can support creative thinking. The breaking down of disciplinary boundaries in a project-based, sustainability framed experience supports the development of collaborative, communicative skills (Lehmann, Christensen, Du, & Thrane, 2008; Guerra, 2014). Innovation can then be supported by intense interaction with the complex social and physical environment, and a project-based approach can exploit this potential (Campos, Dirani, Manrique, & Hattum-Janssen, 2012), but hands on work, and increasing complexity is not necessarily equivalent to an ability to develop creative design solutions. Each skill set, be it collaboration, communication, teamwork a wider social context, raises the potential for more innovative approaches, but such potential can be always be ignored rather than exploited. There are questions, moreover, about the variation in rigor and quality of different project-based experiences and how, with such a range of formats, we can measure their support for creative processes (Tan, 2009). Project-based learning can be shown to have value, then, for multiple aspects of student engagement but it may not actually improve creative skills unless explicitly included in the learning process (S. R. Daly, Mosyjowski, & Seifert, 2014).

Since the 1990s many universities have filled the creativity teaching curriculum gap with a final year 'capstone' or a first year 'project' course in which design is experienced as a taste-test experience. While valuable in themselves, however, curricular capstones usually reinforce the segmented notion of specialized training, excluding creative potential by isolating inquiry from exploration, and avoiding the complex integration of the various languages of engineering. The pedagogical values of such courses are many, particularly for motivation, content retention, and skill transfer. However project-based, or capstone-framed work is not design teaching; design practice is much more effective when it takes place with self-awareness and integrated specific creativity tactics. Better design pedagogy is tied to experimentation and project based work, but is not identical to it (O. Eris et al., 2005). Although PBL and capstone courses remain the most common design teaching setting, alternative design pedagogic possibilities remain open.

A final difficulty in integrating design teaching into the engineering curriculum is its incompatibility with traditional engineering teaching practices; dynamic processes and iterative solution generation is difficult to fit into a traditional curricular sequential structure. (O. Eris et al., 2005; Lawanto & Febrian, 2016). Specifically within the curricular context, the skills to systematically undertake open-ended work are difficult to pin down; student designers must develop an unfamiliar ability to take on layers of uncertainty and ambiguity.

Visual Cognition

Design inspiration is accessed through spatial cognition; designers build upon the craft of observation, using spatial visualization to visually describe in a sketch and conceptually extract an essence (Pendleton-Jullian, 1996; Pérez de Arce, 2003; Stilgoe, 1999). Through the abstraction of tangible experience uncovered by sketching and visualization, access can be found to open-ended thinking. Observation and drawing engage a process which uses looking to access thematic exploration, in the same way that improvisation around a theme can give musicians access to new musical structures (Cruz Prieto, 1993).

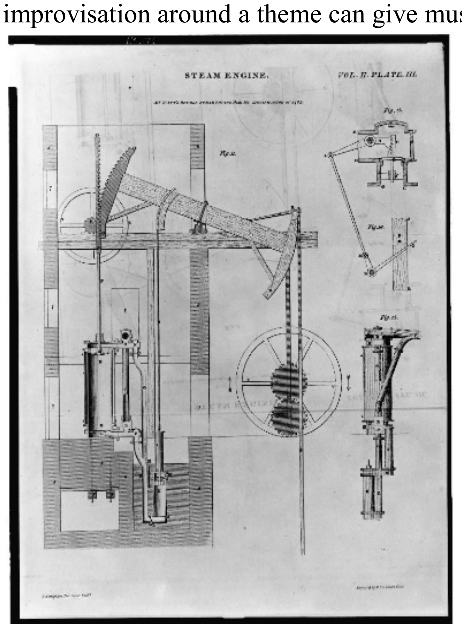


Figure 2- 1 James Watt's double steam engine, 1782.

Images have multiple value for the scientist, in their communicative role, in their support for diagrammatic reasoning, as well as in the creative process (Holliday-Darr, Blasko, & Dwyer, 2009). Essential tools for the designer, drawings not only assist in the achievement of a design form but function for communication and analysis (Ullman, Wood, & Craig, 1990). The productive potential of diagrammatic thinking has a powerful history; from the perspectival innovations of renaissance art and engineering to the highly visualized history of technological development in the industrial age, the diagram has played an essential role in technical thought (Ferguson, 1977). Diagrams, in spite of their ‘weak and fragile’ inscription, nevertheless have the power to dominate, (Latour, 1986) and this dominance functions not only over other observers but within the context of our own creative cognitions.

Sketches are thinking tools; the design process is extended through the use of images as part of the cognitive process of generating design solutions (Shah, 1998; Shah, Vargas-Hernandez, Summers, & Kulkarni, 2001; Ullman et al., 1990). Whether with a pencil or a computer, visualization has greater value to the designer for the active exercise of imagination than for the artifact produced (Buxton, 2007). The cognitive play of sketching restructures, enabling the overlapping different ideas, and new ways of looking (Verstijnen, Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998). During the creative process, sketching can allow the imagination to work somewhere between perceiving and reasoning, giving access to inferences not attainable through text-based exploration (McKim, 1980; Pinker, 1984; Ullman et al., 1990; Shah et al., 2001). When a scientist is at an impasse, switching spheres between cognitive styles from verbal to the visual or spatial, can widen exploration to more potential directions (Kell, Lubinski, Benbow, & Steiger, 2013; Kozhevnikov, Kozhevnikov, Yu, & Blazhenkova, 2013; Simon & Cheng, 1995).

Sketching aids memory, preserves ideas in shorthand, supports self- feedback in the development concepts (Schütze, Sachse, & Römer, 2003) and reduces idea fixation (Ullman et al., 1990). It also has value for spatial manipulation skills in individual engineering domains. (Charyton & Merrill, 2009). Most critical in terms of pre-inventive work, diagrammatic cognition can be both goal oriented and exploratory, providing openings and simultaneously helping to narrow the site of experience (Finke et al., 1996). As type of notation, it is precisely its non-sequential nature and its ability to allocate information by location, that allows a diagram to communicate mathematical structures (Do, Gross, Neiman, & Zimring, 2000; Larkin & Simon, 1987). While in early design stages the sketching positively impacts the design process by helping to make an abstract idea tangible (Newell, Shaw, & Simon, 1962), in later stages it can also affect aspects such as clarity, simplicity and assembly (Schütze et al., 2003). But sketching skills require practice. Iterative repetition can improve sketching skills and reduce inhibition, but these abilities are lost again without use (Booth, Taborda, Ramani, & Reid, 2016).

Creativity thus relies on visual thinking, however sketching or other visualization is rarely taught in engineering curricula as a representational tool, and less still for creative design thinking (Ferguson, 1977; Ullman et al., 1990; Taborda, Chandrasegaran, Kisselburgh, Reid, & Ramani, 2012; Booth et al., 2016; Yang, 2009). From their unfamiliarity with sketching comes engineers corresponding lack of confidence when approaching it. New digital forms of sketching might better support the limited time and lack of user experience in order to help student designers in their development of new quests (Buxton, 2007). The collaborative ideation technique 'C-sketch', for example, is based on freehand sketching as a tool for enhancing creativity in engineering design, and has been shown to have strong empirical results, particularly in allowing openness to a wide variety of ideas (Shah et al., 2001; Ullman et al., 1990). The teaching of visual thinking must include space for exploration and creative play (Song & Agogino, 2004; Taborda et al., 2012).

Design-thinking

Proposed as a new way to innovate and develop alternative creative problem-solutions, 'design thinking' has been leveraged as a process in widely ranging sectors from education and business to healthcare. The methodology is promoted beyond the traditional realm of the design-research community, many of whom remain critical of its tendency to oversimplification, and shy of potential corporatization of the richness of the field of design (Dorst, 2011). Certainly the new focus on strategic design approaches has fed greater academic discourse on design-thinking processes and practices, debates which have grown from the earliest uses of the term (Rowe, 1991), to the international marketing of design-thinking techniques by firms such as Ideo and Frog (T. Brown, 2009; Dorst, 2011; Kelley, 2001).

In engineering, the same word is used to describe both design-problems such as sizing a beam, for which an algorithmic set of possibilities can produce a solution set, and open- innovative design, such as a house for a poet, for which there is no fixed set of variables and the problem is ill defined in terms of solution criteria (Mitchell, 1993). No single representational system or vocabulary is used in design in engineering, making it difficult to teach, assess or even discuss, however this breadth can be a benefit. The overlap between exploratory systems allows engineers to integrate verbal, graphical and mathematical systems in service to the design process, and to communicate with each other, with design as a connector across engineering fields (Dym, 1999). The cognitive activities of design seem to function similarly across disciplines, such that it can unite collaborators from unconnected fields (Adams & Daly, 2008). A key process in design-thinking is the mechanism of asking questions. In a taxonomy of question types, ‘generative design questions’ include proposals, scenario creation, ideation, new methodologies; their intention is not to seek answers but to generate possibilities and ‘trigger’ multiple answers (Ö. Eris & others, 2003). Ideation is most successful when not only many but a variety of divergent concepts are generated.

Idea Generation (IG) Tools in Engineering

A comprehensive critical assessment from 1998 divides engineering idea generation (IG) methods into two broad areas: Logical methods, such as TRIZ (Al′tshuller, 1996) which seek to provide a systematic way to analysis, and re-construct a problem, using specific procedures, and intuitive methods, including morphological analysis (Zwicky, 1969) and brainstorming (A. Osborn, 1948; A. F. Osborn, 1963) in which barriers to divergent thinking are removed to ‘break away’ from a mental path (Schneiderman, 2007; Shah, 1998). ‘Logical’ strategies have lost favor recently due to their more deterministic formal mechanisms, however even the intuitive, such as C-sketch (Shah et al., 2001) or storyboarding bring together aspects to stimulate ideas. Likewise with various group-study creativity techniques similar modes can be identified. Thus, although the use of GIS mapping may be a new approach to teaching creativity, its underlying visual and cognitive processes appear to fall into familiar territory, well documented in the world of engineering education.

Innovation is often the result of deliberate practice applied by domain experts to explore solutions outside the box of expectation. Among practitioners, there appear to be universal strategic ‘promoters’ which designers return to for divergent exploration; cognitively described, these include designer detachment or abstraction, suspended judgement, a change of frame of reference, provocative stimuli and the making of unexpected connections. Various techniques harness such strategies; the most common being brainstorming and collaborative sketching, pre-packaged and made familiar in the more commercial design-thinking context (A. F. Osborn, 1963; Shah, 1998; Shah et al., 2001; Kelley, 2001; Petre, 2004; Sawyer, 2012; Dean, Bielenberg, Tanner, & Leach, 2002) . Strategic collections of similar tools are familiar from creative worlds outside engineering, such as advertising, project management and even dance (Jordan Lane, Roland-Philippe Kretzschmar, Miriam Gullbring, Maktsalongen, & Belatchew Architects, 2012; Thomas Both, Dave Baggereor, & et al., 2013; Wayne McGregor, 2014).

Attempting to explore methods to increase ideation in engineering, and to measure that increase, Shah-Vargas et.al. define a set of 'ideation method components', strategies to open the range of ideation. Their list has parallels to many intentions and indeed, descriptions, which parallel the geo-design cards developed in my SMU classroom, however in Shah's case they were described verbally rather than visually.

Presented verbally rather than visually, similar and familiar ideation strategies have indeed been employed specifically within engineering; these include exposure to examples and altering the frame of reference, intentions involving time and iteration, and flexible representation in order to alter the vision of the content (Vargas-Hernandez, Shah, & Smith, 2010). Pointing out the tendency for professional engineers to more fearlessly explore early phase generative design, Daly, Yilmaz et al. developed a detailed analysis of their working methods leading to a documented set of strategies, or 'rules of thumb', implicit ways in which such engineers explained or their design process development (S. Daly et al., 2010; Yilmaz & Seifert, 2011). Strategic approaches, identified as design prompts, or 'heuristics, were strategies that experienced designers tend to use to help themselves towards wider and more multiple set of design options. Careful observation followed by a coding exercise led to a long list of heuristic typologies, from which were developed a series of design heuristic card, each with visual and verbal example. The cards then served as prompts with which students, with their most limited experience, could assisted in their generative process, by applying these heuristics as strategies towards greater variety in design exploration (S. R. Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; S. Daly et al., 2010). A series of studies evaluate the use of these design heuristic tools, not only for the exploratory early stages of design, but also later in the process as ways to encourage a broadening of their site of exploration, and to cross the notorious hurdle of design fixation (S. R. Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Kramer et al., 2014; Yilmaz, Daly, & Seifert, 2014). Assisted by the tool-production set, mechanical engineering students were shown to be able to achieve an increased range of solution sets and to reach for more unusual design concepts. (Guilford, 1984; S. R. Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2011; Yilmaz et al., 2014).

Digital Creativity Support Tools

The potential for digital tools to serve as structures for spatial exploration has, in the engineering world, focused primarily on CAD software, and outcomes have shown rigid limits or even a negative impact from CAD on fixation and circumscribed design thinking (Lawson & Loke, 1997; Robertson & Radcliffe, 2009; Robertson, Walther, & Radcliffe, 2007). CAD systems automate the hand, but sketching depends on interactions between the creative hand and the creative eye (Mitchell, 1993). Poorly developed as a design tool, CAD is not structured to employ uncertainty, its resolution and inflexibilities in interpreting shapes and its lack of metaphoric evocation struggle to support creative design, limiting ideation. (Mitchell, 1993). (Lawson & Loke, 1997; Robertson & Radcliffe, 2009).

Based on CAD's technological limits many critics condemn all technology as limiting creativity, (Booth et al., 2016; P. Brown, 2009), however, re-framing creative processes in any familiar language, be that mathematical or digital, improves its accessibility (Overveld, Ahn, Reymen, & Ivashkov, 2003), and both digital and analogue visualizations have positive examples of generative design impacts (Bonnardel, Ahmed, & Côté, 2011). In practice innovation and design-thinking processes are not built on any specific tool; in the right hands designers find ways to harness all varieties of visualization towards divergent creative production (Dean et al., 2002).

While rare in engineering, there has been significant research into the creative potential in digital technologies in computation, some of which might serve as a model for creative exploration in engineering. Visual analysis plays an important role in early studies in which digital technology made the move from productivity support towards the 'inspirational' use of technology for creativity. Although the creative act remains in the hands of the user, technology participates in effective searching, rapid discovery, and even collaboration. (Schneiderman, 2007; Shneiderman, Fischer, Czerwinski, & Resnick, 2006).

The study of Human Computer Interaction (HCI) contains a subset of creativity focused research on Creativity Support Tools (CST) in which usable, well balanced digital tools for the support of creative thinking are developed, critiqued and tested (Resnick et al., 2005). The conceptual argument for such tools includes the notion that digital tools can support the creative process by aiding those who might have fear of failure, a lack of specific skill sets, or even a limited amount of time for exploration (N. Davis et al., 2013). Design fixation, for example, is reduced by tools which assist a search through options (McCaffrey & Spector, 2011); another supports practice of failure with metrics to encourage exploring outcomes. (Kim, Bagla, & Bernstein, 2015). TRENDS works as an image support engine assisting designers in their search for inspirational material through divergent analogies (Bonnardel & Bouchard, 2011), while Alchemy software plays a role in generative elaboration (Willis & Hina, 2009). Software based creativity support systems (CSS) enable collaboration in a connected virtual environment, adding the power of social collaboration to brainstorming while reducing its associated inhibition, the fear of group evaluation (Hilliges et al., 2007; Massetti, 1996; Warr & O'Neill, 2007). Finally, for some researchers, human computer interaction (HCI) can allow collaborative approaches to the mechanisms of open play, in which the computer's skill at randomness is balanced by human abilities to select and develop ideas (Dr. Stuart Brown, 2014; Yannakakis, Liapis, & Alexopoulos, 2014).

Few connections have been made between creative engineering design and digital visualization. In the interrelationships between seeing and doing, designers intentions' play a role in the way they recognize and interpret emergent shapes. Information and attributes about objects can be abstractly represented in the shape-grammar of computation. Manipulating such digital representations could have great potential in the search for creative design pathways for engineers (Dym, 1994; Mitchell, 1993).

Measuring Creativity in Engineering

Investigating current practice for the teaching of cognitive creative skills in engineering education, Daly et al. undertook a critical qualitative analysis of a set of engineering courses, confirming the need for new strategies not only for teaching but also for assessing creative skills in engineering curriculum (S. R. Daly et al., 2014). For quantitative assessment to be relevance, different creative skills must be identified, isolated, selected and measured with great specificity (Mansfield, Busse, & Krepelka, 1978). From early attempts to undertake quantitative creativity testing in which tests were primarily focused on measuring the creativity of the individual (Treffinger et al., 2002) numerous different testing and assessment strategies have been developed, both qualitative and quantitative, and each with a set of measures, categories, and systems to measure change (Charyton et al., 2011; Charyton & Merrill, 2009; S. R. Daly, Christian, et al., 2012; S. R. Daly et al., 2014; Dean, Hender, Rodgers, & Santanen, 2006b; Gerhart & Carpenter, 2012; Guilford, 1984; Liikkanen, Hämäläinen, Häggman, Björklund, & Koskinen, 2011; Mansfield et al., 1978; Parnes & Noller, 1972; Schneiderman, 2007; Shah, 1998; Shah, Kulkarni, & Vargas-Hernandez, 2000; Shah, Smith, & Vargas-Hernandez, 2003; Sternberg, 2006; Vargas-Hernandez et al., 2010). The difficulty, then, for anyone attempting to participate in research in this area is not so much in finding an assessment tool as in selecting from among the many measures available, and justifying that selection.

Early tests, such as the Purdue Creativity Test of 1960, were designed to identify the relative creativity of the individual. Based on 126 questions, engineering students were rated highly creative, or less so. Similarly, the Purdue Spatial Visualization Test-Rotations (PSVT_R) (Charyton et al., 2011) which usefully focuses on measuring 3-d spatial skills for engineers, tests for native spatial visualization abilities rather than the successes of specific training strategies. Designed specifically for engineering, the Creative Engineering Design Assessment (CEDA) tests both divergent ‘problem finding’ and convergent ‘problem solving’ using sketches as data. However with a focus on image annotation there is little discussion of ranges of visual quality, and the test appears to prioritize solutions over open-ended explorations (Charyton et al., 2011). However the strategies used to measure creative outcomes in both the PCT and the CEDA are highly relevant to this study as the basis for almost all later assessment studies. The CEDA assessed *originality* (new ideas), *fluency* (count of ideas) and *flexibility* (different kinds of ideas) (Charyton & Merrill, 2009), with an additional creative outcome, *usefulness* added in the revised CEDA (Charyton et al., 2011). Both *fluency* and *flexibility* were numerically described, however *originality* and *usefulness* were described qualitatively through a rubric ranging from dull to insightful, in which numbers emerge from qualitative description (Charyton et al., 2011).

Building on Amabile's definition of consensual creativity as something that can be recognized in the work itself, (Teresa M. Amabile, 1982) this study thus avoids those measurement systems designed to assess and individual's creativity to focus on those which assess project outcomes, further narrowed to systems that use sketches and exploratory diagrams as assessment data.

Shah-Vargas model

The 'measures for ideation effectiveness' devised by Shah & Vargas, formed the basis for my own quantitative ideation metrics, and I will spend some time explaining their strategy. Focused specifically on engineering, albeit mechanical rather than civil and environmental, not only are they are designed to measure ideation effectiveness (Shah et al., 2003) but to do so based on an assessment of sketches and notes. The strategic and mathematical approach to measuring each variable is well described in a clear structure that can be followed and adapted.

Defining the 'design space' as the space of all possible ideas, they seek to assess the extent to which divergent thinking takes place by how much different methods 'expand' the design space (divergent thinking) or 'explore' the design space (deepening thinking). Four operating variables are proposed, the *Quantity, Quality, Novelty, and Variety* of ideas generated.

Quantity is very straightforward, as the number of ideas generated in a specific amount of time. Conceptually connected to the classic term *Fluency* it which shows how prolific an individual is. *Variety* similarly is applied not to a single idea, but to a student's full set of explorations. The range of difference over a set of proposals is assessed based on function. A genealogy tree allows assessment at different ranges of detail, based on a reduction in weighting for ideas at smaller levels of detail. While the total number of ideas is a factor, division into a greater number of sub-paths can reveal breadth; alternatively, many similar ideas do not lead to as high a score as a few very different ones. *Novelty* is a measure of the unexpectedness of any single ideas, and is graded for relative unusualness compared to the full set of solutions. Finally, *Quality* is also independently rated for each idea. The hardest to define, it is a measure of expected to desired value of key attributes. Technical feasibility and performance are part of the measure although Shah-Vargas point out that such measures are hard to extract in a quick brainstorming phase project.

Each variable is related to specific outcome metrics and the interaction between the different effects is described, however the authors take pains not to combine these metrics into a single score. In their assessment, a creativity tool is worth using if it is able to improve any one of the four measures (Shah et al., 2000, 2003). *Quantity* and *Variety,* as strategic approaches, are proposed to be easier to improve but may simply show improvement in process and not necessarily in the work itself. The more important long term metrics, they argue, are *Novelty* and *Quality*, primary outcomes which, however, can be argued to build on the success of the 'process related outcomes' (Vargas-Hernandez et al., 2010).

Liikkanen el al. similarly developed five quantifiable variables for experimental conditions: along with *Quantity* and *Novelty*, they assessed *Feasibility* against the diversity of results in the pool, and *Quality*, once again, by independent experts within the domain (Liikkanen et al., 2011).

Within the broad range of studies attempting to assess creativity in engineering education lie not only a range of systems, but a complex untidiness in the use of similar terms to measure different ideas or old strategies. Researchers take different approaches to selecting and naming characteristics and how to measure them. Some researchers find novelty to be sufficient, whereas others require its combination with usability, effectiveness, clarity, or efficiency. It is hard for such studies to build on each other without a shared language. Undertaking the mammoth task of creating some order from this chaos, Dean et al. brought together 90 studies on creativity and its assessment, and attempted to regularize the use of terms,

Table 5. Dimensions Measured Separately and then Combined Explicitly

#	Study	Novelty	Workability	Relevance	Specificity
7	Barki and Pinsonneault, 2001	Originality	Feasibility	Effectiveness	
8	Diehl and Stroebe, 1991	Originality	Feasibility		
9	Mumford, 2001	Novelty, Unusualness	Logical, workability	Potential plausibility	
10	Gallupe et al., 1992	Originality	Feasibility		
11	Hender et al., 2002	Originality; Paradigm Relatedness			
12	MacCrimmon and Wagner, 1994	Novelty; Non-obviousness	Workability	Relevance	Thoroughness
13	Straus and McGrath, 1994		Feasibility	Impact	
14	Potter and Balthazard, 2004	Creativity	Feasibility	Relevance	
15	Sosik et al., 1997	Originality, Imaginativeness , Innovativeness		Value addition	
16	Cady and Valentine,1999	Novelty, Excitement	Adoptability; Non-violation of known constraints	Applicability, Ability to solve the problem, business potential	How well described
17	Miura and Hida, 2004	Novelty, Originality		Utility	

2-2 Identifying idea measures, partial list from Dean et al. 2006 bringing together the most frequent and consistent in the literature.   (Dean et al., 2006b; Dean, Hender, Rodgers, & Santanen, 2006a). Working with an action-research approach, Dean et al. categorized assessment strategies to extract a common language for the analysis of creative work, from which they extracted four dimensions of understanding described as *Novelty, Workability, Relevance, and Specificity*. For each study they matched descriptive intentions to their four categories to develop a level of consistency.   While *Novelty* of ideas was almost always measured, the attributes of *Quality* tended to range more widely (Dean et al., 2006b). Avoiding the term altogether they defined three other sub-categories of that term. The Dean Measures focus on the assessment of individual works and omit assessment of a range of a combined works over an exercise. However one can integrate the vocabulary and granularity of the Dean study into the assessment of *Quality* by including their three sub-dimensions, in order to design a set of measures which are not only more fine-grained, but also more easily compared with other studies in the profession.

Visual data, as data for creative assessment in educational research, is unusual and often appears only in supplemental assessment. Precedents describe the promise of such deliverables as ‘insightful artifacts’ for study, however few models have found ways of retaining the in-built richness of visual data, or of assessing more than one aspect of any drawing. By simplifying drawings through coding them into groups of single categories, researchers in effect narrow the visualization that they had, purposefully, intended to expand through their processes mapping technique (Vargas-Hernandez et al., 2010). Given the multi-layered ability of a sketch to communicate a shorthanded sense of quality and intention, such assessments reduce the rich sketch to a simplified code, on the other hand, without such coding structures, visual data is incredibly hard to assess, either quantitatively or qualitatively (Fernandez, Purzer, & Fila, 2016).

Chapter 3

Landscape, Mapping and Data

The first marks made onto a site, the first urban land decisions, are often made by a civil engineer. The hidden bones of a site are its overlapping systems; road networks, water systems, drainage patterns and freshwater networks, the landscape systems of spatial data include power supply, waste collection, paths and bus routes. Each individual data set can be collected and mapped; together these overlapping infrastructure systems form the pattern for our lived environment. Such a connected matrix is spatial, a web-like field. Cities thought of as collections of objects and lines become competing independent solution-elements. The city is a field, a layered fabric of data patterns inter-woven through both the spatial priorities of the natural environment and the social aspects of the community fabric. (Ahern, 2007)

Infrastructure design is land design, and its designers are civil and environmental engineers. Yet, in the academy, we hardly recognize this. While mechanical and materials science engineers strongly participate in the design education conversation, there is little such discourse in civil and environmental engineering (Baillie, 2002). While critical of civil engineering's abdication of design creativity to the architect (Stouffer, Russell, & Oliva, 2004), CEE studies tend to focus on project-based teaching potentials. The creativity conversation circles around the valuable abilities of civil engineers to innovate, compete and manage design work within the firms of engineering practice (Salter & Gann, 2003), yet there is still little conversation about the place for design-thinking in the academy. But the next generation of civil and environmental engineers will have great need of such creative skill in order to remain competitive in the critical and ethical future of engineering (Stouffer et al., 2004). In our climate challenged future it is precisely the physical environmental context of a civil engineer's work that makes access to an innovative outlook even more urgent. Site sustainability, as a concept, is valued by ABET (ABET, 2015), but there is little recognition that the spatial site design of a water system or a highway interchange has primary impact on the broader sustainability of the city.

3-0-1 AA student landscape-urbanism study

While landscape architects and urban designers pursue ecological design ambitions and practice in the contemporary city, with books, conferences and whole degree plans focused on ‘landscape urbanism’, or ‘ecological urbanism’ (Mostafavi & Doherty, 2016; Mostafavi & Najle, 2003; Waldheim, 2002, 2012), their conversation ignores civil and environmental engineers, precisely those with the primary responsibility for designing such systems. As an urban environmental discipline, civil engineering takes responsibility for the city content almost entirely without a theoretical discourse or design context (Bélanger, 2013). Efficiency and safety take priority in civil engineering, but vital aspects such as social or spatial design conditions often remain outside the project proposal, resulting in decontextualized and isolated project work, revoking the responsibilities of the engineer and also their potential for future leadership. This disconnect of expertise and spatial systems, and the ensuing infrastructure construction positioned without a design context, can result in urban blindness, spatial marginalization in which environmentally or socially damaging built works can become responsible, if unintentionally, for social strife (Bélanger, 2013). A design context in which social and ecological spatial data were to be brought into collaborative interaction with imaginative vision, technical efficiency and cost is the necessary first step for green-infrastructure solutions but clearly such integrated work cannot take place without the development of engineering skills in cohesive site-design thinking.

Not only do engineers have the opportunity to position themselves as full participants and even leaders of the site-design conversation; it may be negligent for them not to do so. And the opportunities are enormous. Civil engineers thinking creatively about the overlapping networks of infrastructure and ecology could not only moderate the damage caused by mammoth construction investments, they could put into place an urban vision in which ecological investment also helps the support infrastructure systems, in which social data is integrated into transportation flows and layered site systems allow economic efficiencies while they give visible order to communities.

Landscape as System

A 'spatial-turn' acknowledged across the humanities and sciences looks to the authentic knowledge of place, recognizing that all knowledge is constructed in specific sites and contexts (Lippard, 1997). The interdisciplinary overlap between cultural and environmental understandings has developed since the 1990s, recognizing the interdependence of the traces we mark on the landscape, historical, agricultural, or ecological (Jackson, 1984a). Sustainable site thinking connects ecological and social data, information in constant change not only in space but also in time. In contrast to the visual emphasis of the eighteenth century, our experience of space in motion is an essential aspect of contemporary thinking about landscape, experienced in weather and time, ecology and place. (Bann, 1983, 2003; Conan, 2003; Lassus, 1998). Like landscape's natural systems, urban networks ebb and flow, interacting not only with each other, but with community, economy and maintenance. The dynamic electronic contemporary city requires a creative approach to infrastructure urban design in which large spatial networks in change and motion are inherent to the work.

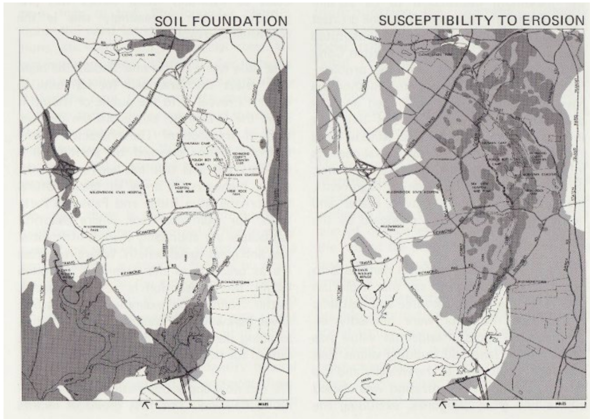
> *"There are, then, different kinds of 'flow': [ ] and these flows leave different traces on the landscape. [ ] It is not so much that 'things' move in time and space, as if time and space were somehow a fixed template within which the world simply is. It is more that these flows- be they walkers on ridges or droplets in a water cycle - produce different forms of time and space: for example, cycles, channels, reversals, folds, scapes, interferences, inversions, convergences, divergences, expanses, details. And patterns." (Harrison, Pile, & Thrift, 2004)*

With increasing understanding of the complex interdependency of our ecosystem, constructed networks of civil and environmental engineering can no longer conceptually isolate themselves from ecological, social or economic contexts. Each mark of infrastructure participates in and alters the larger environmental context of its site. Decisions made on territory layout are no longer merely political, practical or visual, as they might have been in the days of the Jeffersonian land grants. Now environmental effects, local water impact and social planning conflicts are integral to primary land planning decisions, based on a wide range of data. Contemporary planning reflects international awareness of the limits to growth of traditional policies and practices of development, both locally and globally (Ahern, 2007; Beatley, 1999; McHarg, 1969; F. Steiner, 2011). Such thinking grows from a strong history of environmental urban thinking reaching back to the first critiques of the industrial city (Engels, 1987; Geddes, 1909, 1915; Howard, 1902; Mumford, 1961), however it has taken on new urgency in the face of environmental deterioration and global resource limits. Green urban infrastructure approaches sustainable cities with a recognition of the relationships between the patterns of urban infrastructure and their connectivity. All such systems are hierarchical, that is the dynamics and capacity of the system are interrelated; in the same way as a local roads are connectors to the hierarchy of the highway system, so too landscape and its ecological and hydrological processes, are nested spatial systems with inter-related scales (Ahern, 2007; F. R. Steiner & Forman, 2002; Waldheim, 2010). Such intentions of interrelation of functions must be brought into the civil urban environment (Mostafavi & Najle, 2003; Rouse, 2013; Stokman, 2008). The ecology of the landscape, the mechanisms by which it provides services that moderate climate, detoxify waste, purify air and water, cycle nutrients and maintain biodiversity, is the context of infrastructure and site planning (Ahern, 2007; Bélanger, 2013).

Mapping and GIS

> *Acts of mapping are creative, sometimes anxious, moments in coming to knowledge of the world, and the map is both the spatial embodiment of knowledge and a stimulus to further cognitive engagements. . their spaces of representation can appear liberating, their dimensionality freeing the reader from the controlling linearity of narrative descriptions and the conforming perspective of images. (Cosgrove, 1999)*

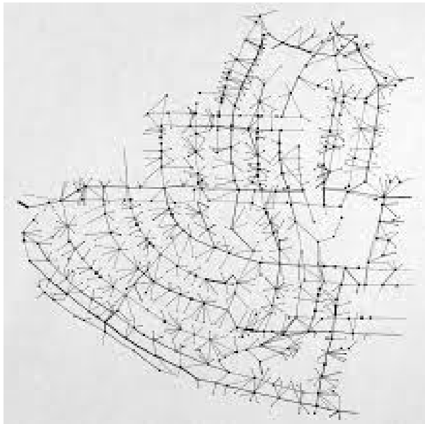
Landscape architects use maps not only to illustrate a site but as a creative structure, a methodological tool for revealing potentials for its development. Since the groundbreaking regional analysis strategies developed by Patrick Geddes, himself a botanist as well as one of the fathers of regional planning, the regional site has been investigated as a series of overlapping systems. Agricultural, economic,



3-2 Ian McHarg layered map analysis 1969

transportation, political, and design choices have been developed within the context of that layered understanding (Geddes, 1915). McHarg first layered transparent sheets of spatial data; view-sheds, forested zones, drainage patterns, to create the first analogue GIS drawings, and used these drawings to thoughtfully site new highway locations and to develop the first sustainable subdivisions (McHarg, 1969). Maps take on enormous instrumental expectations as notations of site information. Projections of the interests of the map-maker, there is power latent in such a visualization, limiting movement, demarking and enforcing social divides, supporting land and political claims. As a value laden image the map has often silently served the orders of power while simulating transparency (Harley, 1998; Wood, 2010; Wood & Fels, 1992). The communicative role of the map plays an important role in this persuasion, convincing in its spatial consistency (Harley, 1998). The value, for the engineer, in understanding such power is that one can subvert the typical by giving visualization to aspects that have otherwise been ignored. Implicit prioritization has been made in the representational choices in our urban maps, vital but hidden street water drainage systems remain unrecognized, for example, while land-use decisions are made on the basis of voting patterns. Corner points out that maps ‘gather and show things presently invisible’ (Corner, 1999b), indeed, the communication of meaning in map takes place precisely because they ‘filter out all the chaos in the world and focus obsessively on one item.’ (Glass, 1998; Wood, 2011). Engineers as designers are thus able to choose to document aspects of a site that they know to be vital but which are not usually prioritized. In terms of creative practice it can be precisely the process of noticing and gathering data, be it wires or sound levels, which can inspire creative alternatives for thinking about a site (Stilgoe, 1999).

The issue of time is built into mapping as it is into landscape. Landscapes grow and erode; digital site mapping systems allow the framing of this rate of change so that functions can be spatially visible. The



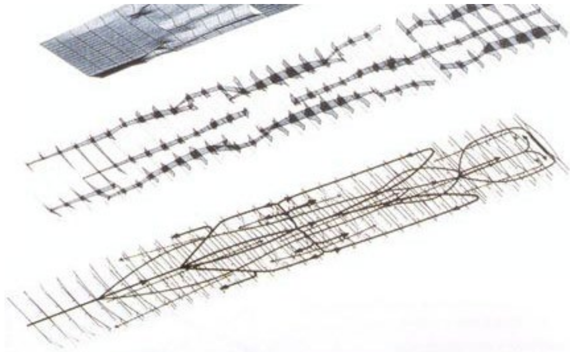
3-3 overhead wires, Dennis Woods 2010

decision to map a function focuses the documentation on process, allowing the map to reveal data in change. A site can described as a catalogue of its procedures privileging data that reveals change. Urban growth or ecological change such as weather and pollution become discursive tools when visualized in a digital map. Similarly cultural flows, such as site history, can alter the discourse with the potential to reveal patterns for change. The interpretation of a site-data as a series of functions is an engineering design potential hidden in the discourse of landscape, and articulated in geo-spatial mapping.

The Diagram and Data

The work of gathering data, and making it visible has developed a speculative role in urban design and landscape practices. This mapping activity, quite familiar in design schools and landscape practices, has not only a descriptive outcome but is an explorative practice (Cosgrove, 1999; Foucault, 2013; MacEachren, 1995). It is not the 'map' object itself that is important but, like a diagram, the exploration of its content. Less interested in its cartographic representation, designers exploit the exploratory work of making the map, and the conversation it opens. The map becomes a design process tool, a diagram which allows one to see past the specific data structure to investigative ways of working.

The discourse on the diagram as a design tool is based upon Deleuze' notion of diagramming as a phase of artistic creativity 'like an animal on the page, out of control- struggling to emerge' an image familiar to artists from Bacon to Alvaro Siza. (Deleuze & Boundas, 1993; Gilles Deleuze, 1981; Moneo, 2004). The power of the diagram lies in its ability to abstract, to leave out inessential qualities in order to allow pointed discussion, and to expose something beyond the familiar. For Deleuze the conceptual diagram is always outside of the work itself, referring to its potentials, 'the possibility of fact- it is not the fact itself'. (Gilles



3-4 FOA Yokohama port transit diagram 1995

Deleuze, 1981). Similarly, the designer's diagram has been described as an active agent, a divergent process rather than a carrier of meaning (S. Allen, 1998; Eisenman & Somol, 1999). Precedents for such 'diagrammatic thinking' abound in architectural practice; such as FOA's diagrammed transport systems for the Yokohama Port; or Eisenmann's movement data for the IIT student center. Such diagrams were generative, not only of form, but in the designers' creative processes. Similarly in landscape design, in Abalos and Herrera, or Corner at Freshkills, maps are developed not only as tools of analysis but as tools of creativity. Privileging difference over representation, individual data itself becomes less important than the arrangement of its series, a quality embedded in digital GIS maps in which data layers overlap and are 'always already' visible for a moment. The digital map project is never a fixed representation but always momentary.

Data-collection is the first creative opportunity phase. Learning to look at a site is exploring, with an outcome that can spark curiosity and reward scrutiny (Stilgoe, 1999). Traces of social and political history are revealed in the ordinary marks of the built environment, and mapping them reminds us of their value by altering their visibility (Jackson, 1984b). Shared observation practices are embedded in the dynamic experimental structures of the Ciudad Abierta, Ritoque Chile, constructed from exercises in observation, annotation, drawing and poetic text, the collaborative built works are able to be analyzed as part of a cohesive social and community vision (Cruz Prieto, 1993; Escuela de Arquitectura, PUCV, 1991; Pendleton-Jullian, 1996; Pérez de Arce, 2003). Like a series of participatory 'diagrams' mapped onto the territory by the community, the shared memory of the poetic action becomes the context for new work (Marshall, 2011).

Mapping's first operation is the problematization of an issue and the search for evidence of that issue in the physical, social, or political site data: routes, ecological systems, topography, value or vegetation; but also the perceptions and sensations which are part of the deep archive of our experience of place.

In choosing which data to collect and which to exclude, a position is taken on both the work and its context; a bounded vision of the site. Data gathering is followed by analysis choices, then visual representation repeated over a number of iterations, each phase embedded with design intention. Taking on the task of visually representing qualitative data, or spatial data in change, designers can articulate such functions upon the site. Students discover that community context alters the way the world is seen, and mapped (Sletto, Muñoz, Strange, Donoso, & Thomen, 2010). Creative juxtaposition, the bringing together visually and conceptually of otherwise unconnected aspects of site, projects unexpected connections to valuable generative effect.

GIS Systems in Engineering: project, place process

An instrumental tool for data analysis and visualization, Geographic Information Science (GIS) mapping and analysis skills support project-focused site mapping of physical, economic and social data. The place-based nature of a geospatial site study opens paths to more sustainable approaches to engineering solution. Finally this study explores the generative potential that can be uncovered through spatial mapping. The effort to harness this potential in a strategic process is an unexploited benefit of spatial data analysis and one that, I will argue, offers engineering students a powerful route to design thinking.

Since the 1990s there have been arguments for the wider recognition of GIS's complex interdisciplinary and social implications. The hidden assumptions of maps leave implicit social goals that should be questioned (Pickles, 1995, 2006). Critical of the narrow instrumental range of ways of thinking about maps even in the geographic GIS community, awareness of a wider epistemology of perspectives and conceptions have been proposed (Gahegan & Pike, 2006).

There is broad support from STEM education national research councils, and committees on geographic and earth sciences, for the notion that spatial thinking plays an important role in scientific and mathematical thinking and learning. The ability to visualize spatial relationships using representational tools serves both problem analysis and dynamic reasoning, and GIS has been recognized as a strong player in this process, particularly in K-12 education. The multidisciplinary, integrative inquiry based aspects of GIS, as well as its data and computationally driven structure, and its link to problem-based learning, can engage and empower students in STEM related contexts, in a way that can be both critical and creative. (Baker, 2012a; DeSouza, Downs, Resources, & Council, 2006; Baker, 2012b).

Most arguments for the inclusion of GIS in engineering education, however, remain focused on software skills for industry and visualization (Pfluger, Dacunto, & Hendricks, 2014). While the use of GIS has proliferated in civil engineering it remains primarily embedded in traditional data modeling and project implementation (Miles & Ho, 1999). GIS based spatial innovations in engineering reside primarily in land surface modeling applications, for analysis and prediction, strategies brought to bear on hydrological or environmental concerns. Such work, while creative in itself, doesn't use GIS itself as a tool for creative exploration, but rather as a modeling tool applied to innovative engineering work (Storck, Bowling, Wetherbee, & Lettenmaier, 1998). Interest in encouraging its integration with more creative practices, ESRI press describes the potential for spatial analytics to 'spur innovation' (Pratt, 2014), and unite independent issues, allowing their juxtaposition to lead to innovative thinking. Bringing the dense mix of social and cultural assets into proximity through geo-design, can open the door to creative solutions.

Spatial literacy, or the ability to visualize relationships in space, is a fundamental aspect of structural and infrastructural problem solving and particularly relevant to civil engineering. Researchers have argued that complex spatial thinking has particular importance to engineering for its fundamental pedagogic value, and have suggested that GIS be integrated into multiple existing course structures (Cardenas, Kelley, & Roberts, 2013), and exploited as a spatially connected scientific teaching tool (Berry, 2013). Justifying the time allotted to GIS within the dense engineering curriculum, two values are cited; beyond the pragmatic value in synthesis, analysis and visualization of engineering data, the layered mapping process is cited for its potential to assist students to achieve broader understandings of the global societal contexts of their engineering decisions, a critical skill for which many are currently poorly prepared (Ivey, Best, Camp, & Palazolo, 2012).

The American Society of Civil Engineers and the National Academy of Engineering point out that civil design decisions impact not only technical but social, environmental and political outcomes. Reaching towards the creative integration of infrastructure with community planning, the teaching of GIS enables not only interdisciplinary visualization but the development of critical analysis skills for working with multiple decision factors. Bringing the dynamic values of project-based teaching together with GIS through participatory-mapping practices, allows the integration of a number of learning strategies, spatial mapping, global and societal contexts, contrasting data sets, and the experiential opportunities of project-based work. Attempting such complex work would be easier if armed with specific engineering educational methodologies for approaching such spatial design practices.

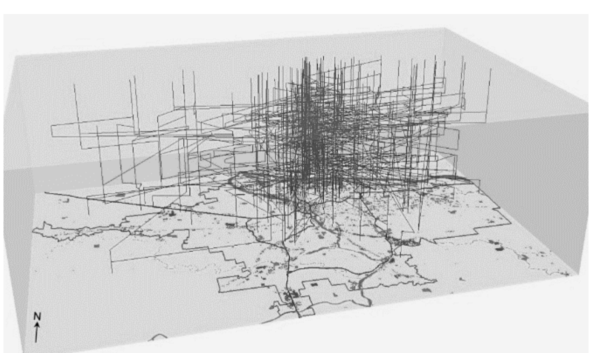
GIS and Creative Agency

Despite recent advances in socially activist uses of GIS, particularly in areas such as public participation GIS (Brown & Kyttä, 2014; Brown, Weber, & de Bie, 2014; Merrick, 2003), many researchers remain critical of the separation between critical discourse and GIS. In many cases, even when narrative research has been elegantly integrated into spatial mapping (Mennis, Mason, & Cao, 2013) the impact on the resultant spatial visualization is minimal. While the qualitative ideas generated are indeed expanded, the spatial study itself remains conventional (Matthews, Detwiler, & Burton, 2005). Setting apart a few forays into linking sketch-maps with GIS, in which zones of perceptual data from interviews are presented as overlays (Boschmann & Cubbon, 2014; Curtis, 2012), most theoretical discussions and guides to the multiple inclusive uses of GIS in qualitative research (Elwood & Cope, 2009b; Steinberg & Steinberg, 2006) are largely illustrated with GIS images which remain primarily visualization.

While primarily serving quantitative data visualization, both geographical and social data, the potential to also use GIS to map qualitative data opens up the field of spatial analysis to a more complex set of community site issues. New deep data sets with coded measurement systems are examples not only of creative work being done with GIS, but also of ways that a GIS system and its measurement processes have inspired provocative or creative conceptual thinking beyond the map itself. Such examples serve as models for GIS mapping as a vehicle of creative agency, even if that agency is not necessarily yet spatial. Defending the scientific rigor of deep qualitative spatial research, Pavlovskaya argues that the spatial intelligence demanded by GIS is most powerful when its power to map the non-measurable properties of human experience provides a new domain for understanding theoretical connections between phenomenon and site (Pavlovskaya, 2006).

A precedent for the exploitation of geo-spatial research as a structure to actively facilitate experimental scholarship comes from the digital humanities. In his history of the geocoded map as a cultural text, Travis develops the notion that through 'deep mapping' GIS can identify patterns or facilitate comparisons which can see beyond the positivistic limits of typical mapping, through an engagement with experiential environments (Travis, 2015). The spatial material is considered by Travis more of an active agent than a passive container, a site for the production of alternative constructs. For these humanists, the constructs sought are those of historical or literary and cultural criticism in which the simultaneity in textual descriptions of place can be visually mapped as a mode of critical exploration. Described as 'the space of conjecture' (Travis, 2015), the web-connected space of the GIS map suggests a direction for scholars to imagine connections between data. Although they do not direct translate into spatially creative site solutions the connections do become the abstract context for qualitative and exploratory visions.

Finally, a few geospatial geographers have developed a robust research conversation on the spatial integration of qualitative geospatial data and analysis techniques with quantitative data (Jung & Elwood, 2010), and a dense theoretical methodology for qualitative work in the spatial context (Elwood & Cope, 2009a; Mugerauer, 2000; Yuan, Nara, & Bothwell, 2014). Kwan's methodology to operationalize time-geographic research by creating 3-d models with time as the vertical axis, for example, enabled new strategies for visualization and qualitative study of human activity patterns over time, re-envisioning data



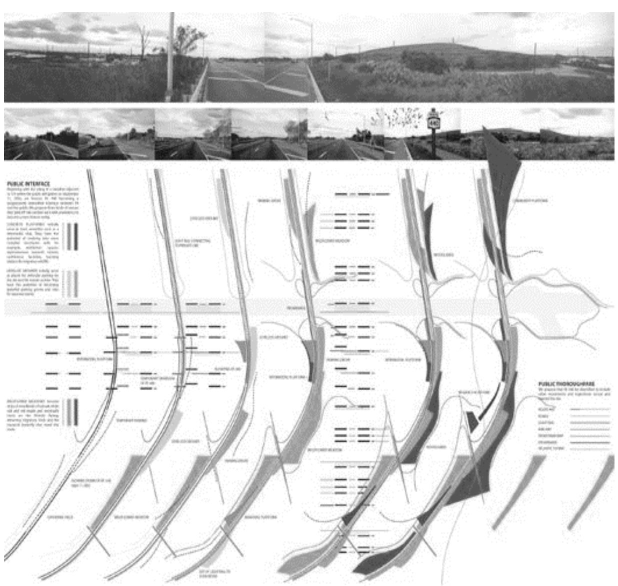
3-5Mei Po Kwan, 3d GIS time space paths, 2004 conceptually and politically (Kwan, 2002, 2004). Based on digitally integrated text analysis of oral histories and biographies (Kwan, 1998, 2000, 2002; Kwan & Ding, 2008). Such maps reveal daily spatial experience and are rich in visual impact as well as exploratory content (Kwan, 1998, 2009). Such dynamic visual studies reveal humanist issues but are also infrastructure maps, connecting site to accessibility and time, the practical significance of which is illustrated by the support of her work by the Federal Highway Administration (Boschmann & Kwan, 2008). However such daring creative agency of spatial abstraction remains rare.

A site of power the map embodies authority through the articulation of its representation (Harley, 1998; Wood & Fels, 1992). As such, maps also have the potential to stand up against such readings and enable social critique, transferring power to the under-represented through the technical transparency of their message. Participatory map-making is embedded in activist land-work, in which communities re-vision their territorial representation, often counter to traditional visions embedded in the maps of authority, by extracting understandings of site from, for example, traditional storytelling or place-names (Guldi, 2017; Ramirez-Gomez, Brown, & Fat, 2013). The contemporary practice of public participation GIS (ppGIS) is built on strategic approaches to inclusionary planning (Brown, 2012; Brown & Kyttä, 2014; Ahmed et al., 2015; Kwaku Kyem, 2004), bringing together qualitative mapping, data development, and participation action research. Socially engaged, ppGIS has historically been used to take on issues of land conservation and aboriginal land traditions (Cinderby & Forrester, 2005; Fagerholm, Käyhkö, Ndumbaro, & Khamis, 2012; Menegat, 2002; Ramirez-Gomez et al., 2013) however the tactics can be applied to environmental and civic contexts such as the mapped systems of resistance created by public spaces of slum-dwellers in Lima, Bogota and in Cairo, (A. Allen, Lambert, & Frediani, 2012, 2014), or public action on street vendors (D'Ignazio, 2013). Contemporary strategies that exploit the agency of public-participation mapping as a planning tool make use of location-based or 'soft-GIS', in which a collaborative approach ensures that community points of view are taken into account to undertake more community-sensitive ethical urban development (Kahila-Tani, 2016; Kyttä, Broberg, Tzoulas, & Snabb, 2013).

Digital GIS technologies have enabled a democratization of participatory map making, for example in Map Kibera, in which local participation which literally put Kibera's informal slum settlement onto the blank-space in Nairobi's map, enabling the integration of services into the community, (Erica Hagen et al., 2009; Hagen, 2011; Menegat, 2002). However over-reliance on technology also can separate community and site, once again returning the well-meaning geographer to the role of external expert (Wood, 2010). For an engineer working with spatial data who understands the responsibility in embodying spatial authority, the opportunity arises to intelligently and purposefully use the process of map-making for multiple impacts: physical, social, political, economic and ecological.

Conclusion

Ambitiously, mapping has the potential to operate on several levels, allowing it to be articulated as political activism, but also as a field of physical and social exploration (Benjamin, 1998; Eisenman & Somol, 1999). This paper is focused on the generative potential of mapping in an education context, however clearly this productive role remains secondary to the primary role of the map in which lessons from data analysis must be instrumental in the visualization and production of new work and its associated social impacts. While its generative role as a design-thinking tool has educational value, the long term impact of GIS as an engineering innovation tool depends on whether the visualization of spatial data can function efficiently on several levels simultaneously.



3-6 J. Corner, Freshkills *design study, Field Operations, 2002*

Discussions of the creative role of mapping in design practice have been haunted by three fears; one is a hope that something vital of the original generative data will be preserved in the built work; the second, is a similar secret hope of a hidden truth uncovered. Third is the fear that the visualization may be powerfully generative, but spatially irrelevant for the actual site artifact (Cousins, 2005). These fears are all based on the idea of a fundamental interruption in the design process, geo-spatial data mapping thus attempts to bridge the gap between the research and design phase. The mapped and layered diagrams of Corner's winning competition entry for the Park at Freshkills landfill on Staten Island are more than illustrations of data, they are both site analysis and site design, setting out a pattern for new development to serve New York as both community and ecological healing. Operating as strategies as well representations the maps unite active strategic design-thinking with representational drawing (Corner, 1999a; Pollack, 2002). The potential hidden in such an overlapping set of mapped discourses might be a model for the visualization of an integrated infrastructure urban-design vision, fully embedded within a living community landscape.

Chapter 4

Research Study Objectives

"Our senior design project was heavily, heavily, 'Here's an idea, a concept. Figure out how to make it'. They never really taught us how to design, or anything. It was kind of a 'here you go, figure it out.' *Eng. student, SMU 2016*

This study explores the potential of spatial data and GIS mapping to spatially enable the teaching of strategic divergent and creative thinking practices for design in civil and environmental engineering students, a practice which is often left to be accessed primarily through intuition and repetition.

Research in divergent thinking, primarily focused in mechanical and material engineering, has revealed the efficacy of specific tactical approaches to the teaching of creative and divergent design thinking processes within the context of the engineering curriculum. A range of qualitative and quantitative precedents provide a clear set of structures by which new proposals within this arena can be convincingly tested.

Given the primary orders of infrastructure networks in the structure of the built environment, civil and environmental engineers must recognize their responsibility in the design of the urban landscape. Preparing engineering students to take on such a leadership role requires developing their skills not only in the interdisciplinary engagement with community, cost and ecology of a site, but the ability to participate in the development of creative visions for sustainable and livable urban site solutions.

Geo-spatial systems (GIS) are designed to allow the overlaying of different data within the spatial structure of a map. Valuable for visualization and analysis, they bring together diverse data into a single overlapping visual and spatial structure, a tool which already supports sustainable site analysis and systems thinking. However given its spatial and visual structure, this technology has the potential to be exploited as a tactical catalyst for creative exploration and design-thinking processes. Aware of the literature on digital creativity support systems (CSS) and more traditional idea-generation methods (IG) this research proposes that the multiple values of GIS allow not only greater efficiency in curriculum design, but in its grounded and data-connected characteristic, greater efficacy.

Why teach GIS mapping to Civil & Environmental Engineering students?

For students studying to become engineers of infrastructure, an exposure to GIS has at least three potential values, defined as a focus on Project, Place and Process.

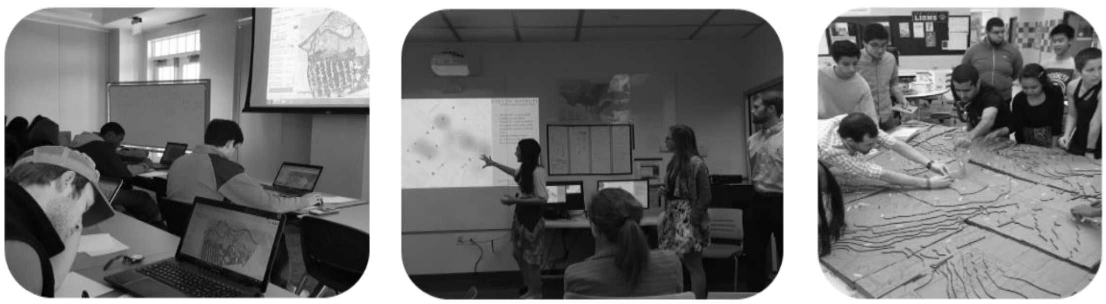


Figure 4.1 Students working in the classroom and in site project-based contexts

Project

Data manipulation skills are increasingly in demand in the marketplace and the ability to undertake collection and visualization of environmental and civic data is an expectation for engineering professionals. Our understanding of the impact of infrastructures' systems on an urban development expands, as engineers are able to accurately describe interactions between physical, social and political urban data systems through the exploitation of layered 'internet of things' (IOT) systems in which multiple embodied layers of information are gathered within a single three dimensional electronic space (Arriagada, 2013). The move from cartography to GIS has only increased engineering's potential to employ maps to explore, synthesize, and analyze data, including critical scientific visualization and exploratory image and data analysis (Kraak, 2005; Kraak & Ormeling, 2011).

Place

Not only geographic and construction data are integrated into a GIS analysis but, increasingly business, social and economic aspects of place are brought together into a site visions which is not only more technically complex, but more environmentally aware (Frank & Raubal, 2001). Often politically persuasive, engineers fall into a stronger leadership role as they communicate integrated spatial and scientific data in the development of strategies for the sustainable urban environment (Shaw & Xin, 2003). Scientific insights drawn from LIDAR and other remote sensing devices is increasingly used to enrich traditional vector geographic data, giving access to less easily measured anthropological data, and empowering GIS based engineering to participate in a social and ecological conversations (Geoghegan et al., 1998; Liverman, Moran, Rindfuss, & Stern, 1998; Moran & Brondizio, 1998).

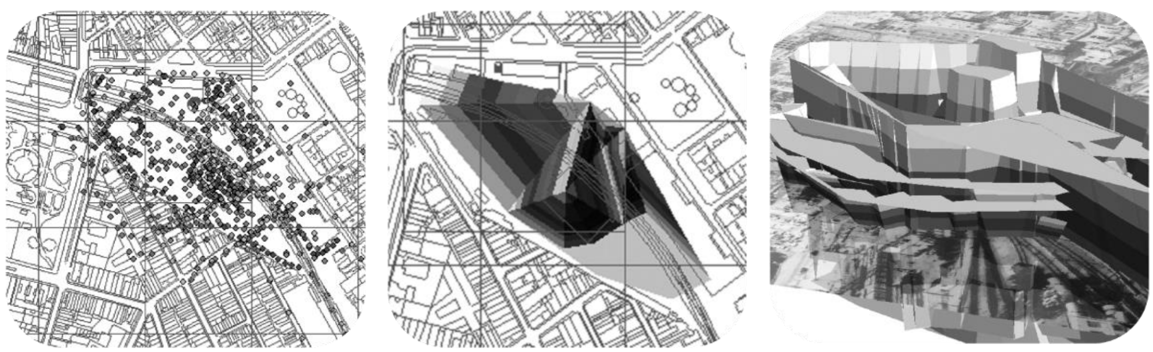
Long embedded into the science of forestry and natural resource protection, the integration of social science GIS into protected area management offers spatial analysis with multi-level connectivity, an example of the combination of spatial statistics, surface modeling and data mining (Beeco & Brown, 2013; Berry & Mehta, 2010). From studies of change error, to models of multi-temporal modeling and spatial behavior dynamics, temporal aspects of mapping are becoming more integral to the way we acquire and document spatial understandings in an urban setting (Egenhofer & Golledge, 1998).

With little consensus on methods for GIS education for engineering, it has been shown that a place-based approach benefits students as their conceptual understanding is integrated with applied site knowledge as well as hands-on training in sustainability practices (Chen, 1998; Drennon, 2005).

Process

Discussing the integration of ideas in space, and the nature of concepts such as continuity, proximity and separation as problem-structuring vehicles in spatial thinking, the National Academy of Science promoted GIS as a strategy for teaching and supporting spatial thinking for students, arguing that its ability to bring together functional analysis with transformational operations opens up not only interdisciplinary visualization but the inquiry process, an aspect with clear links to creativity (DeSouza & Downs, 2006a, 2006b). Like diagrams, data visualizations have the potential not only to communicate information, but to enable it to be read and acted upon in a new way. Active integration of social data such as emotions and ethics into geospatial practice can expose inequalities in social participation (Kwan, 2007). Complex historical and cultural data of an urban site overlapped with scientific data allow systematic relations to be revealed with potential for resilient, socially sustainable urban visions of an integrated landscape (Kuitert, 2013; Steiner, 2011).

'Geobrowsing' is a potential extraction from such multi-layered integrated data-visualization. when acted upon by the viewer, a process that facilitates creative thinking allowing the discovery of new insights (Peuquet & Kraak, 2002). As a spark to the imagination the psychology of creativity describes how visual characteristics as abstraction and ambiguity, often unanticipated by the maker, can provide 'geobrowsing' with the power to uncover new insights (Peuquet & Kraak, 2002). Like 'landscape thinking' the procedure of 'mapping and thinking' can become an active part of the creative process, a practice which includes the strategies of observation, documentation and overlapping to reveal unexpected adjacencies (Corner, 1992, 1999). Active engagement in site-mapping is an operational process, its value is experiential, building on the potential for site discoveries to be found through participation in the data-collection and mapping activity itself.



4.2 Example of exploratory thinking using mapping of geospatial data

Research Question

This research seeks to explore and measure the extent to which, beyond its value as an analytic processes, geospatial data visualization and manipulation can serve as a tactical teaching methodology, opening opportunities for divergent design and creative project-framing. Can the strategic intersection of data, site and technology can serve as a tactic to integrate design innovation processes into civil and environmental engineering education, and do so with both efficiency and efficacy. This study thus tests a number of strategies to exploit GIS spatial data mapping for engineering education, not only as visualization and research exploration, but also as a catalytic process for creative work. The outcome of this study will directly serve not only curious engineering students, but others who swim in these interdisciplinary urban-design waters.

Consisting of three studies, each with a different research methodology, the research takes place within the university, using the classroom as a research base. Primary data is exploratory mapping work by students in the department of Civil & Environmental Engineering in the Lyle School of Engineering at SMU. A broad sample is formed from two student groups: engineering undergraduates were introduced to GIS and site exploration in one-week course-based workshop. Data is composed of map sketches from pre and post-test design exercises, and pre and post surveys. A small graduate course focused on project-based GIS form part of a longitudinal study, spatial data is supported by student surveys and interviews.

Focused on student outcomes, the first paper explores the process-based content of the work, asking whether students, over the workshop process, developed new creative approaches to site-design work. This mixed methods study assesses changing skills and attitudes based on student surveys results, with data exploring change in students' self-assessed creative confidence and any reduction in design fixation.

The second paper focuses not on the creative person, but on the visual results themselves. Pre and post-test mapping work is assessed through a set of quantitative measures using a model from engineering education adapted to the visual data and site-specific focus of this work.

The final paper is a longer phase qualitative study which attempts to deepen the context of the exploration. During a full semester, detailed analysis of the creative process of a small group of graduate students, qualitative analysis revealed that in addition to creative approaches, students, perhaps unexpectedly, also developed new strategies for project-framing tied to site and community specific experience. Using a phenomenographic research methodology, the paper explores the relation between creative problem framing and project based work as mediated by the design-thinking context of the course.

Chapter 5

Mapping as Design Thinking: Can GIS help Engineering Students Approach Design

This project seeks to focus attention on the skills and design approaches that students gain in the process of learning design through spatial mapping, exploring the extent to which spatial design techniques based on an exploration of spatial mapping practices have the capacity to alter students' approaches to creative design work, both in terms of design confidence and design attitude.

Undergraduate civil and environmental engineering students were given a workshop on geo-spatial mapping and site-design. A short site design exercise was given before and after the workshop, followed in each case by a survey on their approach to the work. While later chapters will assess the outcome of the design mapping work itself, this study focuses rather on the student's self-assessed responses to survey questions about learning. This mixed methods study is built on both simple nominal and Likert scale data, as well as longer, more qualitative texts from student's written responses. The data was coded into comparative thematic groupings and compared.

This paper was presented and published in the Design in Engineering Education division (DEED) in the Proceedings of the ASEE (American Society of Engineering Education) Annual Conference & Exposition, June 2018.

Abstract

Spatial site design, accessed through GIS mapping, teaches three-dimensional data analysis skills invaluable for the contemporary engineering student. Integrating design-thinking strategies into such spatial processes allows students additionally to access the cognitive operations of creative design processes. This study will investigate student responses to an innovative site design workshop in which GIS mapping becomes a tactical device for introducing both site planning and design-thinking to civil & environmental engineering students.

After a pre-test site design exercise, 48 undergraduate engineering students were given a basic introduction to layered mapping (GIS) techniques, exploring both digital and analogue strategies for divergent exploration of site design. In the follow-up post-test design exercise, students were taken through a more structured design-thinking approach for a similar site design project as the pre-test. This mixed-methods study explores student self-assessment survey responses to the two design exercises, as well as their written design commentaries, evaluating them for changes in attitude as well as in approach. Data show that even in such a short introductory exercise, students reported an increase not only in GIS skills, but in creative self-confidence, and their responses revealed a more iterative design process, with generally higher values given by the students to their later-developing ideas over a fixation on preliminary concepts.

The value of such a teaching model is that student engineers are able to gain access to open-ended creative design skills, widely accepted as critical to the educational development of the engineer. Furthermore, this exploration, rather than an additive course or exercise, is integrated into valuable GIS mapping and environmental site design coursework.

Keywords: design-thinking, creativity, GIS, mapping, design approach.

Introduction

The creative engineer is in great demand. With expectations of not only competency, but a competitive urgency to innovate, the demands on the new engineer are multiple. While it is recognized that design and innovation are key areas for growth and development within engineering education, it remains difficult to integrate open-ended learning into what is already an overly dense, hugely broad, introductory package of courses (Klukken, Parsons, & Columbus, 1997). We need to explore more efficient ways of fostering open-ended creativity training for engineering students.

The teaching model explored in this paper exposes students to creative design processes as an add-on benefit, whilst they are studying more traditional techniques of data visualization and spatial site analysis. The study will ask whether a first exposure to design practices can be powerfully and efficiently introduced to engineers by embedding them into such spatial mapping processes. It will test whether such training can help provide students with preliminary strategic approaches to design-thinking, and whether, at the end of such sessions, students are better equipped to approach similar open-ended design contexts, with skills to develop a more divergent range of design options.

In this pre-test post-test experiment, exploratory design techniques were integrated into a workshop on basic Geographic Information Systems (GIS) mapping, itself part of an introductory first-year engineering undergraduate course. The amended workshop was designed to explore the potential for GIS and site mapping to support creative learning practices for students through an embedded introduction to design-thinking processes.

Design & Site Design in Engineering

Infrastructure design is land-design. Site design and community place-making grow out of the deep patterns marked onto a site by its infrastructure networks: water systems, transportation lines, communication systems, and physical structures. These systems are not static; flows of site reveal the temporal qualities of that place. And all these patterns, the underlying bones of place, mark the structure of our environment.

The process of marking the landscape through the design of its infrastructures is, in its essence, a creative practice, and its practitioners are civil and environmental engineers. The first step in a site design is the thoughtful study of that place and its spatial attributes, a practice that starts with map-making and the observation and documentation of a site's physical, social and perceptual networks. The knowledge and skills of design are integral to engineering site practices.

The practice of design, is rarely taught to engineers in early stages of their training. While there is increasing documentation of the importance and value, for industry, for young engineers to be both creative thinkers and innovators, and increasing agreement that such strategic skills must be taught in engineering schools (Baillie & Walker, 1998; Klukken et al., 1997), there remain reservations and limits to the practical process of integrating such unwieldy content into the already over-scheduled requirements of the engineering undergraduate (Baillie & Walker, 1998; Cropley & Cropley, 2000; O. Eris, Dym, Agogino, Frey, & Leifer, 2005).

Supportive teaching structures have developed for first or final year design courses, in which students practice idea generation and evaluation, idea sharing, team-work and concept critique based on user-needs, all of which are tied to creative design processes (Baillie, 2002; O. Eris et al., 2005). But the specific teaching, and practice of idea-generation techniques, while common in artistic fields such as music composition and dance, remain relatively rare in schools of engineering. Even as design-thinking practices emerge in a handful of engineering programs (Goldberg, Somerville, & Whitney, 2016; Plattner, 2012) such as Olin or the d-school, they remain little known in most departments of Civil and Environmental engineering (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2011; Klukken et al., 1997; Lande & Leifer, 2009).

Integrating design-thinking into other coursework may be a useful strategy. Not only is it more efficient to double-load teaching time by combining design teaching with technical GIS training but, perhaps surprisingly, also more successful. Mapping, as a context for teaching design to civil engineers, may have advantages over more independent ideation teaching techniques.

Design Creativity in Education

While early creativity literature focused on the personality traits of the creative individual, creativity education focuses rather on the characteristics of creative practice, and the processes which allow creativity to take place. Since Guilford, there is broad recognition for the notion that not only can individual creativity be improved, but as a skill, it can be taught and learnt (Finke, Ward, & Smith, 1996; Gowan, 1977; Guilford, 1973). Specific creative stages in engineering processes have been identified, moving from context study, idea incubation and cross-fertilization, to production processes. During the early phase of idea creation, a divergent or open thinking phase is contrasted with that of convergent, or critical assessment; idea development emerges from an iterative interchange between the two (Amabile, 1982; Ö. Eris & others, 2003; Sawyer, 2012; Treffinger, Young, Selby, & Shepardson, 2002) .

Engineers are accustomed to problem solving, and some familiar creativity techniques, such as TRIZ (Al′tshuller, 1996) build on creative approaches to such convergent thinking. The divergent process of problem finding may be less familiar. However Sawyer, Guilford et al. argue that 'divergent production' is a key process of creative thinking, and that, as in brainstorming, the production of a greater number, and wider variety of ideas leads to higher possibilities of an unexpected idea emerging (Guilford, 1984).

Attempts to measure increases in creative approaches towards an engineering problem are complex, and have spawned a range of tests and metrics, both of the creator and, following Amabile, of the product that ensues (Amabile, 1982), (Torrance, 1972).   Bringing together definitions from over 50 studies, Dean et al. extract an overarching consistency from such studies, in which creative work is measured using four scales where the originality or novelty of an idea must be balanced by its flexibility or workability, its relevance to the solution set, and its specific elaboration (Dean, Hender, Rodgers, & Santanen, 2006; Guilford, 1950; Shah, Smith, & Vargas-Hernandez, 2003).

In this study, however, we are less interested in the eventual creative product and more interested in the self-efficacy, or change in design confidence gained by student engineers through the workshop process. While the metrics described above may serve to uncover changes in creative qualities of consecutive designs, they will not necessarily reveal changes in a student's creative approach, their confidence in approaching open-ended work, or their self-perceived ability to engage in design. Unlike artists, engineers, and engineering students, tend to be more confident working in a deterministic process, in which a final target gives a direction, and limits uncertainties (Fantauzzacoffin, Rogers, & Bolter, 2011). Such an approach encourages early exclusion of divergent directions, and tends to lead not only to a narrower early set of design ideas, but also supports a tendency to select and stick-with an early stage idea, or design fixation. Criticism of the use of CAD as a design tool is precisely its tendency to support, rather than reduce, engineering students' propensity for idea fixation (Kramer, Daly, Yilmaz, & Seifert, 2014; Robertson & Radcliffe, 2009). This study, then, will explore creative practice from the point of view of the students themselves. Following the workshop's teaching experience do they approach design work with greater confidence? Are they more open to divergent approaches, and do their new skills and tools lead to any reduction in idea fixation?

GIS Mapping as the context for Design-Thinking

Spatial and visual explorations play a vital role in design; sketches and diagrams allow designers to visualize, abstract and manipulate their spatial processes (Buxton, 2007; Verstijnen, Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998). In a quick sketch, an idea can be captured, recorded, and remembered in a loose structure that remains open to re-interpretation and exploration. Critical of the lack of teaching of sketching skills, researchers have explored ways to introduce such diagrammatic tactics into engineering education (Booth, Taborda, Ramani, 2016; Ullman, Wood, & Craig, 1990; Yang, 2009).

Maps, we propose, can also function for designers as spatial and diagrammatic structures. Beyond its expressive visualization and communicative role, the map allows the designer to construct a simplification and abstraction of space, manipulating image and idea in the process of exploration (Corner, 1999). Like diagramming, map-making is a subtractive process, implying a fixation on one aspect of the world, be it roads, geology, or current (Glass & Wood, 1998; Wood & Fels, 1992). Through observing and marking, decisions are made of what is seen and what omitted. Strategic thinking is embedded in such work, an active thinking process which can serve as a design tactic.

Furthermore, the designer's engagement in two active processes of map-making, observation, and annotation, add additional value. Through careful observation and gathering of site data, the map-maker's own vision of the site and environment is broadened and often altered, allowing the development of a more divergent set of views (Cruz Prieto, 1993). Through mapping and visualization of apparent or hidden quantitative and qualitative site data possibilities emerge for moments of inspiration. But can engineering students learn to exploit and harness this by-product of the site visualization process and to uncover such inspiration in the diagrammatic phase of mapping, one which is often overshadowed in the path towards the map-product?

As a diagrammatic structure, a system that isolates and reveals only certain aspects of a reality, a map can serve as a tool for re-visioning and re-framing. Such conceptual processes of mapping have been identified by architects and landscape architects as valuable devices for creative agency and used to reveal abstract qualities of site, an uncovering that becomes a strategic tool enabling innovative approaches to spatial design (Corner, 1999; Eisenman, 1999). Yet such powerful process have not yet been similarly taken advantage of by engineers. Not only could engineers profit from such a creative tool; the process appears to give greatest support to early stages of creative thinking and to divergent thinking, those phases of creative research for which engineers traditionally have fewest models (Guilford, 1950, 1984; Liu & Schonwetter, 2004).

Finally, for engineering students, many of whom are more confident with technology than with visual exploration, the familiar systems-based structures of GIS may allow then to approach with greater daring than they might if exposed to design-thinking or even spatial mapping in a less structured laboratory environment (Overveld, Ahn, Reymen, & Ivashkov, 2003).

Tactical Tools for Design Exploration

Familiar to painters who develop techniques to confront the paralysis of Van Gogh's blank canvas (Vincent van Gogh, 1884), similarly dancers, musicians and writers develop strategic tools for stepping out into the creative process of composition. Sets of composition or design heuristics, gathered into a structured collection of approaches and process tools, and frequently packaged as a set of cards, are becoming somewhat familiar creative process tools. Precedents can be found in dance, for example, with Wayne McGregor's 'Mind and Movement Process' (Wayne McGregor, 2014), and in design where the d-school 'Bootcamp'(Thomas Both, Dave Baggereor, & et al., 2013, p.) has been shown to support the often frightening process of jumping into the unknown. Daly, Yilmaz, et al. have developed a large, encompassing set of design heuristic cards for the design context of mechanical engineering and have argued convincingly that such heuristic tools can assist engineering students with both design confidence and in developing divergent design solution sets (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Kramer et al., 2014).

Building on these models, over the course of three semesters, a deck of thirteen tactical geo-design cards was created by, and for, an engineering graduate course in GIS mapping and interdisciplinary research. Each card describes a strategy for using a GIS toolset or technique as a creative heuristic and illustrates that strategy with an example project completed by students in previous classes. The deck serves new students as a tactical set of possibilities helping to spark designers to reach towards an unfamiliar direction, giving clarity and confidence to their process and potentially widening their mapping design solution set. Introduced into the short context of the undergraduate workshop in this study, their primary intention was to serve as illustrations of GIS inspired creative site-mapping, but with some potential to inspire design exploration with spatial data-sets. Recognizing that their role clearly remained minor both in the workshop and this study, we were still interested to find out if the cards might, even in this context, assist students towards a broader range of mapping than otherwise imagined. While the role of the cards as design heuristic tools was neither fully explained, studied nor developed for these undergraduate students nevertheless they may have served as idea triggers towards a more divergent set of design possibilities.

The teaching model proposed, then, is the integration of design-thinking techniques into a GIS mapping workshop such that the teaching of divergent approaches, as well as the introduction of specific GIS-based design tactics, are wrapped within the framework of the spatial mapping exercise.

Research Focus

After a workshop focused on design process one would hope to uncover two independent, measurable results; first, that students show improvements in design confidence, in design approach and in strategic understandings which could be used in their own later work beyond this exercise. Secondly, independent of the student, one would also hope to be able to assess whether the creative quality of the post-workshop work itself is more successful. (Amabile, 1982) Isolating these two ambitions, this paper chooses to defer the second to a later study and focus primarily on the first, that of creative confidence and approach.

The experiment thus explores a skills-based outcome: is there any change in students' attitude and approach which impacts their confidence in undertaking creative design work? We seek to assess the impact of specific GIS spatial and site-specific practices on these outcomes. Less interested in the designed products themselves, this study focuses on changes in students' methods and approach uncovered through pre- and post-test surveys of their workshop experiences. How do they describe their motivation and apprehension? Do the words they use to describe their approach change?

Research Methods

Participants

A cluster sample was formed of 46 undergraduates from two different sequences of an introductory Civil and Environmental Engineering course. Although the sample is convenient it is also relevant as precisely the population whom the research intends to serve. Through the semester students had been exposed to connections between engineering and sustainability; transportation, urban water and the interaction between social, economic and technical solutions. Late semester a guest-taught workshop introduced sustainable site design through a hands-on exposure to geo-spatial data, digitizing and spatial analysis tools. The experiment was slipped into this workshop setting. Sampling bias was minimized by asking students about previous GIS or design exposure; while 11% of students (5) had some previous GIS none had design training. Of the 46 students who completed the experiment there was an equal ratio of men to women with 76% being 17 to 19 years old.

The workshop structure in which students were led through open-ended explorations of site meant that the GIS and creativity training were inextricable, with the mapping itself developed as part of the design experience. Any impact of the inherent spatial qualities of mapping on student creativity was thus inseparable from the explicit design-exploration built into the workshop. Further, since GIS was taught as part of all students' coursework there is no control group who did the post-test study without GIS training. These elements would be both interesting to attempt to isolate and explore further in order to uncover the extent to which spatial mapping alone, as well as the learning experience of test repetition, might impact post-test results.

Description of project and data collection methods

After an introduction to the project themes and consent process students were given a pre-test site design exercise. A local site was introduced through maps, images and a description of civic and civil issues. Students were given a base map and a set of site-planning building blocks drawn to scale including roads, structures, drainage systems, trees etc. and a stack of transparent paper and colored markers. After four minutes to 'investigate and think about ideas' the students had 35 minutes to draw site-plan ideas. Asked to 'do as many different design ideas for the site as you can in the time', 'write notes on the drawings', and 'move on to new ideas when you are ready', the exercise context was purposefully casual, accompanied by

Figure 5.1 Sample illustrations of site design exercises; pre-and post-test (front & back).

conversation and laughter. Afterwards, a one-page survey assessed student approach to the work and their confidence in their own design process.

The second session was a hands-on workshop structured around an introduction to ArcGIS and mapping. Using the same local site students were introduced to GIS data layering, attribute isolation, feature drawing, buffers and the inter-connectedness of spatial and social datasets. As part of their exploration students were introduced to the possibility of using GIS in their creative process and given a deck of 'geo-design cards'. These design-process cards, originally created for an upper-level GIS course, help students apply creative exploration tactics using GIS processes.

Although these undergraduate students would clearly master neither the use of the cards nor GIS in this short workshop, the intention was to expose them to tactical strategies in which GIS and mapping could be used creatively. Working in pairs students playfully explored both GIS and site design; they tested the use of at least one geo-design tactic and shared it in an open design review.

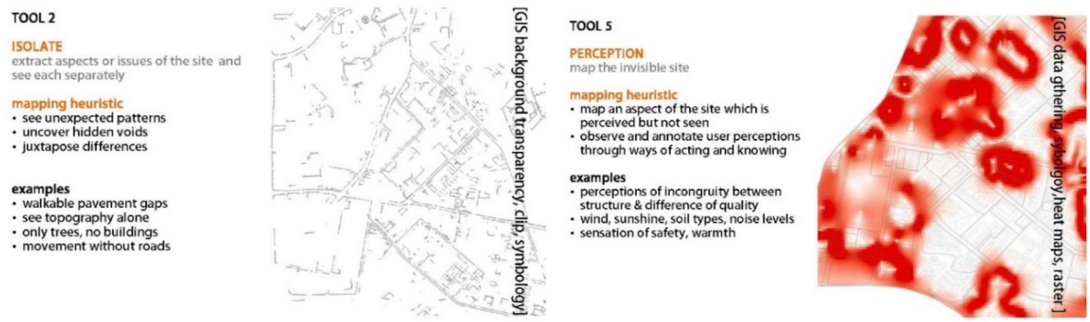


Figure 5.2 Sample illustrations of two geo-design cards

The post-test exercise at the third session was structured as the first, with a similar local site presented with context, history and, in this case, geo-spatial data. As before students were given paper site maps, the site-element set, and tracing-paper mapping tools. However they also had GIS laptop access to assist their exploration and a deck of 'geo-design cards'. Use of either was optional. The forty minute exercise was somewhat more structured than the pre-test, loosely developed from aspects of the d-school crash course model worksheets (Plattner, 2012) with the instructor encouraging casually timed segments. Similarly, additional process structure was provided; where before where before students had been asked to 'write notes' now they were offered optional 'design-process boxes' on the back of their map-sheets to fill out with observations and insights assisting their design reflection process. Most wrote at least a little in these boxes. (*see Figure 5.3*) A one-page survey again asked students for self-assessment of their confidence, approach, and requested information about their opinions and use of the tools.

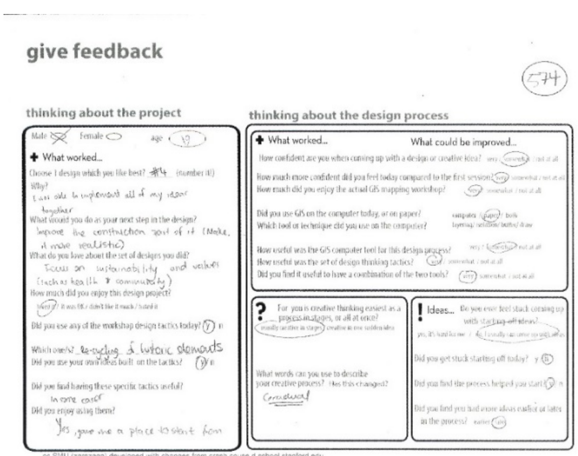


Figure 5.3 Sample of student survey responses

To sum up, three new site design tactics were introduced between pre and post-test. First, and with greatest time dedicated to it was the GIS, teaching spatial ways of working with site and community. Methods of working with GIS layering and isolation were introduced allowing students to re-visualize site issues in new diagrammatic ways. Secondly, at post-test, students were given some design-process structure in which pauses for re-thinking parameters might help them re-focus their impetus for design iteration. Although fully integrated into the exercise structure this methodology was not explicitly emphasized in the teaching process. Finally, students were given the set of 'geo-design cards', open ended heuristics for spatial design offering alternative ways to jump-start design ideas.

The total number of map drawings produced by each student was summed, both pre-and post-test. All other data was gathered through the two surveys. Beyond the simple nominal and Likert scale data gathered from student survey responses, data was also gathered from students' written responses to open questions about both their process and their projects. This data was coded into comparative thematic groupings which emerged from the qualitative text answers and the numbers of responses within similar thematic groups were compared, pre and post-test. Finally, responses to two questions were passed through Voyant, a web-based text-analysis tool, which allowed comparison of pre and post-test word use and frequency; extracted words were then related to the categorical groups.

Data Analysis & Discussion

Three specific aspects of design approach are analyzed. The first is any change in self-assessed creative confidence when approaching design work. Secondly we measure any increased value given, by the students, to idea evolution; that is, any move away from design fixation towards multiple divergent options. Finally, through self-assessment and text analysis, we attempt to uncover to what extent students have become more self-aware of their design process and of their own ability to manage it.

Creative Confidence

Students self-assessed their general, or overall design confidence consistently, retaining a solid level of 65% both pre and post-test, with only a small reduction post-test (from 7 to 4) in the number of students who reported no confidence at all. (*Figure 4a*) More suggestive was the confidence change students reported for ‘today’s workshop’. During ‘this specific design process’ those who felt at least somewhat confident increased from 62% to 79% post-test (17% change). While a low level of confidence in the first exercise might be partially explained due to lack of familiarity with this type of site planning exercise, even if we compare not to the 62% pre-test result but to the general 65% overall confidence level reported, we find a solid design-confidence improvement of 14%. This more modest result is interesting, since it reveals greater confidence in approaching the second site design the exercise based, presumably, on the GIS tools and mapping tactics even though no actual site design teaching had taken place.

One intention in introducing the GIS mapping was to assist students’ exploration and their ability to expand divergent design possibilities. Pre-test, a consistent 60% reported usually finding it hard to get started on creative work. However, when asked about ‘today’s’ post-workshop experience there was an 18% reduction (to 46%) in those who said they got stuck on preliminary ideas with 81% reporting that the new GIS mapping process helped them get started. (*Figure 4b*) Such an increase, regardless of design quality, is a vital stage leading to divergent processes.

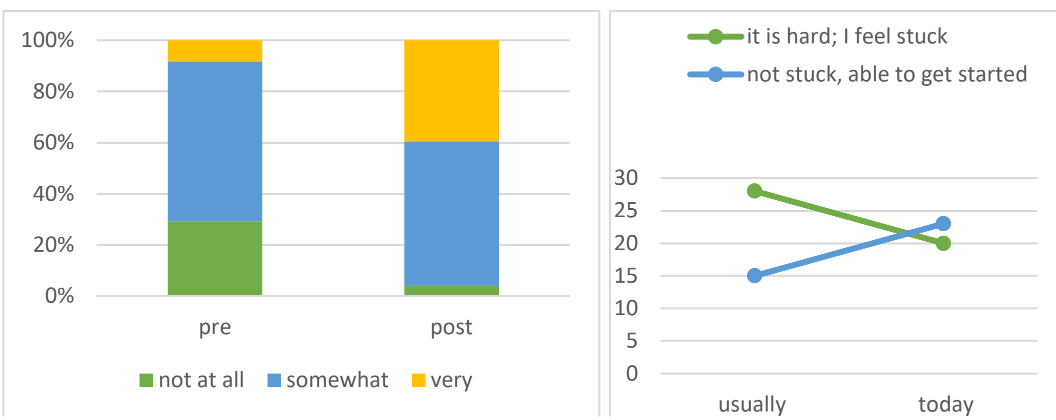


Figure 5.4 Students’ survey responses (a) on design confidence (b) to feeling ‘stuck in getting started’

Building on the idea of computational creativity support, it was hoped that technical comfort with the GIS system might assist student design confidence in addition to its primary role as a tool for assisting in open design exploration. Responses showed that even if they didn’t really enjoy the creativity exercise, fully 93% of the students quite enjoyed the GIS mapping confirming, at least, students’ level of digital comfort.

While pre-test explorations were drawn with layered maps on tracing paper, the GIS workshop introduced both analogue and digital technologies. In the final exercise students were invited to use both technologies to develop their design, submitting their final sketches on paper. Interestingly, 54% of the students did use the computer when given the option, a high percentage given the new tool's complexity. Although only 19% primarily used digital GIS to develop their ideas, another 35% combined digital and paper mapping processes. The system's greatest value seems to have been as a tool for re-visualizing; whereas only a fifth used the GIS to draw, two-thirds used layering or isolations tools.

Asked to assess the value of the different elements of their toolbox 21% of students found the digital GIS tools very useful to their process, (75% somewhat useful), and 23% ranked the 'design tactics cards' as useful (86% at least somewhat useful). Most powerfully 45% found the combination of both the design cards and GIS to be very useful in their design process, with 93% of the students reporting the combined set at least somewhat useful. It's interesting not only that the response was so positive but more that bringing the two tools together seems to have helped students find greater value than in either one separately. In the future, it would be valuable to redo this exercise with a wider range of control groups; while the cards cannot be used without GIS the map process could certainty be taught without the cards.

Of the thirteen cards, most students used the two which introduce methods to play with re-visualization; exposing unexpected site visions through manipulation of GIS layers. 67% said that they did find the cards at least somewhat fun to use. Interestingly, 70% found the card tactics open enough that they added their own process ideas to those discovered in the cards.

Design Fixation or Idea Evolution

An average of 3.92 site design maps were drawn by each student post-test, compared to 1.60 pre-test. (*Figure 5*) This result that appears to powerfully confirm students' move away from design fixation, however, it must be taken cautiously. Although in both cases students were asked to "draw as many ideas as you can", in the post-test exercise students were offered more design-thinking structure as they worked. They were invited to pause, think through issues and return to drawing. This imposed framework, although

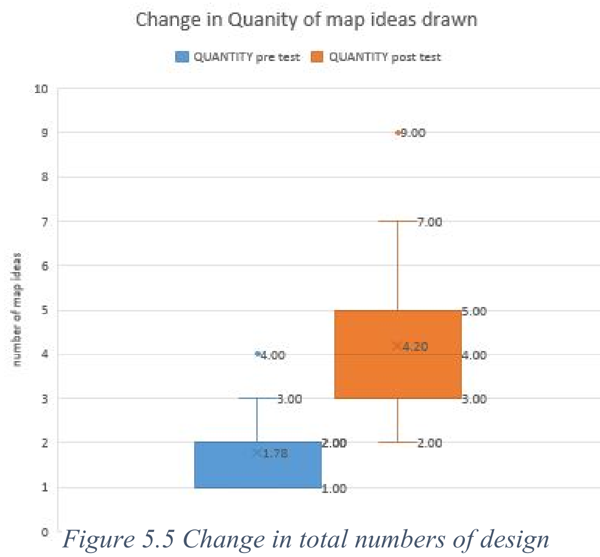


Figure 5.5 Change in total numbers of design ideas drawn by each student pre & post test

optional, may have influenced their creative pace and be credited for some of the post-test change in quantity.

More interesting, perhaps, is the design evolution that students appear to have integrated into this process. Beyond creating more designs, students started to experiment and, moreover, to give value to their experimentation process. In pre-test, 81% (39) described their first effort as their favorite design; by post-test only 23% liked their first or even second design best (5 preferred 1st, 6, 2nd). The biggest group (63%) now preferred their 3rd or 4th drawing, (13 liked 3rd, and 17, 4th) and a small group (11%) liked one even later in the process.

Looking deeper, when asked why that design was their favorite, post-test answers show, for some, a change in attitude focused on the site design less as a solution to a problem and more as an exploration of ideas. Pre-test, (for those with more than one map) favorite designs were selected for three reasons. Most enjoyed the way their site design responded to environmental quality: 36% (15) focused on open space: “I put in more landscape in a very urban area” and “bike path creates community attraction to exercise in a good environment”; while 12% (5) prioritized community. Another 17% focused on measurable issues such as organization, or drainage. “I was able to introduce an appropriate green to grey ratio in terms of houses and open areas”. Voyant text-mining [42] reveals that pre-test, students’ comments focused on site qualities, the highest frequency word extracted from the response text files being ‘park’, followed by ‘community’, ‘green’ and ‘pond”.

Post-test, however, a new primary category of response emerged revealing students’ new awareness of design as a process leading to multiple solutions, in which 38% of students (as opposed to 10%) now gave value to a range of site design proposals, and posed one as a preferred rather than an ideal solution. Of their favorite design students wrote, “the most complete drawing, [it] incorporates most of my ideas”, or “it has more ideas, several that carried over from earlier designs.” Thus even when selecting favorites we find new awareness of the rich potential of combining ideas into alternate visions. While half the students retained a tangible focus (26% on the environment, 14% on technical solutions, and a slight increase to 17% on community) the powerful change was this new focus on the abstractions of design and form. Text-mining confirms this greater focus on process; when submitted for analysis, the word ‘ideas’ was extracted as the most frequent, followed by ‘incorporates’, a word intriguingly linked to the GIS concept of overlapping layers.

In pre-test descriptions of their creative process, many were unsettled; “never done [this] before and not sure if any design could actually work”, and very few mentioned time as part of their creative process. Four actually wrote they were not creative. Pre-test 30% (14 students) described their creative process as a single intuitive moment: “Hope a cool idea just comes to me”, or “sometimes good, sometimes not”. 65% identified their most creative moment as their first sketch.

Not only did GIS mapping processes help them get started but responses made clear that student thinking about their creative approach was affected by the workshop. Some revealed struggles; their process was “forced, difficult” or “needs improvement”. For others, new notions had emerged; creative work was “a bit more fast paced” or “random, because what I'm inspired by changes each time” and even, “browsing, random, trying things; this has changed!” Powerfully, 23 students (48%) now included the issue of time and design-development in their post-test descriptions, an increase of 17%, writing “it takes several times to get a solid idea” and “come up with an idea and then build off that until more ideas pop-up”. Some even referred to the training, “it is hard to make up designs, the toolbox is helpful”, and, “I start with analyzing present physical features then build around”. Only 21% (10) reported that their design process had not changed at all.

Several described changes to their structure: “process has changed a little bit, most ideas at first, then slowly build” and “step by step, yes, it has changed”. Others referred to particular tactics taught: “Yes. The tools help you come up with new ideas as your design progresses", or "browsing, random, trying, yes, this has changed." In a beautiful description, one student wrote: the process is "abundant, and has changed to be more logical with respect to design and mapping". Post-test, when asked about idea development, fully 73% reported having more ideas later in the process, revealing a clear move away from design fixation towards idea development. It appears that at least some aspects of the new multiple tool-set: the GIS techniques, the design cards and a measured process, clearly assisted students to expand creative explorations.

Self-awareness of process

When asked what they 'loved' about their set of project designs pre-test student response focused overwhelmingly on tangible content, specifically the design's connection to nature. Ecological issues excited 66% (23) of those who responded. [I loved] "all the parks!! and "I want to live by the pond". Only

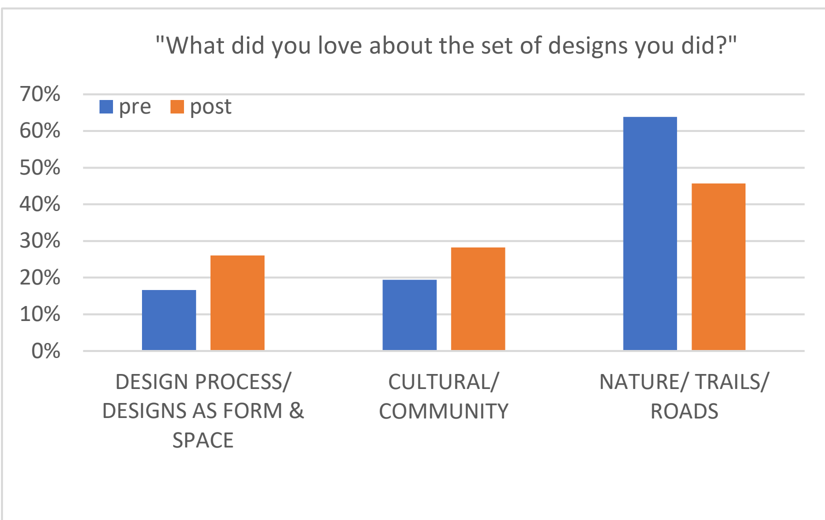


Figure 5.6 Pre and post-test response to 'what did you love about the designs"

14% (5) focused on the creative design challenge itself. "I like that everything is included in one drawing" "They are my own ideas and there were no boundaries. I can design anything".

We were interested in assessing whether the GIS based teaching model might help students become more aware of their own control of the design process. Such self- awareness could impact their approach to future design efforts even beyond the specifics of this exercise.

Attention to nature and water did retain the majority of students' primary interest post-test, focused on "the big green recreational parks & pavilions, the bike trails were pretty cool too", and "the use of water as a feature". However the proportion who responded thus was reduced from 66% to 46%, with a slight increase in focused on human-centered issues (28% up from 20%). Most interesting in terms of this study, however, was the post-test increase in the proportion of students who, when asked what they 'loved', now chose to describe spatial or methodological aspects of their design-process. While remaining the smallest group overall, an increased 26% (from 14%) of students described "the wide variety of ideas and unlimited amounts of generators [I was] able to produce", and that "[my designs] give the same goals with different layouts"

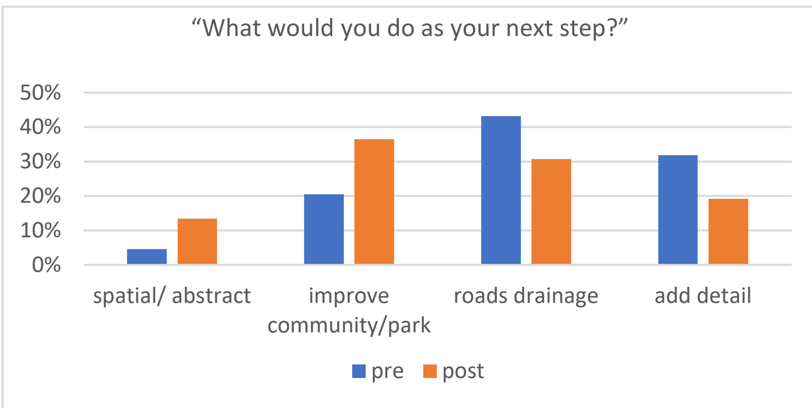


Figure 5.7 Pre and post-test responses to: "What would you do as your next step?"

A comparison between pre and post-test responses to a question about the 'next step' they would take, provides a similarly revealing illustration of change in design-process thinking. Nervous about stepping into open-ended design pre-test, many students proposed a swift move into more familiar technical aspects of their project. The majority, 73%, proposed "after this rough design I would calculate materials needed & find proper drainage patterns", "design drainage systems" and, "see if my idea made sense with the environment and was possible". *(see Figure 3.7*)

Although still focused on technical development as a logical next step post-test student visions reveal a more process-oriented state: "I 'd relate infrastructure like roads, water, management" or "I would include drainage systems, schools and roads"; a layered description of structure perhaps influenced by GIS. A slightly greater focus on human-centered issues such as "plan out how it would best fit with the existing community", reveals a more holistic site approach. However the tendency towards abstraction is most powerfully confirmed in the increase from 4% to 13% in the number who proposed 'next steps' in strict design terms, wanting to "[add] something in the right side", "rearrange structures/ design to use space better", and "try to bring all the ideas together". Voyant text-analysis (Sinclair, Stéfan & Rockwell, 2016) finds that while words related to the development of water and roads remain primary in the both pre and post-test descriptions, heightened awareness of the inter-relatedness of issues is revealed through the post-test frequency of words like 'community' and 'systems', understandings which may have emerged through the layering of diverse data sets as well as new design processes.

Conclusion

Design confidence

Open-ended design can be a leap into the unknown for engineering students. One way to make this leap less daunting is to help students become familiar, early in their educational experience, with strategies and tactics to support creative processes. Practicing site design gives students an opportunity to work through such strategies at the same time as they explore ways in which the development patterns of infrastructure networks impact the design framework of an urban proposal.

Creative thinking in GIS itself has mostly taken place within the context of the specific creative map-product. Kwan's groundbreaking geographic work on qualitative GIS and, within engineering, visual exploration of dynamic time-space interactions have begun to stretch GIS mapping possibilities (Kwan, 2009; Shaw & Xin, 2003). However these explorations have not yet been exploited for the creative potential they might bring to exploratory processes beyond map making. Researchers in the digital humanities, such as Travis, have started to explore GIS's potential to suggest unexpected directions; however, such processes remain firmly literary not straying into spatial design (Travis, 2015). Most critically, few of such explorations have made their way into engineering or civil site design. This is perhaps surprising given engineering students' confidence with computing technology. Certainly digital creativity support tools have been studied extensively in the context of game design and computation (Schneiderman, 2007), however there has been little exploration, beyond some studies of graphic capabilities of CAD, of the potential for digital spatial systems to serve as support tools for creative thinking in civil and environmental engineering.

In this teaching model both digital and analogue GIS mapping were brought into the laboratory as tools. They were additional tactics not just for map-making but for design exploration. Familiar in the context of computational creativity support, the role of the technical tool is not only to open up creative exploration but, in its technological familiarity, to support students on the path towards design confidence. Although our students' self-assessment of their long-term creative confidence didn't change, they did report having developed greater confidence in approaching this particular kind of site design process. Such a result, of course, could be biased due to the duplication of the exercise post-test. A further control group, while educationally difficult to arrange, could help clarify this.

However, if we take the notion of no longer 'getting stuck' at a project's start as a confidence measure then the results are more powerful. Survey evidence confirms that the availability and use of new tools for divergent exploration, the GIS mapping and the design cards, increased student confidence in creating 'starting-off' ideas by 18%. This finding is particularly important because the wider exploration of divergent concepts can be the first invaluable step in developing more creative solution sets, and a step that is difficult for engineering students who tend to have been better trained in convergent, critical analysis.

Because students were given three new tools to assist them in their site design process it is difficult to assess the independent value of the parts. The primary focus of the workshop was, of course, the GIS mapping itself and the layered spatial thinking which emerges from its use. Both the workshop timing process and the geo-cards were developed as secondary teaching tools to help students strategically better access the GIS as a creative tool. Neither the design process nor the cards can be used without the GIS mapping. At the very least, with the help of these crutches, evidence shows that GIS mapping used tactically can indeed allow engineering students an improved degree of design confidence. Supporting this statement is the evidence from students' value assessments; almost all students found the GIS, the geo-cards and most especially, the combined set of tools, to be useful in their creative exploration.

Design fixation

Evidence of increased idea iteration confirms that the GIS workshop tactics did impact student design processes. Certainly, we must be cautious of giving too much credence to merely increased numbers of site designs produced. Student responses, however, support the claim that the process taught students to generate not only more, but more thoughtful collections of solution sets. Design fixation evident pre-test in which 81% preferred their first effort, was clearly overridden by the more than 68% who, post-test, were instead delighted by their 3^{rd}, 4^{th} or later iteration. Such a finding might be even more valuable longer term, if student confidence were found to grow further once iteration is practiced. Another future impact of such reduction might be quicker starts: first ideas are less daunting if they aren't expected to be the right answer. Finally, their comfort level with technology may explain, to some extent, the high 81% who reported that the GIS mapping process helped in this struggle to get started. Rather than criticizing students' reliance on technology this methodology reveals an opportunity to exploit it.

Self-awareness of process

While unable to contribute to research into student idea development beyond primary ideation, this study does explore the potential for students to begin to become self-aware of their own design process, a vital cognitive step in design-thinking. Stepping outside a narrow focus on numbers of ideas we attempt to evaluate broader impacts on students' developing abilities to question their work and their processes (Ö. Eris, 2004). Not only did students become aware and give greater value to the iterative, 'browsing' nature of design but they began to move away from site-based design descriptions to more process-based discourses. While the total number of students who had taken this step towards abstraction was small, post-test evidence seems to show a tendency towards broader spatial design aims. It would be very interesting to follow up on the extent to which the spatial qualities of GIS play a role in this change. Can the shift from site-specific ideas to more abstract notions of idea transformation be facilitated by the spatial nature of the GIS framework and its tendency towards abstraction through layering? The place-based abstraction of a GIS map may be helpful for engineering students in the extent to which it remains tangibly grounded to site and data while at the same time allowing transformative idea exploration.

Limitations and Future Work

The short nature of the workshop severely limited this study. Not only was the GIS skill level obtained very minor but even student familiarity with the site design process was low, given that they were in early stages of their engineering degree. This population had been purposefully selected in order to test the value of this methodology as an introduction to design-processes for early stages in the engineering curriculum. However, such a population also gives limits to the results. It would be interesting to test student responses were these same tools to be introduced to, say, final year civil engineering students, or to those with GIS expertise but little design experience.

This paper chooses to focus specifically on the extent to which certain tools and teaching methodologies allowed students to improve specific design skills including design confidence, openness to iterative practices and self-understanding of their design process. What the study has not tested is the effect that these processes and tools had on the design work itself, or any outcome showing improvement upon the ensuing site design project. It also did not test the possibility for using such tools in a collaborative design environment, another aspect of student learning which has been shown to support creative practice. Both of these issues would be worth following up in future research.

In more conceptual terms, a powerful aspect of GIS and mapping and, indeed, of several of the geo-design cards is the extent to which GIS may be able to assist students to undertake creative exploration through an abstraction of the social and civic ideas and data they have uncovered, by taking such tangible structures into the realm of spatial transformation. It would be really interesting to further explore this aspect of spatial abstraction and to uncover the extent to which student designers might be able to conceptually separate spatial explorations from the specifics of actual site plans. One can imagine that it could be precisely the potential of spatial abstraction of non-visual site data that could give mapping, like diagraming, an increasingly powerful role on the path to more creative, divergent idea sets. An analysis of these kinds of exploratory design processes, however, would require a more detailed focus on specific steps, ambitions and tools used by individual designers, and a longer, narrower qualitative study of the ways in which student designers can navigate the spatial design process.

Chapter 6

Evaluating Geo-Spatial Mapping as a tactic for Creativity and Generative Design in Engineering Education

Working from data gathered from the same set of experiments as the previous study, this paper seeks to focus attention on the actual project outcome as revealed in the mapped results themselves. Attempting to measure any change in creative outcome of the pre and post-test product this paper seeks to assess creativity using a qualitative methodology. The measurement system for this study is based on precedents from similar studies in engineering education, however with adaptations to allow the object of measure to be a map-design. The outcome of the study is a series of statistical results of the variables associated with creativity measures, compared for the pre-and post-test maps.

This paper was submitted to the ASEE 'Journal of Engineering Education' on 12 December 2018, and is under review by the Journal's editors. Manuscript number JEE-2018-0315

Structured Abstract
Background
The teaching of creative thinking and generative design processes must be added into an already dense civil and environmental engineering curriculum. A potential solution is to integrate such training with geo-spatial (GIS) mapping in support of infrastructure site-design.

Purpose/Hypothesis
This study will evaluate the efficacy of geo-spatial mapping as a generative site-design tool for civil and environmental engineering students and asks whether students produce more creative outcomes after exposure to design methodologies integrated into a GIS workshop.

Design/Method
Undergraduate engineering students participate in a spatial-mapping workshop in which layered data systems are introduced in the context of site design, creative exploration and generative processes. Map data from pre-test and post-test design exercises is assessed for change in design creativity, defined as *quantity, variety, novelty and quality*.

Results
Both *quantity* and *variety* increase over the workshop. Average *novelty* shows modest increase, while measures of *quality* reveal an increase in *relevance*, a small increase in *vision*, and no change in *specificity*.

Conclusions
Applying creativity tactics to a technically based spatial-mapping project seems to have assisted engineering students to quickly access generative strategies and to integrate them into site-design approaches. While the increases in *quantity*, and to a lesser extent *variety*, may be argued to reveal training specificity, increases in *novelty, relevance* and *vision* reveal the added value of the geo-spatial exploratory context and support its integration into design-teaching for the development of more creative future engineers.

Keywords:

geo-spatial data, mapping, creativity, generative design, design pedagogy, GIS, landscape

Introduction and background

Increasing demand for the intangible but evident skills of innovation and creativity within the engineering profession has energized universities to investigate and support the development of specific training for engineering students in design thinking and creativity (Baillie, 2002). ABET, the academic engineering education accreditation body, defines the necessity for engineering students to gain 'an ability to apply creativity in the design of systems, components, or processes' as one of the key skills which engineering and applied science programs must teach for the program to receive engineering accreditation (ABET, 2015). However methods for both teaching and assessing creativity in engineering education remain complex, contentious and uncertain (Treffinger, Young, Selby, & Shepardson, 2002).

Long studied as a personality characteristic and an inborn natural ability, creativity cognition has broadly been re-assessed as a skill which is both learnable and teachable (Sawyer, 2012). Divergent production of multiple ideas is defined, in the componential theory of creativity, as the generative phase of creative thinking, a process which increases the range of the outcome set supported by intrinsic motivation and exploration. Early stage generative processes include association, mental transformation and analogical transfer, often followed in cognitive studies by additional exploratory processes such as context shifting and functional inference, creative actions which impact the breadth of idea generation (Finke, Ward, & Smith, 1996; Gowan, 1977; Sawyer, 2012; Sternberg, 2006). This phase is followed by a convergent phase of intellectual criticism, usually within the limits of a domain of study (Amabile, 1982; Guilford, 1973, 1984; Sawyer, 2012). The iterative interaction between generative and exploratory processes develops under the pressure of external problem constraints (Cross, 2004; Finke et al., 1996).

Traditional engineering education excels at training students in the essential critical and evaluative processes of convergent thinking. However it often falls short in its ability to develop students' skills and confidence in the divergent phase, and few engineering instructors know how to teach specific generative teaching practices. (Baillie & Walker, 1998; Cropley & Cropley, 2000; O. Eris, Dym, Agogino, Frey, & Leifer, 2005). On the other hand, especially for engineering students, it appears that creativity training is most useful when it is specific with clear strategies to assist students in developing preliminary concepts

(Ahmed, Wallace, & Blessing, 2003; Daly, Mosyjowski, & Seifert, 2014). The focus of creativity research in engineering education has often been framed as a search for, or assessment of, specific cognition training techniques, such as Osborn's 'brainstorming', method 634, the Delphi methods, TRIZ, Synectics and others (Al′tshuller, 1996; Finke et al., 1996; Osborn, 1963; Pahl & Beitz, 1996). Such tactical approaches, however, best function within an academic atmosphere that also gives space to open-ended questioning, repetition and practice. (Baillie & Walker, 1998; Felder, 1988). Structural stimulators to creative work include a classroom framework of metacognition or self-analysis, risk encouragement and both project based teaching and team interaction (Cropley & Cropley, 2000; Fontenot, Canales, & Quicksall, 2014; Fosmire, Johnson, & Mentzer, 2016). While such contextual changes to the academic environment may allow for creative work they are similarly shown to be more effective when integrated with strategic ideation training (Ö. Eris, 2004; O. Eris et al., 2005), but finding time for such specific creativity training in the demanding undergraduate engineering curriculum, is challenging. Ideally, the teaching of ideation tactics could be integrated into other aspects of engineering teaching that simultaneously serve additional curricular or analytical processes.

Alongside the development of new strategies to teach creative processes in engineering rides a parallel need for precise creative skill assessment techniques (Mumford, Scott, & Leritz, 2004). If such assessments are to have quantitative rigor, specific creative aspects of student outcomes must be identified, isolated and measured with great specificity (Mansfield, Busse, & Krepelka, 1978).

Early tests, such as the Purdue Creativity Test of 1960, were designed to identify the relative creativity of the individual test-taker. Torrance *Tests of Creative Thinking* (Torrance, 1972) moved the focus towards measuring processes of divergent thinking. Similar to the CEDA (Creative Engineering Design Assessment) (Charyton & Merrill, 2009) it compared each individual's ability to perform within an experimental setting through assessing a range of outcomes from submitted student work. The CEDA measured three aspects of creativity: *Originality*, how new the ideas are, *Fluency*, numbers of ideas, and *Flexibility*, a measure of different idea types, to which the revised CEDA (2011) additionally added the measure of *Usefulness* (Charyton, Jagacinski, Merrill, Clifton, & DeDios, 2011). Building on these early standards, powerfully but somewhat bewilderingly, multiple qualitative and quantitative tools for the assessment of creativity in engineering education have been developed, discussed, shared and themselves assessed. (Charyton et al., 2011; Charyton & Merrill, 2009; Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Dean, Hender, Rodgers, & Santanen, 2006; Gerhart & Carpenter, 2012; Liikkanen, Hämäläinen, Häggman, Björklund, & Koskinen, 2011; Shah, 1998; Shah, Kulkarni, & Vargas-Hernandez, 2000; Shah, Smith, & Vargas-Hernandez, 2003; Vargas-Hernandez, Shah, & Smith, 2010).

Starting with Amabile's consensual definition of creativity as an attribute of the product as assessed by domain specialists (Amabile, 1982) this study first chooses to eliminate those measurement systems designed to assess traits of the individual and focuses instead on systems that intend to measure quantitative change in the work itself. We focus particularly on those precedents that attempt to assess visual outcomes of creative work using sketches and diagrams as primary assessment data.

A primary model for the assessment tool we developed for this study was the Shah-Vargas 'measures for ideation effectiveness' (Shah et al., 2003) which focuses on outcome based assessments specifically for the generative phase of creative ideation in engineering education. It seeks to assess the extent to which creative thinking both 'expands' the design space (generative thinking) and 'explores' the design space (deepening thinking) (Shah et al., 2003). Of particular value to this study, the model is based on the assessment of sketches as well as annotative notes, although developed originally for projects in mechanical engineering design. The Shah-Vargas model develops four rigorously defined measurement variables, *Quantity* and *Variety* (parallel to the traditional CEDA traits *Fluency* and *Flexibility*) which measure aspects of the set of each student outcomes; and *Novelty* and *Quality* which must be measured for an individual design attempt (Shah et al., 2000, 2003).

Without standardization in measurement systems it is hard for studies to build on each other. Undertaking the mammoth task of creating some order from the broad range of studies working to assess creativity in engineering education, Dean et al. (Dean et al., 2006) brought together 90 creativity studies with the intent to extract a common language of understanding. Using an action-research approach they categorized various assessment strategies attempting to regularize terms used, compare measurement strategies and find consistency in the literature. Focused on the variables which measure individual ideas rather than groups of works, the authors found that *Novelty*, (related to CEDA *Originality*) was similarly structured in many studies. However the attributes of their other primary measure, *Quality,* tended to range very widely in terms of vocabulary, measurability and intention. Building a database of scales, Dean et al. (Dean et al., 2006) avoided the term *Quality* altogether, moving towards narrower definitions of its internal aspects such as *vision, relevance, specificity, effectiveness* and *implementability*. In the development of a fine-grained and domain-specific assessment structure for *Quality* for our study we brought together aspects of the vocabulary built by Dean et al. with insights from other precedents including Liikkanen et al. (2011) who assess ideation based on *Quantity and Novelty* but bring in an additional variable, *Feasibility*, as well as further aspects from the rigorous assessment approaches of Daly, Linsey and others (Daly et al., 2012; Linsey et al., 2011).

Shah-Vargas takes pains not to combine creativity metrics into an overall score suggesting that any creativity tool being studied is of value if it can be shown to improve even one of the measures (Shah et al., 2000, 2003). Although they argue that *Novelty* and *Quality* are more important long term metrics and unfortunately perhaps those less impacted by short term design exercises, they also point out that these two can be seen as results that build on the success of *Quantity* and *Variety*, the first two simpler process related outcomes (Vargas-Hernandez et al., 2010).

Research Focus

An ever more densely inhabited world requires that infrastructure solutions be integrated within a sustainable and resilient design vision, a task that requires both technical competence and creativity (Lucena & Schneider, 2008; Morris, Childs, & Hamilton, 2007). Long before architects come on board, environmental and civil networks frame the underlying orders of the built environment, yet while responsible for its primary patterns, engineers are not taught to design it. Bringing together social and environmental data into a single spatial context, GIS allows engineers to efficiently integrate, visualize and analyze site data through layered digital mapping (Cardenas, Kelley, & Roberts, 2013) an effort which furthermore aids in the envisioning of more integrated, sustainable infrastructures. In engineering, the teaching of geo-spatial data skills have thus begun to move beyond visualization towards interdisciplinary analysis, bringing together ecological, social and increasingly complex spatio-temporal exploration (Ivey, Best, Camp, & Palazolo, 2012; Kwan, 2004, 2009; Shaw & Xin, 2003). The spatial intelligence of a Geographic Information System model (GIS) allows the exploration of logical and theoretical connections between phenomenon, data and a specific site providing a domain for theorizing and, potentially, for creative exploration (Pavlovskaya, 2006; Travis, 2015).

This paper explores the possibility that the conceptual reformulation of an engineering problem within the layered GIS mapping environment might have cognitive value for engineering education as a catalyst for creative practices beyond the analysis role of the map. Outside of engineering, geo-spatial mapping systems have already been used as creative structures to actively facilitate exploratory spatial investigation (Peuquet & Kraak, 2002; Raumer & Stokman, 2014; Corner, 1999). Including design ideation processes within the teaching of a digital mapping skill-set would thus allow engineering students to develop technical, spatial and creativity skills within the efficient framework of a single course structure. In order to justify such a proposal, however, two questions must be posed: Can civil and environmental engineering students can be taught to exploit geo-spatial mapping as a tool for creativity, and does it have real efficacy in this context as a tactical tool for the generative phase of creative ideation?

To examine its potential as a catalyst for creative exploration we assess the degree to which preliminary exposure to GIS mapping through an introductory workshop, along with some specific training in its use as tool for generative thinking, can be shown to increase creativity in students' site-design outcomes. The study focuses on the creative potential of spatial mapping for civil and environmental student-designers in the generative and exploratory stages of ideation. Although it is likely to also impact later stages of creativity it may be hard to separate mapping's impact on the critical or evaluative stages of creative outcomes from the broader impact of teamwork, site-based learning and other learning inputs. This study thus evaluates only the extent to which first phase ideation process outcomes have been significantly impacted through a quick exploration of spatial data practices. The experimental design approach (DOE) of this study follows that recommended to facilitate a scientific understanding of the effectiveness of a new idea-generation teaching method (Shah et al., 2000; Linsey et al., 2011).

Research Methods

A cluster sample was formed of 46 first year students enrolled in two consecutive offerings of an introductory Civil and Environmental Engineering course. Likelihood for sampling bias is minimized by asking about previous related exposure; only 11% had some GIS exposure and none had studied design. Half of the students were female and most were 17-19 years old.

The late-semester study took place during a GIS mapping workshop taught as part of students' coursework. All were exposed to the same spatial training, and the design-approach practices were fully integrated into the technical aspects of the workshop. The lack of a control group meant that any inherent spatial insights a student might develop in the use of the GIS process itself cannot be separated from the explicit design teaching received, something which would be interesting, if difficult, to try to isolate in future studies. In this quasi-experimental pre-test post-test study the three hour workshop in which students were exposed to digital GIS mapping techniques and some divergent design thinking was sandwiched between parallel pre- and post-test site-design exercises taken under matching circumstances.

After an introduction to the themes and a consent process, students were introduced to the pre-test site-design context through maps, site images and a description of social and community issues. Given a base-map, a series of building-block site-design elements drawn to scale, and a ream of transparent paper and colored markers, students had four minutes to 'investigate and think about ideas' followed by 36 minutes to draw site-plan ideas *(figure 6.1)*. Written and verbal instructions suggested students 'do as many different design ideas for the site as you can in the time', 'write notes on the drawings', and 'move on to new ideas

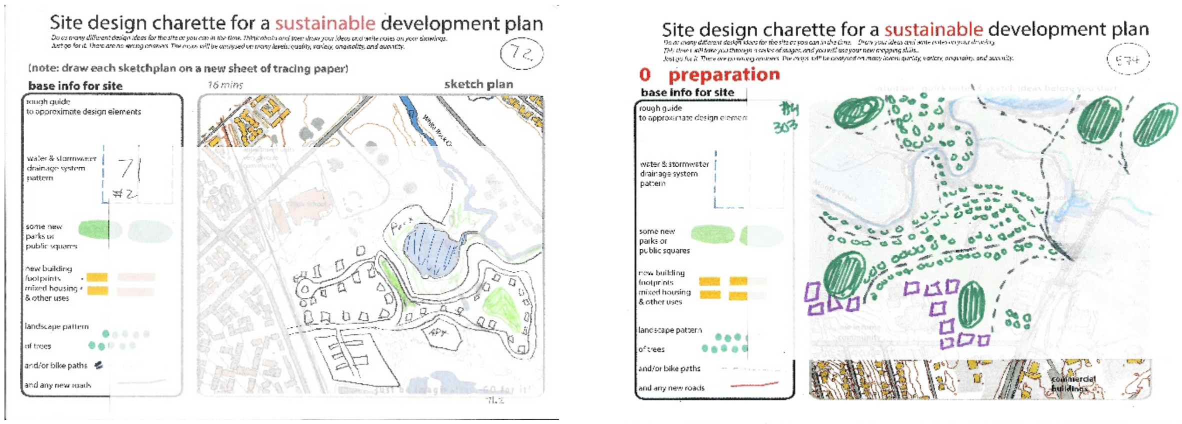


Figure 6.1 Sample pre and post test site-design student sketch maps

when you are ready'. The classroom context was kept purposefully casual to encourage open-ended work rather than a focus on correct solutions, and the work was accompanied by conversation, background music and laughter. Afterwards, a one page survey assessed student attitudes to approach and design confidence. All submissions were anonymous.

In smaller groups over the week, students then attended a three hour workshop on basic geo-spatial mapping skills with ArcGIS online, a web-based software. Using the site-data from the location presented in their pre-test exercise, they were introduced to spatial data layering, attribute isolation, feature drawing, buffering, and to the notion of the inter-connectedness of spatial and social datasets.

As part of their lab students were introduced to the idea that geo-spatial mapping could play a role in the creative process and were offered the chance to play with a deck of 'geo-design cards' *(figure 6.2)*. Building on examples illustrated on the geo-design cards they were shown how spatial strategies could be used to help generate and explore site-design options. The geo-design process cards, originally created for an upper-level GIS course, are a set of illustrated design-process heuristics designed to help students apply creative exploration tactics using GIS processes. The cards had been developed as a set of teaching tools to help graduate-students translate from the practical to the theoretical stages of experimental creative spatial-mapping processes, as a set of spatially focused heuristics (Daly et al., 2012). Each of the dozen tactical cards contains a site design strategy, written examples, suggestions of which specific tools from the GIS analysis toolbox could be used to undertake such a process, and a visual example illustrating the process

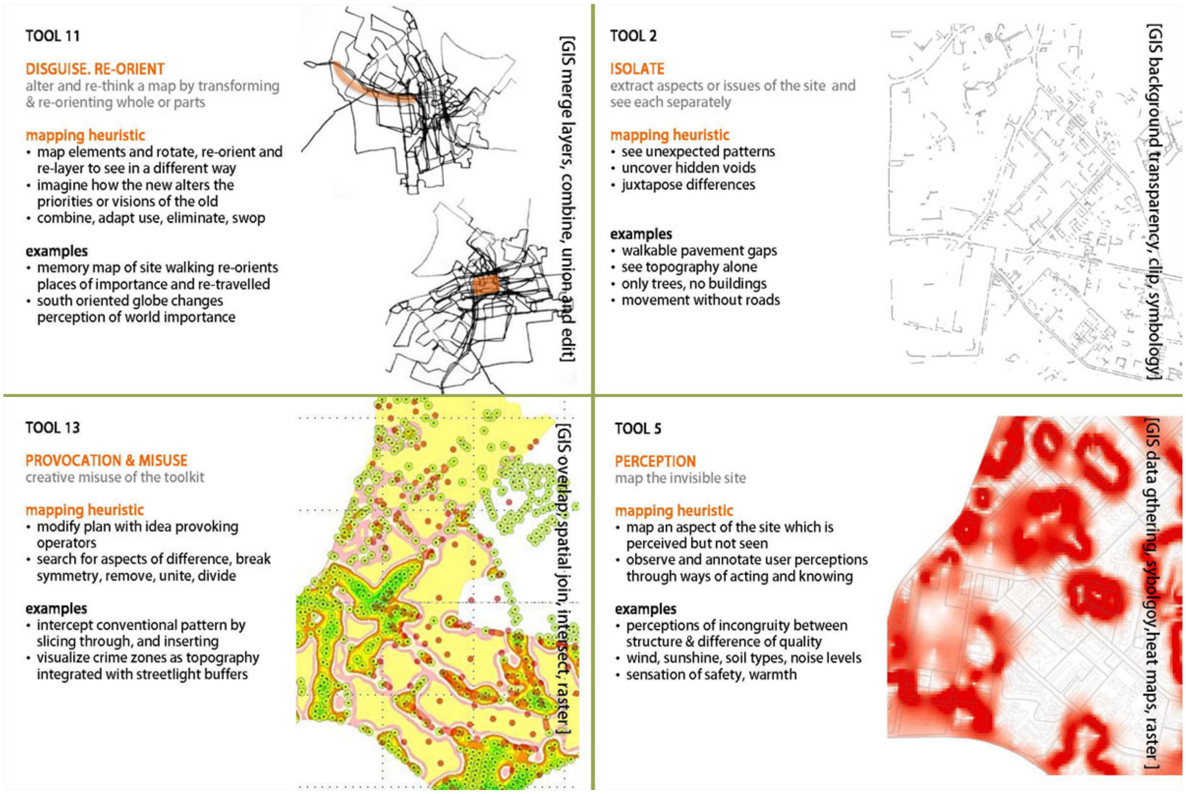


Figure 6.2   Sample illustrations of geo-design cards

impact. The tactics are combined into a deck and were offered to these undergraduate students quite casually, as optional sample approaches that might jump-start them in their design exploration.

During the workshop student pairs were invited to playfully explore, and share, tactical strategies for site-design using at least one of the design cards. Students were not, however, taught specifically how to use any of the particular site-design strategies nor were they given any further site-design training. Although the undergraduate students taking the workshop would clearly master neither the use of the cards nor GIS itself in this short exercise, the intention was to test whether even this short exposure to a creative approach in the use of spatial data and mapping could effectively provide a path to a more divergent and creative set of project-outcomes.

The post-test exercise was structured as the first but with a different local site. As before students were given maps, site photos and a verbal description of the social and historical context. Again they were given a paper base-map, tracing paper sheets and colored markers and asked to draw their site-design strategies as

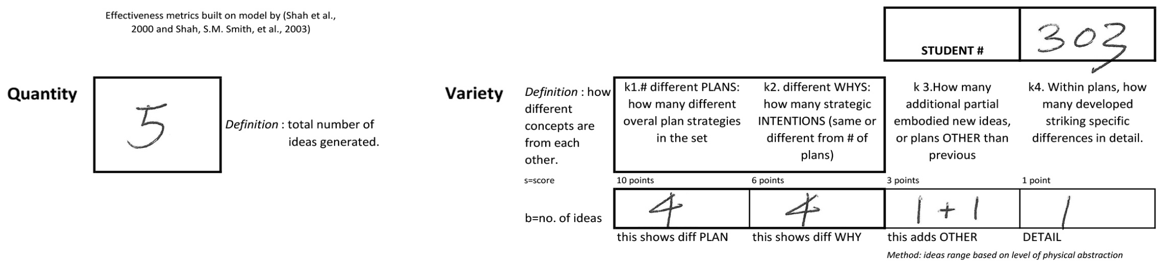


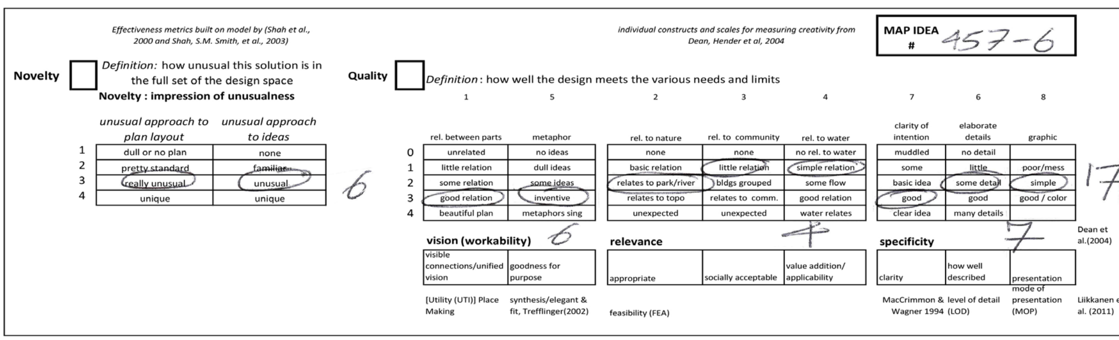
Figure 6.3 Sample of completed assessment for Quantity and Variety

analogue rather than digital mapping studies *(figure 6.1)*. In this case, however, students were also given access to online GIS on their laptops and several local geo-spatial site data layers including structures, transportation layouts, water-distribution networks, and site contours. Use of the computer and digital data for exploration was optional and the final submission was again made on paper. The forty-minute process was slightly more structured than pre-test with the instructor encouraging casually timed segments for pausing and thinking about issues. Where students before had been asked to 'write notes' now they were offered optional process note-boxes on the back of their map-sheets to fill out with observations and idea-reflection, giving them some potential additional process-structure. Most wrote a little in at least one of these boxes. The exercise was again followed by a one-page survey for students' self-assessment of design-confidence and approach.

Pre and post-test data was in the form of site-design studies consisting of map sketches on tracing-paper. All resulting 283 site-design outcomes were assessed with the same set of measures in order to uncover any change in creative outcome. Four operating variables were used in this study as outcome effectiveness metrics: the *Quantity, Variety, Novelty, and Quality* of ideas generated. The design of the experiment assessed the full set of variables across both pre and post-test outcomes and performed a paired sample t-test on each result to expose the statistical significance of any change.

The number of ideas generated over the specific time of the workshop, *Quantity* was both straightforward to measure and a vital aspect of divergent ideation. Conceptually connected to the classic term '*fluency*', in our study it measured the relative prolificacy of an individual, giving their total outcome over each exercise. Similarly applying not to a single design-idea but to the full set of ideas generated at the workshop, *Variety* measured the range of difference over that set of design-ideas. Based on a range of difference coded from the emergent work, the measure is modeled on Shah-Vargas (Shah et al., 2003) in which a genealogy tree gives value difference at various ranges of detail, weighting broader scale variations in form or strategic design intention, against more detailed aspects of the design plan *(figure 6.3)*.

Focusing next on each individual design-idea, *Novelty* is a measure of the unexpected relative to the broad set of study outcomes, and was assessed by identifying key aspects of each design outcome and grading it for its relative unusualness. In our study each design solution was assessed on two aspects, the form of the physical plan (standard, more unusual, very unusual or unique) and then the ideas or intentions embodied in the plan, with the two then combined for an overall score *(figure 6.4)*. Assessed individually for each drawing, the results were then average for each student, with the highest or most novel score for each student's work also identified.


Effectiveness metrics built on model by (Shah et al., 2000 and Shah, S.M. Smith, et al., 2003)

individual constructs and scales for measuring creativity from Dean, Hender et al, 2004

MAP IDEA # 457-6

Novelty *Definition:* how unusual this solution is in the full set of the design space

Novelty : impression of unusualness

	unusual approach to plan layout	*unusual approach to ideas*
1	dull or no plan	none
2	pretty standard	familiar
3	really unusual	unusual
4	unique	unique

6

Quality *Definition*: how well the design meets the various needs and limits

	1	5	2	3	4	7	6	8
	rel. between parts	metaphor	rel. to nature	rel. to community	rel. to water	clarity of intention	elaborate details	graphic
0	unrelated	no ideas	none	none	no rel. to water	muddled	no detail	
1	little relation	dull ideas	basic relation	little relation	simple relation	some	little	poor/mess
2	some relation	some ideas	relates to park/river	bldgs grouped	some flow	basic idea	some detail	simple
3	good relation	inventive	relates to topo	relates to comm.	good relation	good	good	good / color
4	beautiful plan	metaphors sing	unexpected	unexpected	water relates	clear idea	many details	

17

vision (workability) 6		**relevance** 4			**specificity** 7			Dean et al.(2004)
visible connections/unified vision	goodness for purpose	appropriate	socially acceptable	value addition/ applicability	clarity	how well described	presentation	
[Utility (UTI)] Place Making	synthesis/elegant & fit, Trefflinger(2002)	feasibility (FEA)			MacCrimmon & Wagner 1994	level of detail (LOD)	mode of presentation (MOP)	Liikkanen et al. (2011)

Figure 6.4 Sample of a completed assessment for Novelty & Quality

Similarly assessed for each design, the domain-specific outcome *Quality* was the most complex to assess consistently. In line with the terms and granularity of the Dean study (Dean et al., 2006) we assessed each work under eight measures, themselves grouped into three variables: *vision, relevance* and *specificity*, which were then themselves summed to create a sub-set of *Quality* measures more easily compared with similar studies in the profession. Unanchored scales of rating along a spectrum are notoriously difficult to apply consistently (Linsey et al., 2011), so in the rating card that was used to assess the designs each scale is defined through a descriptive rubric to attempt to reduce variation *(figure 6.4)*. *Vision* builds on the traditional notion of workability, or fitness to a particular issue or site (Treffinger et al., 2002), be that through a metaphorical or tactical vision, bringing with it the notion of a strong relationship between parts that make up the whole. *Relevance* assesses how the design idea relates to the environmental aspects of land and water systems, introduced as part of the infrastructure site-design context, and how it relates to the community. *Specificity* measures clarity of intention, or diagrammatic reasoning, as it can be read in the plan, level of detail, and presentation (Do, Gross, Neiman, & Zimring, 2000). Each individual map-drawing was individually assessed, segment scores were totaled and averaged per category and then combined for an overall quality score per map-design.

The pre and post-test survey also asked students for a self-assessment of their approach to creative work, their confidence level in approaching this work and their assessment of any change in creative confidence gained through the experience of this project. Outcomes revealed that, from the student point of view, the exercise and mapping tools, perhaps partly due to their familiar technological nature as well as their specificity of focus, helped students improve creative confidence and reduced design fixation on project outcomes (Zarazaga, 2018).

Data analysis and discussion

Technique	*How it was introduced*	*How it was inserted into exercise*
GIS mapping	*Ways of layering spatial data introduced electronically. Discussion of site as spatial structure & use of data to explore.*	*Digital data sets of site data at post-test allows exploration based on use of GIS. No additional coaching on use. Not required*
Design heuristics	*Geo-design cards presented in workshop as sample strategies for generative use of spatial data and mapping*	*Geo-design cards were available on the table post-test but were not required to be used*
Design approach processes	*No explicit discussion of design approach, however pausing, re-thinking, iterating part of mapping vocabulary*	*Optional 'thinking boxes' on the backs of their work-sheets encourage pause and iteration. Not required.*

Figure.6.5 Summary of new tools introduced to students during workshop

The primary research question in this experimental study tests whether students, after having some geo-spatial mapping and design training, show any change in creative outcome. Students approached the post-test design work with three new tools *(figure 6.5)*; access to digital GIS visualization of spatial data; some implicit design-process structure and a set of open ended 'geo-design cards'. The two process related variables, *Quantity* and *Variety*, were assessed on each student's outcome set, *Novelty* and *Quality* were tested on individual maps and averaged across a student's performance.

Quantity

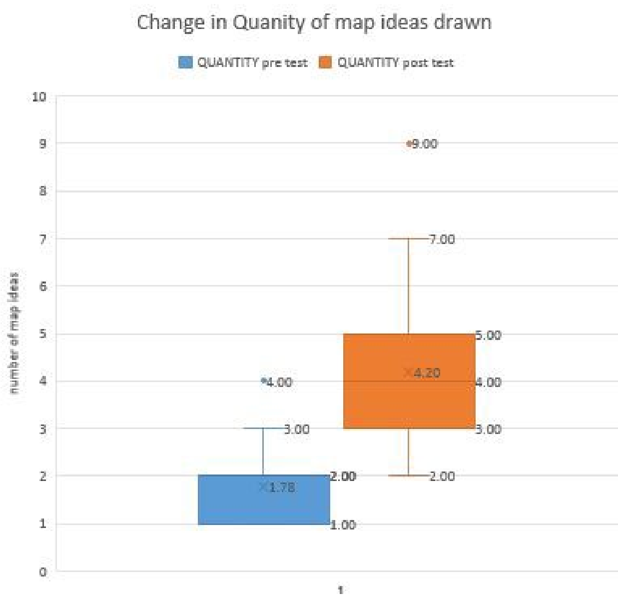


Figure 6.6 Change in quantity of map ideas drawn

For each student, pre-test and post-test, the number of different design solutions generated within the 40 minutes of the full exercise were counted. Excluding unfinished drawings, there was a clear improvement in the total the number of design solutions generated by each student post-test. From the 46 students who completed both sessions 82 map-drawings were produced pre-test and 201 post-test. The student average of 1.78 site-map designs at pre-test increased to 4.19 post-test, a 57% increase *(figure 6.6)*. Comparing categorical means using a paired-sample T-test shows that the result was significant ($p < .01$) *(figure 6.8)*.

While an increase in numbers of ideas does not necessarily mean each idea was more creative, however that increase alone is a valuable result and one that is both measurable and clear. From a larger range of ideas the possibility of more unusual or unexpected ideas is greater. On the other hand, one must admit that the result of an increase in *Quantity* in this particular study is not that unexpected or surprising. Students were indeed encouraged to create more design options as a first step in their training in generative-processes and clearly the training was, at least in this aspect, easy to follow and successful. Duplicate drawings were eliminated, therefore students had indeed expanded the number of solutions in the design-space, a worthwhile objective.

While the results are encouraging, potential interference of the workshop process on the resultant outcomes are several. During post-test, students were given some verbal process structure; although instructions were optional and not explicit students were invited to pause and write notes if they wanted, actions which could have impacted their impetus to start new design-maps. Further, the impact of exercise repetition itself in which post-test may have been approached with less trepidation than pre-test, could have influenced quicker starts and had some effect on design output.

Variety

Variety was defined as the range of difference between all designs drawn by any one student. In assessing how different concepts were from each other more points were given for fully new site-design ideas, with slightly fewer points for old ideas developed in a fully-new form or plan. Partially embodied new ideas and intentions then received some additional points, and small credit was given for further specific detailed developments. While a student's total number of drawings certainly had an impact on their achievable total, the weighting system ensured that many similar ideas did not achieve as high a score as a few contrasting ones (Shah et al., 2003). The result was internally referential since the *Variety* measure is relative to all solutions generated by a participant and not to all theoretically possible classroom solutions. Data for shows that average *Variety* per student rose from 26.97 to 58.47 (54% change), for the 46 students who completed all exercises with a 'p' value showing significance *(figures 6.7and 6.8).*

In this experiment, however, a large number of students (18) rather unexpectedly made only one map at pre-test. *Variety* measures the range of difference across the set of an individual students' work, and clearly those students who only did one drawing had no *variety* at all. The number of students with a base score of 16 (one idea with one visualization) may have caused some distortion in the *variety* measure.

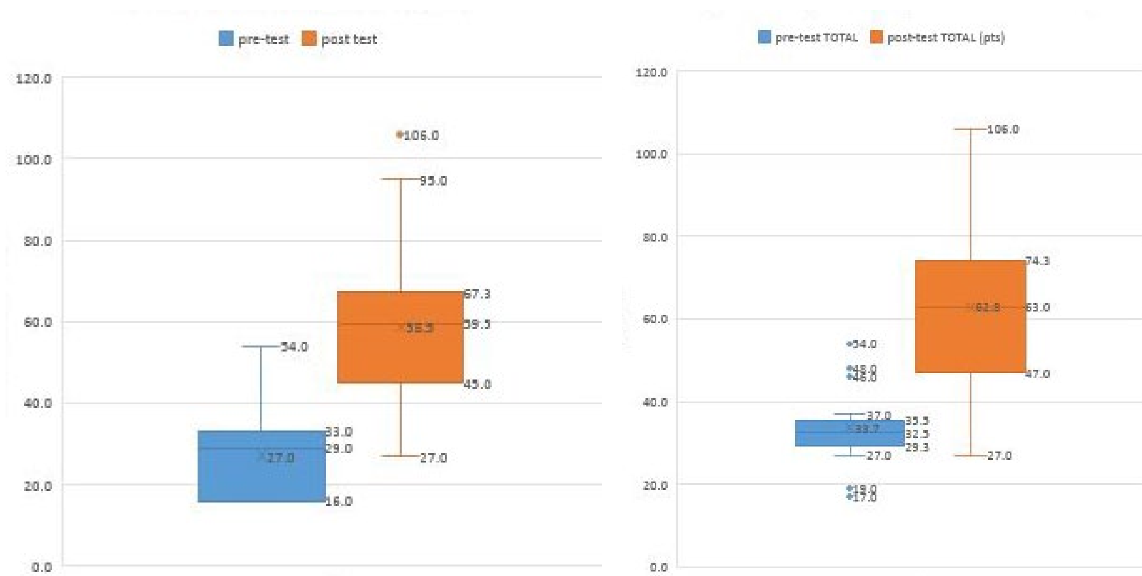


Figure 6.7 Change in variety of map ideas (a) overall; (b) excluding those with one map

After excluding those students who submitted only one result (pre-or post-test) average differences did then reduce to show a slightly smaller increase from 33.7 to 62.8 (46% change) post-test. The less dramatic t-value still retains p <.01, describing the result as statistically significant, however given the much smaller sample size of 28 students this result is a little more suspect and probably not as powerful *(figure 6.8)*.

comparison	Independent Samples t-test			
pre-post test	t	df	sig (2 tailed)	% change
quantity	15.05	45	0.000	58%
variety	12.53	45	0.000	54%
variety (2+)	8.18	27	0.002	46%
novelty (student)	2.25	45	0.029	5.5%
novelty (highest)	2.73	45	0.009	6.5%
quality	2.28	45	0.027	5.8%
vision	3.01	45	0.004	7.9%
relevance	4.42	45	0.000	11.2%
specificity	0.50	45	0.619	-1.0%

Figure 6.8 Results for t-test and significance for all variables

Novelty

While *variety* was defined as the range of difference across all work developed by a single student, *novelty* was measured independently for each design-idea within the context of the full class of outcomes.

Drawings were assessed on two aspects, the unusualness of the plan form and that of the conceptual idea that could be read in the plan, and the two scores were summed. Outcome assessments were then totaled for a student's average score. Results showed that for each student, the average *novelty* of their mapping-work rose from 4.39 to 4.83, a change of 5.56% for the 46 students who completed all exercises. The 'p' value of 0.029 shows this result to be somewhat but not highly significant. Given the very short nature of the workshop, however, even a small average increase in *novelty* is encouraging. It may start to imply that in the process of making more maps, not only did each student produce a greater range of ideas overall, but in doing so they also improved, if only modestly, the originality of the individual ideas that their maps

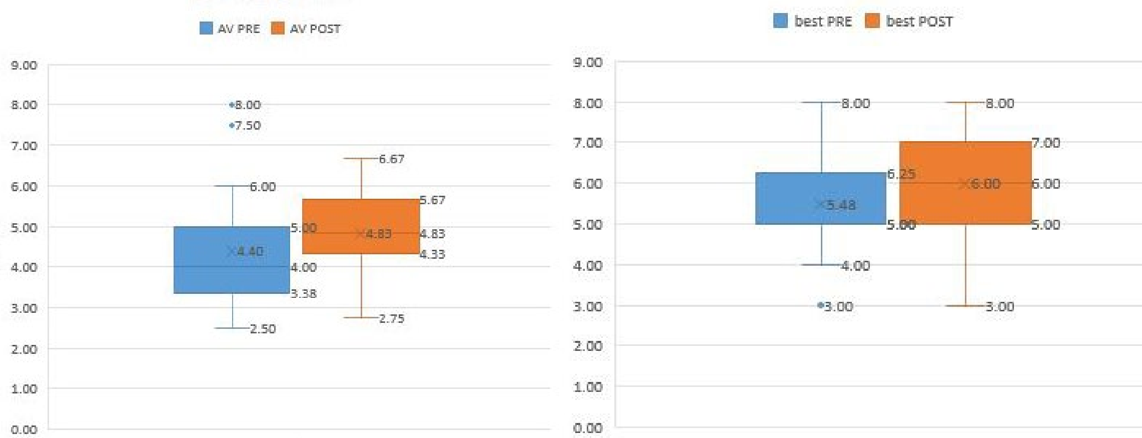


Figure 6.9 (a) Change in novelty of average of all map ideas (b) change in each student's most novel map

were portraying. Assessment of the individual maps allowed question whether the mapping work overall, averaged over the whole class, might show an increase in creativity, rather than the average set of works by any one student. Hence the outcomes were summed for an overall increase in novelty. The results of an independent samples test on all with unequal numbers pre and post-test, showed a similar, or slightly better increase across the full set. However this outcome was judged inconclusive. The full set of drawings included many more maps from some students, mostly those who had more confidence and perhaps better results, and fewer maps from others, thus stronger students' work may have been over-represented in the result.

In drawing more map-ideas, a student-designer has the possibility to draw ideas that are less unusual as well as others that are unique. One advantage of making more ideas is the potential to discard some and retain the better ones. But in our study we averaged all results. It seems relevant to ask, then, whether the most unusual work of each individual student when assessed on the novelty scale, had an improved score post-test, compared to that of pre-test. This query turned out to give a highly significant result, in which the average 'most novel' result of 5.48 pre-test rose to 6.00 post-test, a 6.5 % improvement, with a *p* value just below 0.01 *(figures 6.9)*. Of course, this result doesn't ensure that students themselves would have selected that map if asked to identify their most novel idea, or that the most unusual would rate as well on other measures.

Quality

A domain specific aspect, *quality* is the most difficult to measure, and therefore the most finely measured of the four variables. Average total change in *quality*, between pre and post-test, increased slightly from 12.07 to 13.45, an increase of 5.8%. However the p value shows the result to be not highly significant *(figure 6.8)*. Such a result is not that surprising. Students were trained in methods to increase their divergent generation of map-ideas. Although the generation of more ideas may give the opportunity for some better ideas to emerge, it would be surprising if all the new ideas, averaged, were indeed of higher *quality*. Furthermore, the training that the students received at best will have only marginally affected their technical or conceptual understandings of site-design issues, aspects that are assessed under *quality* but were touched upon only briefly in the workshop.

However if the workshop impacted only numbers of solutions and had no impact on design development, then one might be quite critical of the whole exercise. One would hope to find some change in design *quality* based merely on the encouragement to explore and generate novel ways of thinking about the project. Thus the assessment of sub-sections of the *quality* statistics may be able to shed some light on student idea development.

Ideas were assessed on eight descriptive measures, themselves summed under *vision (workability), relevance* and *specificity (figures 6.8 & 6.10)*. The least improvement came from *specificity*, which in fact showed a small decrease from 5.56 to 5.44 (a 1.0% decrease), a result that was not within the bounds of significance. *Specificity* included aspects of clarity of intention and level of detail, in addition to quality of presentation. Graphic quality was not emphasized pre or post-test, but making more drawings post-test may have led to messier results. A lack of change in the aspect of idea-clarity or intentionality, also a sub-set of *specificity*, may be more interesting. It appears that although students may have experimented and explored different layering strategies, they may not have learnt, as of yet, to transfer that idea exploration to design intentionality. So while there were more ideas, students were not yet able to make the impact of those ideas clear in their map-designs.

Vision, another sub-category of *quality,* was defined as a unified spatial form-making that could be read in the map-design, an aspect of place-making brought together with a notion of relationship between parts. Although it too measures intention and is related to *specificity,* this aspect did not measure design 'idea

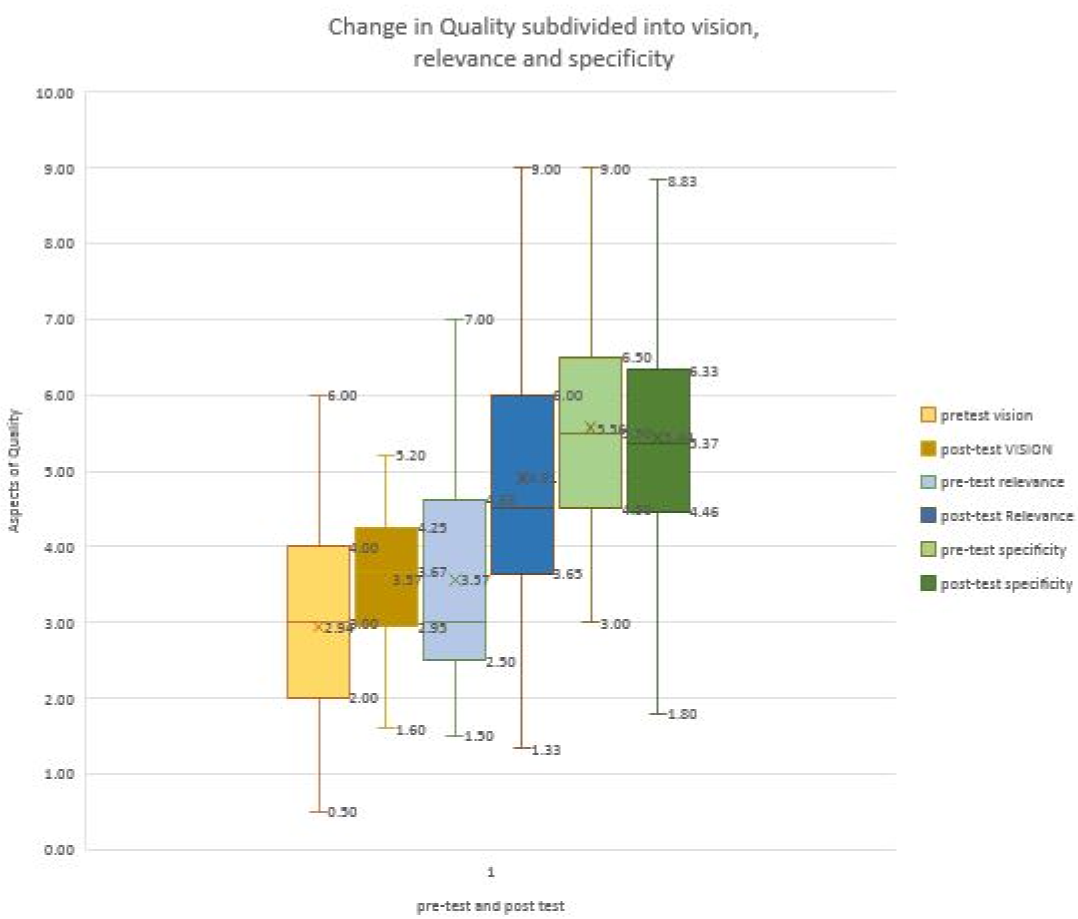


Figure 6.10 Showing change in quality subdivided into vision, relevance and specificity

concept', but rather metaphorical images. A design based around consecutive topographies, for example, could score high on *vision*, but low on *specificity* if the intention behind using such forms were not clear. Scores for *vision* rose from 2.94 to 3.57 post-test, an 8 % increase, which although small, does have a p-value revealing some significance. This is encouraging. Some students clearly began to explore spatial relations between aspects of site, perhaps through GIS layering and the heuristic techniques, and these aspects were able to be seen in the work itself even if not yet translated into a conceptual approach to the full design.

The largest change in the three quality metrics was seen in *relevance*. This measure was built up of combined points for revealing relationships between nature, community, water and site-design, and increased significantly, from 3.56 to 4.90, an 11% change ($p = < 0.01$). It is interesting to wonder why this measure may have shown such positive improvement. Although surface and sub-water drainage and its relation to topography and site design were discussed only briefly in the workshop as basic issues of infrastructure site planning, they are also precisely those aspects that become most clearly visible when layering independent GIS layers. So by observation and play with such layers it appears that even if a student-designers' map-design itself was not more visionary, its connection to physical site aspects seems to have improved. Community focused intent, which was wrapped into this measure, may have improved also from an attention to social aspects of site, a focus which is indeed embedded within a couple of the design heuristic cards.

As with *variety*, the range of scores reviewed for overall map *quality* was greater posttest, with students creating both lower and higher scored map-results than they had before, such that a similar average was created with a greater deviation.

Experiment Limits

Conceptually, spatial thinking is the context of this learning strategy, a structure which, like that of thinking in alternative languages, exercises different cognitive structures so that merely a move into spatial work, even without specialized teaching, might allow student-designers to uncover new approaches. But this change of cognitive framework, while it might have influenced the outcome, is not the emphasis of this study. Instead we ask whether, if trained to do so, students can take immediate advantage of a spatial-mapping skill-set as a pragmatic, practical tool for a generative design task. A valid question to ask is if there will be enough time or practice for reasonable results to emerge from such an exercise.

Certainly, there are limits to creativity outcomes measured with a quick pre-test post-test structure. The researcher-taught workshop raises the potential impact of subject and experimenter effects, as well as typical influences of test-repetition. *Novelty*, for example, set out to test the unusualness of a student's work, however each student's first pre-test exploration was a jump into the unknown and therefore, on an individual scale, extremely *novel*. The post-test exercise, comparatively, was already a repeat. Such individual development, like other incremental changes, are hard to detect, but such subtle learning differences may, in fact, be those of greater importance for the students themselves in the long run.

Conclusion

As expected, and described by Vargas, the process oriented aspects of the generative design processes introduced, were both the easiest to teach, to alter and to measure. Encouraging though it may be, as a teaching outcome that students indeed developed both a greater *quantity* and a greater *variety* of map-ideas, such a result is not that remarkable. Of more value is the increase in *variety*; the higher result post-test does indeed seem to imply that the new tools, both the map-layers and the heuristics, did increase the range of ideas and forms that students were able to envision, and not only the number of different ideas.

More interesting are the harder, product oriented aspects of the creativity measure outcomes. Both average *novelty* and *quality* showed an increase, post-test, with results that were significant, if not highly so. Indeed, while the results are modest, in such a short workshop one would not expect more. Increased outcome results for *novelty* seem to support the idea, hinted at in the *variety* measure, that more unusual proposals have made their way into the outcome set. While the average of all a student's attempts may only have marginally improved, it would only take one or two really new ideas, if recognized and developed, to move a student towards project innovation, the end-game for this whole exercise. Following a divergent-thinking exercise like this one, students would then need to apply skills in critical convergent analysis, using domain specific understandings in order to exclude, narrow and refine the ideas created. But without a wide range of generative novel ideas, that more technically focused skill-set cannot be put to great use. Similarly, real design *quality* is an aspect that develops most strongly over multiple iterations of design work. The lack of a strong average improvement in design *quality* on a first-run exercise is not surprising. What is encouraging, and somewhat surprising, were the results that developed from the sub-categories within the *quality* assessment bracket. *Relevance* was revealed to be the area in which students had been able to improve their design-ideas more quickly, in this short design project. When asked to experiment, and particularly when given heuristic tools which encouraged investigation of layered data-sets of spatial site contexts, students seem to have been drawn to aspects that may indeed be linked to their own passions as young engineering students. Aspects of the natural environment, of water systems and topographic structures became the primary catalysts for visual and spatial explorations, such that the site-design outcome was not only a more unusual formal solution but could be seen to have a relationship with these environmental systems. Such a result is of value not only for the future development of the design heuristics themselves, which would be interesting to modify to encourage this direction, but also provide a link to the possibility that this approach may have a secondary value as a route to helping students integrate more sustainable approaches to their site-design solutions. More novel design ideas, if generated through the catalyst of a spatial mapping process, might then have the side effect of also being more sustainable solutions.

The familiar framework for problem solving in engineering starts by understanding the context, framing the problem and then searching for solution sets. Framing the problem, however, is often a subtractive and idea-limiting process; multiple solutions may be excluded by the frame, narrowing the range of outcomes that might be developed. Divergent creative thinking is thus not only the ability to generate many ideas but also to open the conversation to a variety of different points of view; the analogy with viewing being embedded in the very language used to describe idea development.

As a spatial structure, mapping leads the engineering student-designer to look at their problem from a visual rather than merely a conceptual framework. The process of map-making provides the opportunity to step outside of the given problem-frame and explore alternative perspectives. Maps can be used in creative thinking then, not as a set of problem solving tools, but first as a set of problem opening tools (MacEachren, 1995). Rather than defining limits the mapping process allow the student-designer to open the range of patterns that might, eventually, provide new directions for the work.

The traditional way we look at plans and maps restricts the kinds of infrastructure site solutions we can imagine. Within the context of static drawn maps, we 'see' the world in a given formal structure and tend to see only those design solutions which fall naturally within that framework. Geo-spatial mapping systems enable the creation of multi-layered visualizations of data, possibilities which allow new and unexpected ways of looking, through geo-visualization or geo-browsing (Peuquet & Kraak, 2002). Re-mapping the spatial-data of the environment raises the potential to reimagine the world in greater multiples of ways. Discovering this freedom not only opens to engineering student-designers wider practical solutions for their site-planning exercise. The experience of stepping away to purposefully explore options, and learning to search out a wider range before narrowing their problem-definition, may provide a model for creative exploration which can then be transferred to other non site-planning environments. The analogies and heuristics learnt in the process of re-visioning a site mapping can likewise be applied to other tasks of creative thinking- widening possibilities for innovative work.

A key example for such exploitation of method can be seen in the teaching methodologies of the combined school of design (architectural, graphic and industrial design) at the *Universidad Católica de Valparaíso*. Known internationally for their poetic approach, the school teaches a range of creative design strategies based on a collaborative and community-based investigation of the environment, both social, political, literary and physical. The works that emerge from this '*observacion*' often leave visible marks on the territory through constructions, performance or text. Each project does not begin by framing the problem but rather starts with an act of seeking an enhanced range of visions from which physical solutions can later develop. The open, playful nature of the creative process allows space for the unexpected and has led to a remarkable range of inventive design innovations as well as student design learning. (Pérez de Arce, 2003; Pendleton-Jullian, 1996; Marshall Zarazaga, 2011). The interaction between landscape, constructability and the focus on experimentation create an environment very familiar to an engineer, even if the conceptual exploration may be quite foreign. Perhaps geo-spatial data structures can serve engineering students as a proxy site-exploration voyage, allowing and encouraging new explorations of context, form, community and ecology while remaining within a familiar technological structure. Within the context of tight schedules in engineering education, it is interesting to ask if such a pattern of site exploration, taken beyond the primary phases of generative thinking explored here, could allow not only diverse creative visions, but provide additional connections to more integrated collaborative and sustainable site-design solutions.

Chapter 7

Deep Observation: Geo-Spatial Mapping as a Strategy for Site-Engagement and Problem-Design

Focused on understanding how mapping could serve as a tool to help engineering students approach creative thinking beyond the limits of just a short workshop, this part of the study took an intense and focused look at the experience of a small group of graduate students over the course of a full semester. The qualitative study focused on three sets of data, exit interviews conducted with all students and transcribed, short course surveys and the mapping work itself as a visual dataset.

After the research phase was complete, all data was collected and analyzed and the text data was coded and structured. In the open-ended process of the grounded-theory based qualitative research methodology in which results were allowed to emerge from the data, an additional teaching and learning benefit beyond that originally sought was revealed as an unexpectedly strong research outcome. The process of site-mapping, and specifically the generative design processes that students were taught, appears to have led, beyond the creative exploration, to deep engagement not only with the geographical but also the social and human aspects of the site situation, and promoted a range of stakeholder-based problem-framing outcomes. The pedagogical toolkit designed for this study can thus be shown to have helped students design not only a site strategy but, more abstractly, a community and stakeholder based research approach for their projects. This paper reports on this outcome. Additional data on creativity and creative confidence in student's learning outcomes will be developed into a later independent paper and journal submission.

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Abstract

While project-based learning powerfully brings students into real world economic and environmental contexts, a subject-oriented approach to such work means that they are often able to remain aloof of real stakeholder engagement and participation, even when working on a local site(Lehmann, Christensen, Du, & Thrane, 2008). Given their traditional comfort with abstraction and universalization in the process of problem definition, engineering students can be challenged by the immersive problem-framing processes demanded by a contextual research design investigation (Nieusma, 2018). Using the process of GIS site-mapping as an engagement tool may provide a strategy by which students can develop alternative methods of stakeholder engagement as part of their data gathering process and thus integrate social and community aspects into their site problem-framing in new ways.

Originally designed as an experiment to explore the potential for GIS mapping as a tool for creative spatial exploration in site design, this study uncovered an unexpected additional benefit to the open-ended site analysis processes undertaken. Student focus on geo-spatial site data and generative mapping processes seems to have simultaneously, perhaps through the head-fake of indirect learning (Pausch, 2008), enabled ways of integrating stakeholder engagement with site visualization leading to a range of creative problem framing and problem research outcomes.

Taking a qualitative approach, this study analyses a graduate level Civil and Environmental engineering project-based GIS course and uses a text analysis of student interviews as well as visual analysis of student project work to extract student attitudes and approaches to site engagement. Transcribed interviews are bundled into representative issues and coded into categories by constant comparison (Case & Light, 2011). The resultant analysis describes the variety of ways in which creative geo-spatial mapping as an instructional approach seems to enable alternative ways for students to integrate stakeholder and site engagement into their problem-framing process. Aspects such as sensations of safety, emotional connections, changing businesses and community paths made their way into students' spatial data structures, issues which otherwise might not be integrated into the engineering curriculum. Outcomes

suggest that the specific effort of producing consistent creative spatial-data site visualizations of community and site issues may give students a greater depth of stakeholder understanding or needs than might have been achieved through traditional engagement processes.

Introduction

> *How do we think about problem framing and problem definition as forms of stakeholder engagement? What specific instructional strategies can help engineering students think more creatively and expansively about the process of problem definition?* *(Brocato & Cotter, 2018) [LEES Session Notes and Commentary 2018 Annual Conference]*
>
> *"I never really thought about having a structured way to think about [a problem idea] and get there. A lot of engineering students just don't know how. In my undergrad if I was given a design problem it's like, 'Oh-oh, I've got to do what?'" [SMU engineering student, 2016]*

Used to being challenged with a defined problem question, engineering students are well trained in searching for solution sets. In response to calls from the profession to train students in more responsive approaches to engineering in both the social and design contexts, universities are exploring ways to help students develop more open-ended and creative problem solving skills (Baillie & Walker, 1998). Such teaching starts by questioning the authoritative problem set and unfolding the learning process itself as an experience of invention in which divergent phases of exploration initiate responsive approaches to context, and open-ended visions lead to a generous set of research approaches (Atman, Kilgore, & McKenna, 2008; Eris, Dym, Agogino, Frey, & Leifer, 2005; Dym, 1999). One of the most favored pedagogical models for teaching divergent thinking is project-based learning (PBL) in which hands-on explorations take place in the context of specific real-world projects or site contexts. Students learn to work collaboratively, often in multi-disciplinary teams, on open-ended problems gaining a broad set of knowledge and project management skills that move beyond specific technical competencies (Campos, Dirani, Manrique, & Hattum-Janssen, 2012; Eris et al., 2005). Instructors typically are invited to take on the role of facilitators rather than directors, making space for student driven learning by doing (Bell, 2010). Defined as learning through inquiry, PBL helps students develop research and design phase skills, supports individual initiative and self-directed study, and gives exposure to the complexities of open ended outcomes (Mills & Treagust, 2003). Furthermore, design teaching placed within such a site and project-based environment of necessity develops more human-centered concerns due to the immediacy of the social context (Titus, Zoltowski, & Oakes, 2011; Rulifson, McClelland, & Battalora, 2018; Baillie & Walker, 1998).

While recognizing the multiple strengths of the PBL teaching methodology, researchers have also made educators aware of its limits. In practical terms, project-based learning can be difficult to undertake and complex to fit into academic scheduling; the extra effort involved must be determined to have sufficient payback. Excluding those unusual examples, such the Aalborg school (Kolmos, Fink, & Krogh, 2004) in which it is fully integrated into the degree teaching approach, PBL is often inserted as a single experience within a traditional curriculum as a first-year or final-year experience. In this context the methodology is often also expected to fulfill specific subject-area learning outcomes. The inevitable solution-focused implementation can reduce the effectiveness of the project-based context, enabling students to avoid some of the intended complexities of their exposure to open-ended research and inquiry. A familiar emphasis on short-cycle problem-solving can limit student exposure to precisely that open complexity and deep engagement in participatory processes for which the method was first proposed (Mills & Treagust, 2003; Perrenet, Bouhuijs, & Smits, 2000). On the other hand, the daunting open-endedness of immersive design research can be conceptually foreign to engineering students compared to traditional problem solving, and it can be difficult to integrate these two very different ways of thinking into a single context (Nieusma, 2018). The application of familiar instrumental problem solving methodologies to a project-based context often leads to an unsatisfactory learning outcome. In this case either the complexity of the multiple variables in a community problem are displaced by the comfortable abstraction of problem solving, or alternatively, a direct teaching focus on creative design methods excludes precisely those essential tactical skills that would allow integration of the two thinking structures.

Randy Pausch, professor of computer science at Carnegie, in his very personal memoir about teaching and learning in engineering, proposed the term ‘head-fake’ for important learning outcomes that take place outside the explicit area of teaching focus (Pausch, 2008). For example, he referred to collaborative skills as the primary learning outcome many parents expect from participation in youth team sports, and he described the some extraordinary computer software outcomes that emerged from a colleague who packaged programming as a storytelling activity (Pausch, 2008). He argued that, perhaps especially for engineering students who like to look directly at a problem, certain aspects of learning can be more powerfully approached by looking askance, by specifically not-focusing on the issue of interest. In the case of our study the ‘head-fake’ was unintentional, but the learning outcome may be shown to be equally powerful for that eventuality. This paper thus reports on a possible alternative sideways-strategy in which the learning skills which might enable engineering students to take advantage of a problem-based learning context is actually more accessible when it is approached indirectly thought a ‘head-fake’, a strategy itself discovered almost by chance when the researchers too were focused on quite a different educational question.

The context of the original education study was a Geographical Information System (GIS) mapping course introducing data visualization and spatial modeling, which emphasized the spatial nature of geo-data analysis through the investigation of a particular physical site. Although the course and the investigation were indeed project-based, it was the use of spatial data processes as a toolkit for creative problem-framing which formed the educational context for the original study, rather than the project-based work itself. The research design of that original qualitative study was focused on the relationship between mapping and design creativity, and explored the variety of ways in which GIS spatial mapping tools, integrated with specific creativity tactics, allowed students to uncover a range of different site approaches and an altered project outcome space, by integrating the patterns of infrastructure with the deep orders of the urban landscape (Marshall Zarazaga, 2011).

Explicitly designed to teach creative ideation practices through spatial inquiry, a series of mapping exercises were embedded into more technical site-based geo-spatial research, exploring, as part of the educational research, their value as support structures when teaching creative processes to civil and environmental engineers (Zarazaga, 2018). Through observation and the collection of data, the attempt to integrate complex data layers and the challenge of visually representing that data as a set of spatial outcomes, students were offered multiple opportunities to develop divergent approaches, enabling a wide range of imaginative project-frames for their site-based research. The choice of a site-based, experiential framework as the context for a creative learning study was partly based on the support that spatial and participatory practices might provide for innovative thinking (McKim, 1980; Sletto, Muñoz, Strange, Donoso, & Thomen, 2010).

The study site was primarily seen by the class as a landscape for exploring innovation in infrastructure site design, as well as the background to an academic learning experiment focused on spatial and creative learning processes. While students were indeed exposed to local social and political issues, the overall learning context was presented to them more as one focused on divergent exploration rather than on methods for understanding stakeholder problems. Project-based community issues were thus neither the focus of the study nor of the student coursework. The gathering of individual site data was emphasized less for its own content than as a catalyst in processes of creative mapping. Focused on the intuitive and often perceptual observations of each student team, site data was contextualized and contrasted with publicly available spatial and census data. Thus one might describe the process as observation-based and site-based rather than explicitly project-based. Prioritizing individual observation, the data collection strategy was designed to encourage exploration of the creative potential of working within, and finding inspiration from, the perceptual and physical specifics of a local spatial and social context as a strategy for creative learning in engineering education. (Aboukinane, Moriasi, Kenimer, Dooley, & Linder, 2013; Lehmann et al., 2008; Pendleton-Jullian, 1996).

The qualitative methodological approach chosen for the education study, a phenomenological structure in which results are allowed to emerge from the coded data, revealed multiple learning outcomes, some of which happened to be different from the original research questions posed. Thus while focused on geospatial site mapping practices as tools for creative spatial exploration, researchers uncovered unexpected additional learning, through the process of constant comparison. In student descriptions of the open-ended site analysis process, in addition to their descriptions of creative learning practices, students also revealed a powerful experience of stakeholder engagement and, based on this experience, described a variety of different problem framing and problem research outcomes. Not the primary focus of the original study, it is even possible that this outcome may have gained some of its educative power specifically through the 'head-fake' of having received little direct attention in classroom teaching.

Research Methodology

Although quantitative research retains priority in engineering education, other alternative methods have been shown to be better suited to certain kinds of research questions (Baillie & Douglas, 2014). Research into qualities such as creative thinking, or abilities brought to the work by the individual such as self-regulation or motivation lend themselves to qualitative investigation and are well represented in published research (Lawanto & Febrian, 2016). A range of qualitative methods focused on rich descriptions of lived perspectives are becoming more visible in engineering education and have become increasingly accepted by the academic community provided they meet rigorous research standards (Borrego, 2007; Case & Light, 2011; Koro-Ljungberg & Douglas, 2008; Walther et al., 2017).

Marton developed the structure of phenomenography in the 1970s as part of a broader philosophy of educational research (Marton, 1989), exploring ways to reveal a "from the inside" perspective on variation in the ways people experience learning in multiple contexts. Based on the open-ended structure of grounded theory developed by Glaser and Strauss (Glaser & Strauss, 1967), which allows emergent findings to emerge through data comparison, but developed specifically for research in the higher-educational environment, its approach maps well to engineering education research. A method for categorizing the set of qualitatively different ways in which people experience, conceptualize and understand aspects of learning, phenomenography documents "the totality of ways in which people experience the object of interest and interpret it in terms of distinctly different categories" (p. 121), (Marton, 1989), so that a full range of learning conceptions, described as the 'outcome-space', is defined.

Building on grounded theory, the researcher identifies fundamental categories within the data, seeking to capture and limit the variation in order to understand if certain concepts or perceptions are more prevalent in one group than in another, and how such differences might be related to different experiences. (Crepon, 2014; Marton, 1981, 1986; Richardson, 1999). Phenomenography is less concerned with describing the intrinsic essence of student perception than with identifying, and categorizing a limited range of student understandings of an issue. (Booth, 2001; Klukken, Parsons, & Columbus, 1997). The methodology was selected to allow a deep reading of student learning, and while originally focused on understanding the variety of students' creative explorations has the potential to reveal additional learning outcomes from the specific context of these students' experiences (Booth, 2001; S. R. Daly, Adams, & Bodner, 2012).

Study Sample & Procedure

An in depth case-study of a single classroom experience, this study was based on a full semester analysis of a group of 10 graduate students with a diverse set of ages, genders, skill levels, professional experience and creative confidence. Most had a civil or environmental engineering background.

Students were introduced to geo-spatial data mapping and analysis as well as tactics for generative spatial design. The original study focused on exploring how the teaching strategy enabled qualitatively different learning responses and classroom outcomes in design creativity, creative confidence, geospatial learning processes and creative project-framing. In the integrated spatial exploration structure of the class, the project based components of the course were inextricable from the GIS mapping assignments such that technically focused exercises were interlaced with project-based generative design and research. To support the classroom and site based exploration, students were given a set of 'geo-design cards' a deck of cards which described ways to use spatial data and particular GIS technical tools as a way to jumpstart new ideas, and illustrated with examples from previous generations of students who taken similar courses. In line with the open-ended structure of the class, the use of the *geo-design* cards was not required, they did not define or limit project exploration, and while some students used specific tactics to aid project development, others described using them rather as a precedent to help explore strategic approaches. Full discussion of these and similar heuristic tactics are found elsewhere (S. Daly, Yilmaz, Seifert, & Gonzalez, 2010; Wayne McGregor, 2014; Zarazaga, 2018).

One-hour individual student exit interviews formed the major dataset for analysis which was integrated with textual data from two inter-semester survey questionnaires. The visual mapped GIS project outcomes were also used as part of the educational research data but primarily served to allow researchers to explore the extent to which the learning experiences described could be identified, at this early stage, to have impacted any creative aspects of the visual project outcomes. Student verbal responses from each dataset described were transcribed, coded by question and bundled into representative issues. Outcomes were compared and groups of answers were allowed to emerge from the data by constant comparison, building on a precedent methodology from engineering education (Booth, 2001; Case & Light, 2011). Although part of the interest in the data gathered is based on the variety and range of conversations observed, conversely confidence was achieved by the way in which groups of students' shared similar perceptions.

Research Design & Objective

The study was designed to allow students to share their learning processes with the researcher particularly as they pertained to the integration of generative strategies with geo-spatial exploration, each individual learning perspective adding to a deeply colored understanding of the variety of student experiences. While studying the site as part of their data gathering, students described the development of individually specific forms of site and stakeholder engagement, an aspect of project participation which was integrated into the classroom methodology but which was not part of the area of focus of the original research project. Within the framework of the creativity-focused research, students described how a range of social and community specific observations were documented beyond the physical aspects of site. These observations not only formed part of their data and creative toolkit, but were powerfully integrated into project decisions and project framing in a variety of ways.

The new research question which thus emerged from the phenomenological study asks whether the processes of GIS site mapping could, in fact, be exploited as a project-framing teaching strategy and intentionally support stakeholder-engagement. Could a spatial mapping focus for certain stages of an engineering project provide a strategy by which students can learn to develop techniques for stakeholder engagement as part of data gathering, and thus develop new ways to integrate community aspects into their problem-framing process?

As a final stage of the original creativity-based study, students were asked to describe any ways in which they saw opportunities to use the strategic ideation tactics as abstract tools that could be applied beyond this class. Again, an unexpected outcome of this part of the study was that the potential for abstracting the methodology was described by students as pertinent not only to the creativity tools but to the whole engagement process. For some students, then, the process of community understanding through mapping was seen as a structure that could be applied to the development of a stakeholder-focused research frame, beyond the limits of this specific project.

Rather than focusing on the positive establishment of a cause-effect relationship between site-based geo-spatial research and stakeholder engagement in project-framing, we attempt to explore a spectrum of outcomes in which specific spatial mapping tactics applied to a local site allowed students to uncover a range of different approaches in the design of their research projects.

Results: Evaluating Students' Experience of Project Framing through Mapping

> *"Usually in other courses I was given the research topic so I've never really thought about it." [University engineering student, 2016]*

This study seeks to explore the variety of ways in which the introduction of creative geo-spatial mapping as an instructional approach additionally enabled alternative ways for students to integrate stakeholder and site engagement into their problem-framing process. Three different learning outcomes relating mapping to processes of engaged project definition, were experienced by students in the course, as seen in table 1. The first was the simple use of site mapping as a tool for enabling student engagement with a community and site, through the necessity to physically gather spatial data about it (see column 1). The second was the way in which the tactical engagement and pedagogical structure seem to have allowed students not only to develop imaginative project ideas but to integrate stakeholder views into that project frame in unexpected ways (column 2, table 1). Finally, this approach to idea-exploration was described by at some students in terms that showed a conceptual understanding of the idea-searching process as an abstraction which could be applicable to other project-definition contexts (column 3).

In many ways the strength of the student learning in relation to stakeholder engagement in the project definition process was an unexpected course outcome. Exploring and describing the range of student experiences is of value in order to reveal ways in which future course structures might support a more intentional development of this strategic approach.

WAYS IN WHICH GEO-SPATIAL MAPPING ENABLED INTEGRATION OF SITE/STAKEHOLDER ENGAGEMENT INTO PROJECT-FRAMING PROCESS				
		1 ***engaged mapping as path to connection with site or community.***	**2** ***engaged mapping as path to student initiated project-definition***	**3** ***tactical approach abstracted as project-framing strategy beyond this exercise***
A	***students described feeling challenged but not yet engaged***	physical data collection enabled minimum connection with place	students challenged by lack of given project-definition	conceptulized process as a way of thinking, rather than just doing
B	***students described finding or developing an approach to engagement***	area of focus or idea found through site experience	students developed a tactic or strategy to define their project approach	identified tactical strategies of engagement as potential model for identifying needs
C	***students described emotional and tactical integration of engagement with project-definition***	site experience led to engagement with community and idea development grew from that	experience impacted creative exploration of project direction; iterative process enabled project development	identified tactical strategies of engagement as model for creative project-definition for research & design

Figure 7. 1 integration of geo-spatial mapping into stakeholder engagement and project-framing

Outcome 1: Active mapping as site connection

While focused on creative mapping processes, the action of GIS data-gathering on site ensured at least a minimum level of physical and social interaction, however the level of engagement which students channeled into their investigative process was revealed to have taken place at very qualitatively different levels of intensity and intentionality. Some experienced restricted site connections limited to physical data gathering (see category A, column 1, table 1). Others did indeed integrate observed data into their project framing process, but limited engagement to that phase (category B, table 1). Finally, some described experiencing ways to take advantage of the data-gathering processes to first uncover and then to integrate discovered aspects of the physical or social site into their full project definition process (category C).

Approaching the project with a defined problem direction, a few refused to allow the site or tactical process to divert that focus (A).

> *S1 No, the process didn't really impact our results, we already decided we wanted to do [a map of] change over time. So when we got there we were just like OK, we need to produce a few other maps just to meet the requirement.*

For most, however site observation and data collection enabled at least a minimum connection with place. Several students, for example, came with their own preoccupations and framed their site experience within those limits. Yet even if the interaction didn't yet make its way into their project approach, students described becoming aware of the effects of their engineering decisions (A).

> *S2 I thought it was just really interesting how we took the ideas that we wanted and then we went and drove, like, up and down every single street, marking everything down. Just being there and seeing it and seeing people interacting in the community and everything, it made it more real which was good, because so many times you do your research project and you spend all your time in the library or computer and you are just looking at data and you're not looking at who it might be affecting.*

Of greater interest, however, are those who described uncovering an idea or focus area through the tactical observation process. (B)

> *S3 Especially because since I'm sort of new in town, I think having to do all these steps was a good way of familiarizing myself with the place, I found it useful for, you know, for getting my idea from the research.*
>
> *S4 Like, at first I focused on trees, then from the trees I saw the urban heat island effect, then I saw the electricity usage. So I don't know, is this creative? I saw opportunities but at first I thought this was analysis not creative thinking.*

Interestingly, some students found that the open-ended search became quite personal. Although its effect on project outcomes remains unclear, the intensity described precipitated an immediacy and focus which clearly impacted their process. (B)

S5 I think I felt like an emotional attachment there, I don't know if that's the right word but something that I connected with.

Through the experience of documentation and mapping the discoveries on site, students described starting to allow their perceptual observations to impact their ideas and their project approach. (C).

S6 So I went to the site and I didn't have any idea what I would do. I tried to observe but it was not until several people told me 'you're talking a lot about noise and how uncomfortable it was'. First when I went and noticed that I didn't think immediately, 'I will map it', because I didn't think of it as something you can put on a map. It was not until after I started gathering data on the site that I pictured in my head how it would look like.

Finally, a few students took the data-gathering process beyond the observation of physical features to engage with community, integrating complex social aspects into the work of problem definition (C).

S5 I mean for me it was very useful just being there and walking it and seeing it and then thinking about things in different ways. I was kind of drawn to the networks, the sewer line and the water line, and thinking how an underground network can be not just be a literal underground network but can also be a network among people and ideas and things. And then came the idea about there being networks connecting magnets of attraction, places where you could bring people together.

Outcome 2: Engaged mapping leads to project definition

The instructional strategy of project framing through spatial data discovery opened the opportunity for students to develop a more engaged version of their problem definition, however there were a variety of qualitatively different ways in which students experienced that link between the engaged mapping and the project framing processes. Unaccustomed to projects without pre-defined problem sets, some students experienced anxiety in the process (see category A, column 2, table 1). Others began to integrate specific issues observed on site into their project approach (category B), while a few fully engaged and developed complex exploratory project approaches through which they framed iterative and layered project directions (category C).

The open-ended approach with no prescribed problem was challenging to some who found it difficult to give value to emergent ideas (A).

S7 I think at first it felt too loose. I was not entirely sure what this research project is meaning, I wasn't sure where we're supposed to go with this.

Many students, however, described developing an individual strategy which gave them confidence defining their project approach. These strategies ranged from integration of a personal interest with the site experience, to the use of the specific instructor-led tactics in the geo-design cards. (B)

S8 Both during the site visit and taking photos I paid particular attention to sidewalks; I've read how planters, street trees, pavers can not only prevent negative storm-water impacts but also improve value and quality of life in an area. With this being an area with high foot traffic I was surprised at the state of the sidewalks or lack thereof in some areas.

S7 For the project we did a talk at the community center and then I visited that neighborhood very many times. The feedback I felt was it's all about motion, so I tried to think about what made motion in that neighborhood.

It is worth reiterating here that although the course context was site based there was no explicit teaching focus on community engagement but rather on creative mapping outcomes, and yet numerous student comments referred to the project-framing process in terms of their experience of site or community. Thus while certainly other students described alternative, and more abstract creative strategies for project approach, of interest in the context of this paper are those whose approach was based on the integration of stakeholder observations. Specific experiences were described by students as having impacted their direction, and led them towards new explicitly community motivated problem frames (C).

S2 We wanted to tell some sort of story that would link to [engineering] interests we have but then we broke it down and ended up going in different directions from where we started. We did the sketch walk up and down every street and that that made a difference; Ok, conditions might not be great, but there might be something really nice right behind it. So it's kind of figuring out what might contribute to that perception and to the feel of the community.

While some found direction in their data collections process, others described an iterative understanding developed through the experience of ongoing data verification. In this case, project-definition was built up as a link between the processes of 'going out there' and 'coming up with ideas'(C).

S8 I did a lot of gathering of my data sets myself so it was a lot of checking maps and then actually going out there and verifying the data. I think when we started, you know, expanding the ideas rather than limiting we came up with some interesting ideas of how to unite the data that we didn't previously have. I'd say that that's where we, kind of entered the more creative part was: 'How to put data ideas together that we haven't previously thought of.'

Powerfully, some students described developing a deep awareness of their role as an expert during the observation process which changed their approach to problem definition, a balance between knowing and listening that can be quite difficult to achieve, or to teach (C).

> *S5 My project is not narrowly defined yet so I think they did understand I wasn't ready to go into this community and say 'here is my issue'. I would like to understand the community a little bit better before.*

This re-alignment of expectation was an unexpected learning outcome from the instructor's point of view. Site data seen through students' own experience was changed, in their eyes, from factually observable data to something dependent on user understandings and viewer perception. Descriptions of site and place were altered through interaction, with a new focus on local specificity in infrastructure. (C).

> *S2 I think [the map] shows pockets where there might be room for improvement or ways that the community could really be able to blossom, like if the homeowners and city are able to come together and really make that improvement, that's something that could really help the community. And I think that perception is the first way that we interact with a community.*

Outcome 3: Tactical mapping abstracted as project definition strategy

In their post-class narratives, students described ways in which specific tactics which had helped them think creatively about problem-framing in this class might be seen as extendible beyond this specific exercise, as strategies for research ideas or project-definition in other areas. Responses ranged from a new awareness of the limits of their own previous methods (see category A, column 3, table 1), to descriptions of the tactics as a complete strategic approach to problem-design (category C).

Some students described finding it hard to be responsible for developing a project approach. Their recognition of such discomfort was, however, already of value as a learning outcome (A).

> *S4 Before what I will do is just to, like, wait for something very interesting. Definitely it was not a process and sometimes I spent a lot of time in choosing the topic because I don't have a process probably.*

However many of those who had found value in the mapping tactics as a strategy for problem-framing, began to describe ways of using such methods for idea-searching in other contexts. (B)

> *S3 I think it's a good work to try to connect to the community and you can turn that into maybe even a business model, try to fulfill that need, put a business around it. I think that tactic is going to be useful.*

One of the more powerful outcomes was when students began to propose that the set of tactical approaches might serve as conceptual tools for framing other kinds of research projects. (C)

> *S2 I think, kind of, taking the general ideas but being able to take it, maybe not on a map, but these are all still tools that could be applied to, like, a future research type design project.*

Finally a few described not only identifying an abstracted approach in this tactical process but understanding that such an approach might help ensure a greater openness to new ideas and unexpected innovation (C).

> *S3 I think, especially the part where we were looking on site for factors that we hadn't thought about before, I think that's, like, the biggest thing I'm going to take away from this class, that I learned here.*

Discussion

The tactical approach and geo-spatial tools allowed students to start to re-imagine a site without needing to begin that work by first conceptually framing their approach. By positioning the data as the site of exploration, students were absolved of the responsibility of initiating a project-direction and site approach, and instead learnt to allow their project-frame to emerge from the observations made.

One unexpected advantage to the process may actually have been its uncertainty. Problem framing for a real community involves not only being open to multiple opportunities but being willing to explore and test aspects that might not have solutions. Openness to failure may have been one of the most valuable learning outcomes in terms of problem-framing skills. Interestingly, the anxiety felt in the open-endedness may have been somewhat offset by the confidence engineering students' found working within the technical framework of the GIS technology, as well as the tactical teaching structure provided. An additional support structure may have been the dual nature of the maps; not only were they tools for exploration but they also became tools for visualization and stakeholder communication.

S6   I think the visual quality of the map is very important to communicate. Especially when we go to the community center with our results I think they have to be clear and visually appealing at the same time and tell a story.

Integrated into the pedagogical approach was the notion of iteration, students were exposed to a context in which processes both of site-study and of idea-generation were presented as cyclical, such that any single data exploration or project direction were just one phase in an ongoing process. This notion was made most explicit in repeated visits to the site and community for data gathering and analysis, but gradually that physical experience became implicit in the process of re-visioning the project-definition, in the work outcome and, interestingly, in students' descriptions of the process.

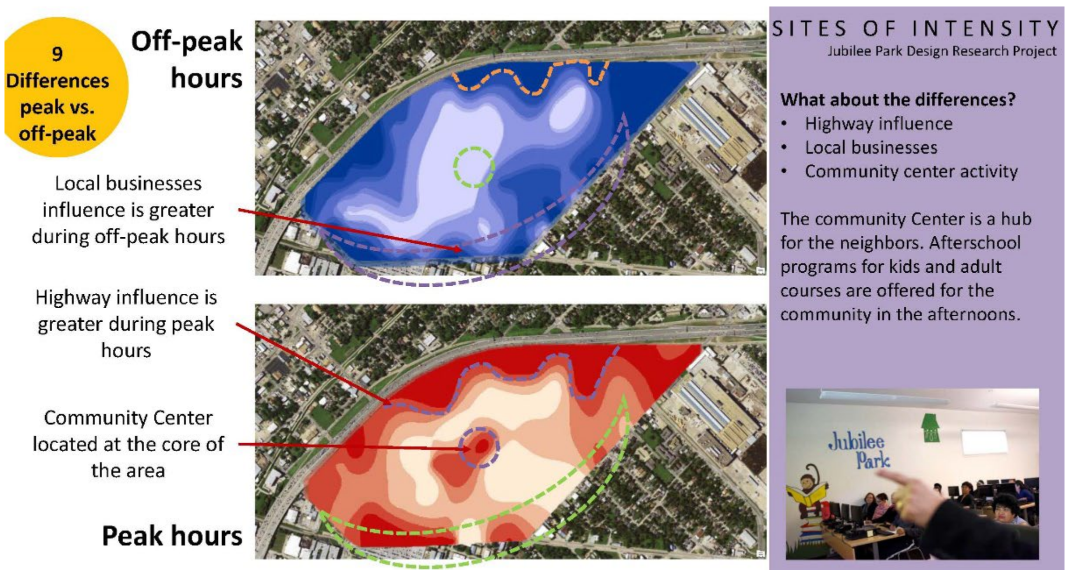


Figure 7.2 Example of group final neighborhood map study

The physical outcome of the projects themselves were a series of map studies in which overlapping issues of physical, perceptual and social data were visualized (see figure 1). From these explorations project-frames were developed, and community-specific engineering projects proposed. Of greatest interest, in the context of this paper, were those proposals in which students used the observational intensity of geo-data exploration to avoid early project fixation, and to allow the project-focus to emerge from the interaction of the physical, social and perceptual data. Thus some of the project-frames presented to the community were aspects which neither the students nor even the stakeholders themselves would originally have verbalized or selected as sites requiring engineering solutions.

Conclusion

Engineering and its associated technologies affect people's lives in multiple ways, not only the physical aspects of health and safety but the social and human aspects of communication, integration of systems and equity of infrastructures (Titus et al., 2011). It is of little surprise then that the experiential strategies of project based learning (PBL) can help students learn to better approach engineering within a social context. Indeed PBL has been shown to be a valuable teaching strategy for the integration of sustainable development practices with more technical engineering content, and moreover, to do so in a manner that offers heightened potential for the development of innovative engineering solutions and creative learning outcomes. (Rulifson et al., 2018; Gonzalez, Bremer, & Mercado, 2011; Lehmann et al., 2008; Boni & Pérez-Foguet, 2008).

On the other hand, the integration of these aspects into the engineering education framework is not easy. Not only do traditional education methods and timetables have difficulty in supporting the more open-ended aspects of both project-based and human-centered design, but these two aspects of engineering innovation, the solution-centered and the design-centered, may in fact develop out of completely different knowledge systems, such that expertise and disciplinary experience in one is very hard to integrate with expertise in the other (Nieusma, 2018).

The tactical teaching approach that Pausch named a 'head-fake' in which learning in one area takes place specifically through the trick of focusing carefully elsewhere (Pausch, 2008), may provide a way for engineering schools to approach this conundrum. Might students be able to better exploit a new way of learning if they come across that learning structure by chance while focused on a more familiar task, rather than being asked to jump headlong into a difficult and unfamiliar human-centered conceptual thinking context?

Map making and creative mapping processes seem to provide the context for such an opportunity. While focused on the gathering and analysis of spatial data, students seem to be more willing to allow the open-ended implications of site and community to slip into their work, from the side. The mapping project requires focused observation, intense communication and thoughtful investigation of social and physical aspects of a site. This hand-on work of data gathering itself may be key to the 'head-fake' mechanism; clearly the looking is as valuable as the mapping, but it is hard to undertake intense looking without the goal of a focused job that needs to be done.

Designers and artists sketch when they visit a site. In spite of their cameras and recording systems designers still tend to record observations with a pencil, on a page. The sketch works as a shorthand notation for things that have been noticed, it allows text and figure to be united on single page. Further, the diagrammatic nature of the sketch allows observation to lead to thinking during the process of drawing (Buxton, 2007; Pendleton-Jullian, 1996; Schütze, Sachse, & Römer, 2003; Ullman, Wood, & Craig, 1990). But the process of sketching is also an excuse, it is a way to take time, to allow the eye and the mind to fully observe, it stops the mind from following familiar paths of solution finding by interrupting facile thinking with active doing.

Like sketching, the gathering of data and the making of maps may have as much value for the engineering student as a process as it does as a product. While making maps, the work of looking and imagining is able to happen in the background, while the mind is engaged in a practical spatial task. Indeed, this aspect may be exactly what gives mapping value as a creative tool for engineering. It is, then, perhaps not surprising that in the looking, social and human aspects of site are revealed and absorbed into the creative work process. The inherent and vital perceptions which were otherwise hard to uncover can quietly slide into the project-frame while student attention remains comfortably and firmly focused on the technical collection and analysis of data.

> *S6* *You know I think [the process] was natural, sometimes it was difficult at the beginning to map in this project, some social aspects are difficult to imagine.* But *then when you just do it, it becomes very clear. Well now that I've been focusing more about the process itself rather than the result, I think that helped me trying to go outside my comfort zone. At the beginning, and I think that's because of my undergraduate degree, I will define the results I want at the very beginning, so I will do all the work toward that result only and maybe that cut my vision for other possibilities. While here because we are more focused on process sometimes unexpected things pop up.*

Chapter 8

Conclusion

Infrastructure & Site Design

The urban landscape is a pattern of interconnected data: physical, experiential, social, political and historical, connected and ordered through its infrastructure networks. Infrastructure forms urban space, and engineers design its dynamic flows. Water, transport and ecological processes are orders which are understood spatially and are given a sustainable structure through integrated site-design. This site-design is a creative process.

Mapping reveals the nature of a site through a study of the patterns of the landscape in which social and ecological factors are dynamically integrated (Ahern 2007). The task of map-making requires one to look deeply, visualizing social, political and ecological systems, the geometry symbolizes messages of political power and a community's relationship with the natural environment. (Cosgrove and Daniels 1998; Harley 1998). Population growth, income inequality and climate change impose enormous responsibility upon the designers of our built environment to define its future sustainability as well as its livability and beauty. Such work takes technical skill, knowledge and creativity. Civil and environmental engineering students will need to take on these future responsibilities. As design-team leaders they must be equipped with both situated understandings of sustainable site design, and the creative confidence to lead the search for innovative solutions. Yet their current educational structure provides few strategic approaches to prepare them for such a task

This research seeks to explore and measure the extent to which geospatial data visualization and manipulation might be able to serve as a tactical methodology for teaching generative design and creative project-framing for engineering students. The strategic intersection of data, site and technology enabled by

GIS systems, when integrated with site-based teaching, can be developed and exploited as a way to integrate design-innovation processes into civil and environmental engineering education, and do so with both efficiency and efficacy.

Geo-Spatial Tactics

Focused specifically on the extent to which the new geo-spatial tactics and teaching methodologies impacted student design habits, the research first analyzed responses from a large group of undergraduate students, measuring the extent to which improvement could be seen in their design confidence, openness to iterative practices and self-understanding of their design process. Diving next into a measurement of the site-designs, rather than the students, we then tested the impact that the geo-spatial teaching tools and processes had had on the ensuing set of preliminary project outcomes. Finally, in a deeper look at the ways that student understanding developed over a full-semester study of more advanced students, rich qualitative outcomes were carefully analyzed to reveal a high-level of stakeholder impact on the problem-definition process, an aspect of site-design which is conceptual rather than visual, and highly transferable across disciplines.

Analysis 1 (Ch 5): design confidence

Approaching site-design with a package of tactics and geo-spatial mapping processes assisted young student-designers with divergent exploration and short-term design confidence. This assertion, built on broad student survey descriptions was revealed with great clarity, and may be the most positive result in this study. The Geo-design cards were well received by the engineering students, and data shows that the full package of GIS tools, design approach and tactics did indeed facilitate the move into open-ended design exploration, helping students feel less ‘stuck’ at the project’s start and supporting them on the path away from design fixation. While exploration did not ensure innovation, divergent exploration was certainly an essential first step towards wider and more creative solution sets.

Analysis 2 (Ch 6): creative outcomes

Problem solving in engineering often starts by narrowing the problem and then searching for solutions. Exploratory map-making provided students with an alternative work structure, inviting them to use data-layers and spatial play to widen the given problem-frame and explore alternative perspectives. Maps were introduced in this design-thinking strategy not as a set of problem solving tools, but first as a set of problem opening tools (MacEachren 1995).

Process oriented aspects of the generative design method were fairly easily taught and measured; results showing a greater *Quantity* and a greater *Variety* of map-ideas may only imply that the new tools did indeed teach students to increase their range of idea types, as well as the actual number of different ideas. More valuable was evidence that more unusual proposals seem to have joined the outcome set, the increased results for *Novelty* seems to show that the together the heuristics and the experimental context did inspire at least some creative experimentation. Given the short-structure of the workshop exercise, the lack of a strong average improvement in overall design *Quality* was not surprising, however the improvement in contextual *Relevance* was unexpected, and encouraging.

Taking a longer-term qualitative look at the same tactical approaches, study showed that the geo-spatial mapping tactics did seem to have enabled increased confidence in exploration. This creative play with data is tied to the idea of geo-browsing and can be seen as a way of inviting student-designers to reimagine, and re-describe the world in multiple ways.

Analysis 3 (Ch 7): inclusive problem-framing

The activity of data gathering, like sketching, was shown to have as important a learning value for its process as its product. The practical task of site mapping served as a deep observation tool for student-engineers, and invited the integration of environmental aspects of the site with social and human ones. The creative mapping processes analyzed were revealed to support a high degree of community-based problem-framing alongside the creative exploration, and to have helped students develop individual research-project definitions which were based on not only physical but social data of the real site.

Given the short nature of the experiment, it was difficult to see whether the shorter, classroom-based exploration into GIS mapping had any effect on students' integration of stakeholder views into their problem-framing. However, data shows that student project-outcomes revealed a significant increase in design '*Relevance*'. This sub-aspect of design *Quality* was measured by assessing student designs for visible connections to specific site issues such as topography, water systems and community structure, and its increase seems to imply that the focus on spatial data as a medium for creative exploration may at least have raised awareness of these situated and interrelated issues.

Future Work

Because students were given three new tool-sets to assist them in their site design process (a design-approach structure, the geo-design cards, and GIS itself) it was difficult to assess the independent value of the parts; while neither the process nor the cards can be used without the GIS mapping, it would be interesting to test the extent to which GIS alone might impact student outcomes or whether the tactical approaches provided an essential strategic element in the attempt to exploit the spatial structure.

Taking the same tactical approaches and tools into the longer study we observed that geo-spatial tactics do seem to have assisted student confidence in exploration as well as some level of creative data play, or geo-browsing (Peuquet and Kraak 2002). However, longer term iterative practice in the use of geo-spatial tactics would be interesting to study further, as well as any rate of increase in project-framing starts: first ideas may be less daunting if they aren't expected to lead to immediate correct answers.

Similarly cross-pollinating, it would also be interesting to use the quantitative measurement structures of the short study to assess the design project outcomes of the longer-phase teaching context. Although quantitatively weak due to the small sample size, outcomes would none-the-less be interesting to reference back to the qualitative results described in student interview data.

The project and site-based nature of the experiment was integral to the design process, but it also enabled a strong level of stakeholder engagement in project-framing outcomes. These outcomes would bear more quantitative study. It would be interesting to follow up, in later research, to see if long-term studies continue to reveal a positive ongoing focus on human-centered aspects in students' actual work outcomes beyond the project-frame. Identifying specific processes and tactical tools used could also reveal how stakeholder focus might be retained beyond the structures of social and civic data, and further integrated into students' creative spatial transformation.

Perhaps geo-spatial data structures can serve engineering students as a proxy site-voyage, encouraging explorations of context, form, community and ecology while remaining within a familiar technological structure. Within the context of tight schedules, one might ask if such site exploration, beyond the creative-generative thinking explored here, could also assist engineers towards more fully collaborative and sustainable site-design solutions.

A final valuable research outcome was an indication of the potential broader applicability of the design-learning skills taught, based on student descriptions of transferability. Reflecting on their experience of using spatial play to widen their topic exploration, a number of students described the geo-design process as a model which they imagined being able to make use of, in other environments. It would be interesting to develop this further, to work on strategies to increase such an important benefit, and to ask whether such transferability is limited to the broad process framework, or whether specific heuristics could also be re-applied, by students, to different tasks.

Several of the specific geo-design cards focus on creative exploration through abstraction of the data, by moving tangible structures into the realm of spatial transformation. It would be interesting to further explore this spatial abstraction to uncover the extent to which student designers might struggle to conceptually separate spatial explorations from the specifics of actual site plans (Cousins 2005). One can imagine that it could be precisely the potential of spatial abstraction of non-visual site data such as human-centered or social data, that could give mapping, like diagraming, an increasingly powerful role on the path to more divergent idea sets. Furthermore, in such a longitudinal study, a developing cognitive awareness of their own design process would probably have a greater impact on students' abilities to develop their own processes (Eris 2004) giving greater value to the 'browsing' nature of design and less to specific heuristic tactics. An analysis of these kinds of exploratory processes would require a more detailed focus on specific steps, ambitions and tools used by individual designers and a longer, qualitative study not only of the ways in which student designers navigate the spatial design process, but on the specific designed outcomes from their work.

Creativity in Engineering Education

Preparing engineering students to approach site-design with creative confidence and skills requires training students in creative design processes. This study attempted to identify opportunities within the processes of geo-spatial mapping in which a tactical engagement with site-specific spatial data might open opportunities for creative design-thinking approaches. The shift from site-specific data to the generation of ideas was facilitated by the abstraction of the geo-spatial digital framework. The results of this work propose to support educational outcomes for civil and environmental engineering students in three ways. First, by designing and testing specific teaching techniques and heuristic tools, the research developed a methodology to support the teaching of design creativity focused specifically on civil and environmental engineering students. Secondly, by using geo-spatial structures as the medium for these techniques, the research postulated the efficiency of double-dipping; spatial structures also serve engineering students in analysis, visualization and site-engagement, thus connecting student-designers to additional benefits while they explore creative practices. Finally, by exploring student outcomes in both quantitative and qualitative ways, the research was able to demonstrate that beyond its impact on specific design outcomes, the geo-spatial design practices enabled, for some, a heightened degree of community engagement, and may also have potential, in its spatial abstraction, to be applied beyond the boundaries of these specific site-based contexts, to wider engineering problem-framing challenges.

APPENDIX

Heuristic TOOL 1

UNBUILD
the environment inspires the function or pattern of the new

mapping heuristic
- uncover hidden nature
- map the natural as a model for the new

examples
- water sources as model plan structure
- wind or topography as pattern
- invisible aspects: sound or shadow, impact new vision

engineering idea
environment plays a role in function or product physically incorporated

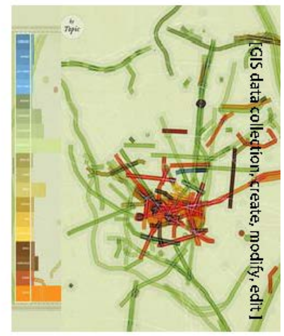
Heuristic TOOL 4

USER HABITS & VISION
incorporate user preferences and user understandings of the environment

mapping heuristic
- map community use patterns
- uncover local site imagination
- imagine a new site approach direction
- allow use model to impact physical site

examples
- media mentions of addresses mapped
- childrens vision and site knowledge
- local landmarks and sites of memory
- local place knowledge & imagination

engineering idea
human-centered product design interfaces with user input preferences



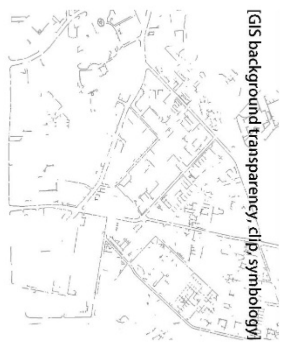
Heuristic TOOL 2

ISOLATE
extract aspects or issues of the site and see each separately

mapping heuristic
- see unexpected patterns
- uncover hidden voids
- juxtapose differences

examples
- walkable pavement gaps
- see topography alone
- only trees, no buildings
- movement without roads

engineering idea
break problem into pieces to address each attribute separately



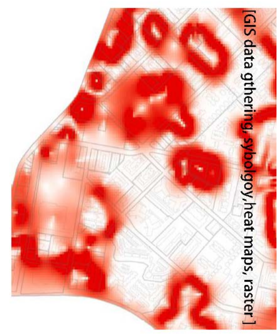
Heuristic TOOL 5

PERCEPTION
map the invisible site

mapping heuristic
- map an aspect of the site which is perceived but not seen
- observe and annotate user perceptions through ways of acting and knowing

examples
- perceptions of incongruity between structure & difference of quality
- wind, sunshine, soil types, noise levels
- sensation of safety, warmth

engineering idea
product develops from observation & careful annotation of user engagement planning description



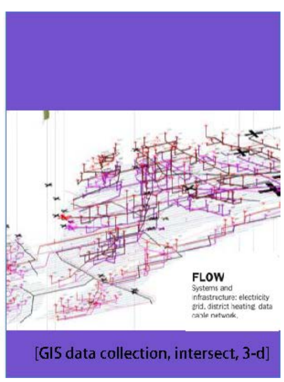
Heuristic TOOL 3

OVERLAP & CONNECT
bring together & connect different flows, explore sites of overlap in space

mapping heuristic
- generate questions from the overlaps
- flows of the city alter the patterns
- investigate sites of overlapped systems

examples
- infrastructures, cable network, electric grid as model for plan structure
- overlap between dynamic maps of heat island effect & transportation system

engineering idea
product has physical connections between components that serve distinct functions



Heuristic TOOL 6

UNCOVER MECHANISMS
re-cycle historic elements or site processes for new forms or functions

mapping heuristic
- map historic elements as patterns
- map existing or old site systems, delivery systems, cultural networks, as patterns for new use structures

examples
- disappeared historical streams and blocks as model for new city structure, interrupting modern grid to form park
- delivery route informs public pathway

engineering idea
product incorporates repurposed product as a functional component

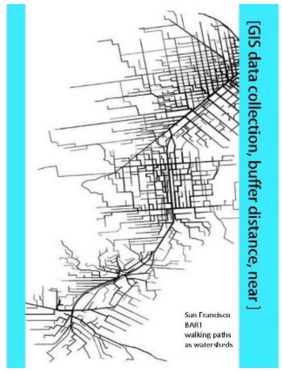
Heuristic TOOL 7

SEQUENCE
represent motion as form,
impose a new hierarchy on the site

mapping heuristic
- map movement across the site in time
- imagine starting from a different place
- make time and quantity visible in order

examples
- walking paths of near train stops
- bus routes mapped as solid paths
- overlapping webs of ways of coming to know the neighborhood

engineering idea
product function vision evolves as a series of steps



Heuristic TOOL 8

CHANGE IN TIME
map change perceived through time

mapping heuristic
- map the function and then show how it changes in time, as a third dimension
- map time in motion or sequence

examples
- movement of the river over the years
- process of coming to know, mapped, as a topography of comfort
- layers of movement overlapped in time form a new spatial model of site

engineering idea
a component serves multiple functions or alters its function over time

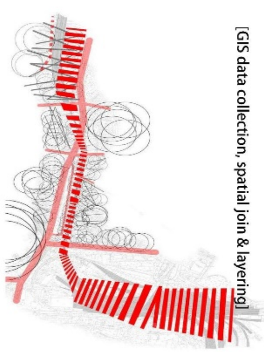
Heuristic TOOL 9

EXTEND SURFACE PATTERN
environmental patterns inspire the new

mapping heuristic
- unwrap and trace existing eco-patterns, warp, distort or extrude representations
- existing aspects are re-diagramed, textured or extended as a new model

examples
- diagram circulation as density & density values as length
- interactions between city grids and grid distortions due to water flow patterns
- topography interaction with memory site

engineering idea
product surfaces are longer or wider than assumed, geometry is recreated, wrapped



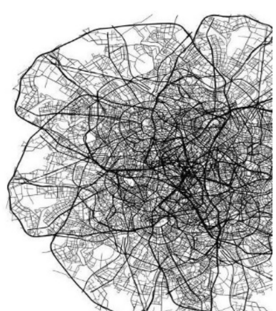
Heuristic TOOL 10

REPETITION & SCALE
surprise and disrupt the plan with unexpected adjacencies or dependencies

mapping heuristic
- array multiple layers of elements in plan
- re-position layers at different scales

examples
- maps city street lines & rotate/repeat, creating pixelated array model of site
- scaled land forms revisited as site forms
- familiar site plan layout re-imagined by multiple positioning options.
- map to create a pixelated land pattern

engineering idea
repeat multiples of the same functional component



[GIS edit, intersect, redraw, merge]

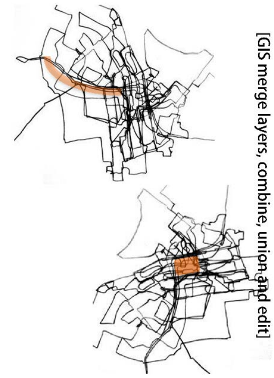
Heuristic TOOL 11

DISGUISE. RE-ORIENT
alter and re-think a map by transforming & re-orienting whole or parts

mapping heuristic
- map elements and rotate, re-orient and re-layer to see in a different way
- imagine how the new alters the priorities or visions of the old
- combine, adapt use, eliminate, swop

examples
- memory map of site walking re-orients places of importance and re-travelled
- south oriented globe changes perception of world importance

engineering idea
product flips horizontally/vertically, transforms, swops for different function



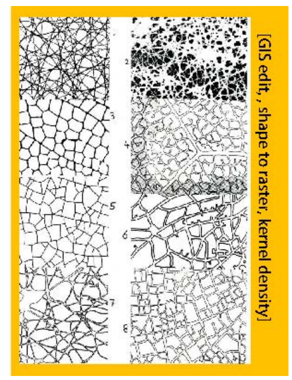
Heuristic TOOL 12

ANALOGY
re-describe plan idea through analogy: like a tree or like a biological structure

mapping heuristic
- bring a pattern from different structure
- map elements so they seem similar to something natural, or familiar
- subdivide and add to site-lines to create pattern through analogy

examples
- site value reimagined as topography
- street-light buffer seen as site structure
- familiar form adapted via biomimicry

engineering idea
transfer information from familiar to new to construct new ideas



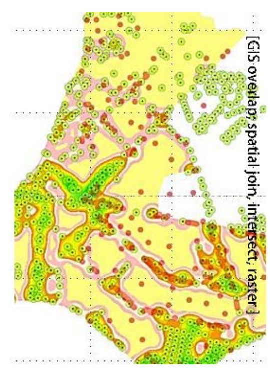
Heuristic TOOL 13

PROVOCATION & MISUSE
creative misuse of the toolkit

mapping heuristic
- modify plan with idea provoking operators
- search for aspects of difference, break symmetry, remove, unite, divide

examples
- intercept conventional pattern by slicing through, and inserting
- visualize crime zones as topography integrated with streetlight buffers

engineering idea
modify concept using idea provoking operators: unification, multiplication, division, object removal



OBSERVATION TOOL 1

GO FISH: AMAZING MAPS
precedents and inspiration

- **collect, gather, notice, record**

examples
- surprising and simple information
- ordinary data made visible
- communicates in unexpected ways
- share and discuss

engineering idea
reading previous research to explore alternative approaches

OBSERVATION TOOL 2

PILE-IT ON DATA
just gather everything you can

- **collect, gather, notice, record**

examples
- surprising and simple information
- newspaper information
- census information
- stories
- numbers
- sizes
- problems issues

engineering idea
LOTS of additional data to allow opportunity for unexpected to appear

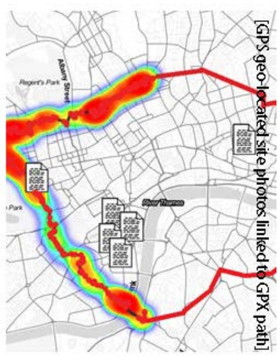
OBSERVATION TOOL 3

PHOTO_WALK
observe and record a journey

- **collect, gather, notice, record**

examples
- wind or topography as pattern
- invisible aspects: sound or shadow, impact new vision
- a user-centered insight *(talk!)*
- connect to a personal expertise
- something very small
- something very large
- something that shows contrast
- something that shows a pattern
- something that surprises you
- something that disrupts assumptions
- a window to the community
- an aspect that shows challenges
- a unique personal perspective

engineering idea



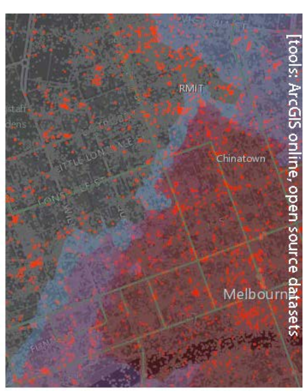
OBSERVATION TOOL 4

OPEN PLAY
explore data and maps through play

- **collect, gather, notice, record**

examples
- a. explore a range of data including an unexpected online datasets
- b. bring together at least 2 wildly different sets
- c. combine layers to make something beautiful and interesting
- d. tell a story in the map

engineering idea
explore through open experimentation and intuition



POSITIONING TOOL 1

SQUEEZE THE SPONGE
extract results from your journey

- **expose alternative positions on the site & community**
- **collaborate & challenge**
- **think, share, write perspectives**
- *"our POV on the site is..."*

examples
- uncover a pattern
- invisible aspects
- a user-centered insights
- personal expertise uncovered
- a surprising unexpected intuition

engineering idea
brainstorming on a napkin

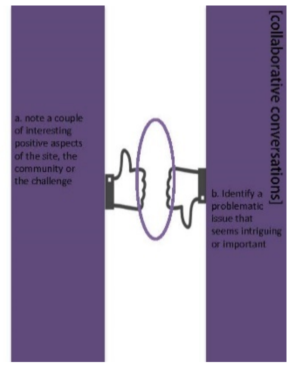
POSITIONING TOOL 2

THE GOOD & THE BAD
learn from uncovering extremes

- **extract POV on values & problems**
- **collaborate & challenge**
- **what tensions are shared?**
- *"this may be true but this also means. ."*

examples
- uncover a pattern
- invisible aspects
- a user-centered insights
- personal expertise uncovered
- a surprising unexpected intuition

engineering idea
brainstorming on a napkin



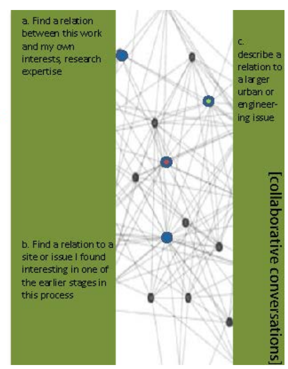
POSITIONING TOOL 3

CONNECT THE DOTS
describe imaginary relationships

- **expose alternative positions on the site & community**
- **collaborate & challenge**
- **think, share, write perspectives**
- *"our POV on the site is..."*

examples
- discover connections
- invisible overlaps inside & outside
- user-centered ideas
- personal hopes
- unexpected intuition

engineering idea
brainstorming on a napkin



POSITIONING TOOL 4

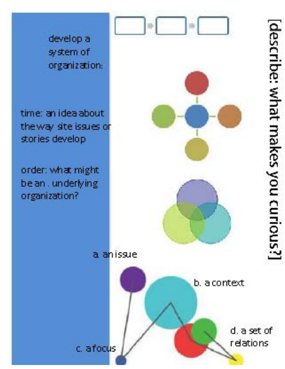
STRUCTURAL DESIGN
build challenges into a story

- **a way to link ideas that inspire**
- **direction for curiosity**
- **dont stick with the obvious**
- **remember the obvious**

examples
- try to write first (POV) statements

"our POV on the relation between the site and this issue might be..."

engineering idea
team structures and areas of research



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