PAPER PROCEEDINGS

Intersections Between the Academy and Practice

Innovative Technologies in Design and Delivery

AIA ACSA
2016 AIA/ACSA INTERSECTIONS SYMPOSIUM

Intersections Between the Academy and Practice

PAPERS FROM THE 2016 AIA/ACSA INTERSECTIONS SYMPOSIUM

SYMPOSIUM CO-CHAIRS:

Rashida Ng, Temple University
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Intersections Between the Academy and Practice:
Innovative Technologies in Design and Delivery
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The American Institute of Architects (AIA) and the Association of Collegiate Schools of Architecture (ACSA) are pleased to partner on this 2nd annual symposium, dedicated to the integration of education, research and practice of technologies at the 2016 AIA Convention in Philadelphia. This symposium focused on TECHNOLOGIES; specifically innovative technologies and unknown areas that will revolutionize the built environment. Practitioners and Researchers shared their investigations on impactful technologies, ideas in testing stage, or profound mechanisms that have the potential to reform the design and building industry.

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Pedagogical Explorations of an Open-Source Architecture Paradigm in Emerging Design Technologies

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Open-Source Architecture is an emerging paradigm advocating peer-to-peer collectivity, inclusiveness and participatory culture in architectural design. These conditions support a broad interest at the intersection of education, research and practice in emerging design technologies exploring formal complexity, performance, biomimicry and responsiveness. In the last decade, rich participatory, open-source communities, open-source software, and open-source hardware, created by and designed for the fields of parametric and algorithmic design, visual programming, and physical computing have emerged with resulting opportunities for change in architectural education. We discuss pedagogical approaches that introduce pathways for open-source cultures in architectural design and personal learning networks for professional development.

OPEN SOURCE CONCEPTS

With the popular trend of individual media creation via Web 2.0 technologies, open source is a term and concept associated with the notion of participatory culture. While this concept was initiated by the software programming community, it has evolved into open source culture, open source hardware, and open content. Wikipedia, Flickr, YouTube, research communities of biotechnology (e.g., BioBricks Foundation) are a few examples (Cheliotis 2009; Ceraso and Pruchnic 2011; Hope 2008; Voyce 2011). Open source is also associated with leveraging voluntary labor in the form of crowdsourcing to outsource portions of a larger task to an indefinite group of volunteers, or 'prosumption' to involve consumers in the production of goods and services or beta testing to enhance usability(Ceraso and Pruchnic 2011). Figure 1 illustrates various open source concepts that have evolved from the initial collaborative software paradigm to other areas with the technological advancements of Web 2.0 platforms and social media, and into a broader open source culture.

OPEN SOURCE PRODUCTION MODES

Cheliotis (2009) explains the fundamental difference between producing functional and cultural goods. Functional goods such as software programs are typically developed based on a common vision for functionality and involve well-coordinated efforts to facilitate integration and exchange of individual components. In contrast, cultural goods such as music are encouraged to create variations of the same product to appeal to the taste of diverse audiences. Cheliotis (2009) observes that online communities of cultural products adopt loose- or no-coordination strategies compared to the well-coordinated organization of software production. Thus he terms software production modes as *branching, merging and forking*. This describes how software developers *branch some version of source code independently from the core of the software and merge the code back when appropriate. Forking is a variation that happens when one version of a source code is developed into an independent version without merging, when some developers seek to develop new versions because of opinion differences or specific needs*. On the other hand, cultural products which are sought for their artistic value adopt *ad-hoc and emergent* patterns of collaboration. Figure 2 diagrams and compares production modes of software and cultural products. The creation and sharing of cultural products inevitably involve consideration of copyright issues which are traditionally devised to protect the creator. The following section discusses copyright issues that are impacted by open source production.

INTELLECTUAL PROPERTY AND LICENSING

The history of protecting the copyright of original work in the United States is as old as the country's founding. The Copyright Act of 1790 was focused on the "rights and liberty of printing, reprinting, publishing and vending" while Article I, Section 8, Clause 8 of the United States Constitution grants the power to "promote the progress of science and useful arts" to Congress. A copyright on intellectual property is granted automatically and immediately upon creation of a work. Open source, by its very nature, is created with the intention of becoming part of the public domain. This is where a mechanism for sharing open source content is required, explicitly allowing for open sourcing and third party augmentations.

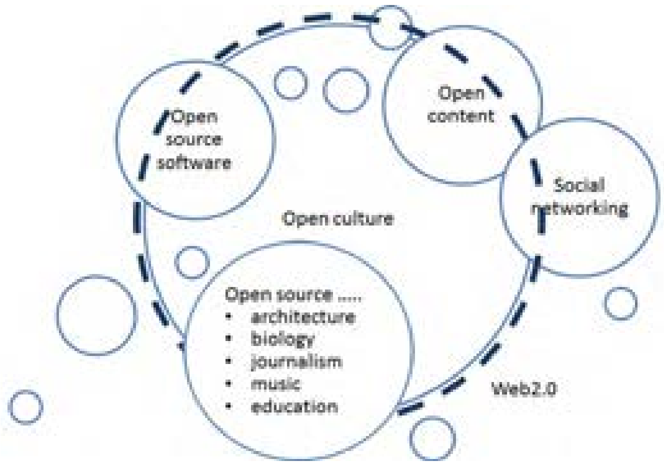

Figure 1. Open Source Concepts.

Before we continue on with the licensing of intellectual property for open source purposes, it is important to discuss why a person or firm would want to participate and contribute within an open source community and why we should feel encouraged revealing our own work and allowing others to augment, revise and manipulate our work. We will discuss the following reasons in the Business Opportunities section later, but it is relevant to mention them here: 1) it has been shown that the work of the contributor to an open source community will benefit from the exposure and; 2) it builds the reputation within the open source community by "producing positive network externalities for the author or inventor" (Cheliotis 2009).

Once a creator has decided to share his or her content as open source, it is important to license the work as intended. Creative Commons (CC) is currently the most substantial avenue for licensing available. A visit to the organization's website (creativecommons.org) will allow a user to utilize the CC License Chooser tool. By answering several questions about the intended use of the content, a three layer CC License is created for use with the work to be shared. The three layers make the CC License unique by providing 1) the legal code, 2) a common deed or "human readable" description, and 3) CC Rights Expression Language (REL) or "machine readable" information that makes the work searchable and indexable by search engines (creativecommons.org 2016).

Using the CC License, an author can choose to share his or her work with or without restrictions. Common restrictions include: not for commercial use, share-alike (copyleft), and without augmentation. Careful consideration of the license by the author will allow the open content to have the most impactful life within an open source community.

OPEN CONTENT IN ARCHITECTURE

Examples of open content in architecture can range from digital models, computer code, script, audio-visual recordings, architectural or engineering plans, drawings, and specifications. In recent years the broader adoption of parametric modeling, visual scripting, and BIM has been accompanied by the rapid growth of online communities which focus on digital design environments and their user support, component, examples sharing, and learning (e.g., grasshopper3d.com, revitcity.com), or software development (e.g., processing.org, food4rhino.com). Such online communities have become platforms for users to find scripts, add-ons, and software that address commonly needed functionalities, and also direct interfaces for software developers to better understand customer needs. At the same time, many users share original scripted or digital models which offer inspiration to other users who may reuse modeled components, or customize examples for their own purposes. Some websites adopt standard copyright conditions for sharing material on their websites while others are covered under the creative commons license for non-commercial use.

A few architects have manifested open-source strategies (Van den Bergh, 2013). For example, UNStudio launched in 2013 an open source initiative and online platform (i.e., *Knowledge Platforms*) to disseminate selected topics by the firm's team members. Knowledge is shared in the form of blogs and articles which can be accessed by the general public and be commented on or rated, and shared via social media after registration. The site has a 'MYPLATFORM' function (Figure 3) which allows users to select, organize, and contribute their topics of interest. UNStudio aimed to make this platform a knowledge repository and exchange platform with external collaborators. The intent is to engage with and co-create beyond the office boundary for new directions. The depth and scope of articles varies from short promotional articles to more in-depth research topics related to construction materials, innovative and smart systems, and sustainability. The platform performs as a repository of selected topics, a marketing and dissemination tool, and a community forum with external members. MYPLATFORM is bound by the Creative Commons Attribution-NonCommercial-ShareAlike license ("CC License") which allows free sharing and adaptation of others' work when giving appropriate credit and acknowledging modifications and distributing contributions under the same original license. The work cannot be used for commercial purposes.

Chilean architect Alejandro Aravena advocates open-source strategies for the global affordable housing needs. On his firm Elemental's website (Figure 4), four low-cost housing projects' drawings including site plans, architectural plans, and details, are shared in CAD and PDF file format, to convince developers and government agencies of the viability of proven designs. The architect disclaims legal responsibility of the plans reuse by others and issues the plans as guides to be adapted to meet local building codes and material and construction constraints. The use of the firm brand ELEMENTAL is not allowed.

Within the context of sharing architectural research with the general public, Michael Green Architecture (MGA) released in 2012, a 240-page research report on wooden skyscrapers, including details, sections, cost and reference projects (http://mg-architecture.ca/work/the-case-for-tall-wood/). The architect publicly shares this report through the firm's website.

The WikiHouse project (http://www.wikihouse.cc/) by Architecture 00 is an open source initiative that advocates open design with a global community incorporating principles of user driven design, mass customization, digital fabrication, and plug-and-play systems. The backbone of the project is a commons platform (Figure 5) linked with Google Drive which can be accessed after registration to review others' work and to create new projects. The commons is shared under a CC-BY-SA 4.0 (creative commons attribution-sharealike 4.0 international) license which allows free sharing and adapting others' work when giving appropriate credit and acknowledging modifications and

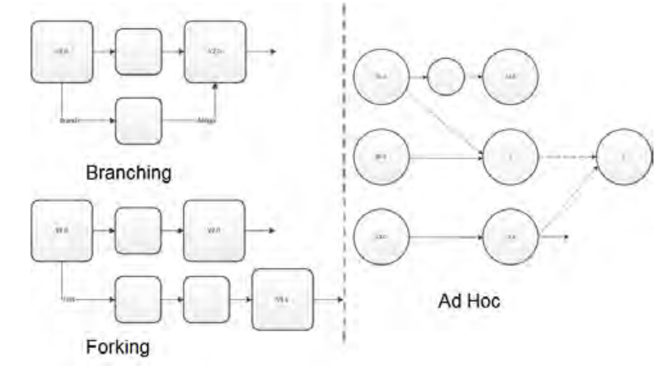

Figure 2. Open source software production (branching, forking) and cultural production (ad-hoc) (adapted from Cheliotis, 2009).

distributing contributions under the same original license. WikiHouse uses a disclaimer that puts responsibility on the user to meet local codes and regulations, to ensure safe use of the information, free sharing of contributions, compliance with the creative commons license, and restriction of use of the WikiHouse logo.

Opendesk.cc (https://www.opendesk.cc/) is a furniture design collaborative that connects designers, manufacturers and customers. The designs are prepared for CNC fabrication. Designers can choose to open source their designs or sell proprietary licenses via Opendesk. Users can either download for free complete design d ocumentation(cut sheet files in Autodesk dxf file format, PDF assembly instructions, CC license text file) to non-commercially manufacture themselves, or purchase through a local registered professional maker on the Opendesk network.

The examples discussed above can be classified based on the type of content (i.e., script, digital model, drawings and plans, technical report, marketing material) and whether the product is shared with the intent for collaborative peer production or one-way dissemination (Table 1). Sharing digital models, code, script, or CAD files allow copying, modification of the designs while technical reports include sufficient details about specific building technologies. It is notable that original plans or technical reports are published for others to use at their own responsibility. Material that includes photos, diagrams, and textual information but not enough specifics can be classified as marketing material.

Table 1. Categorization of open source examples in architecture by content and mode of sharing

	ONE-WAY DISSEMINATION	COLLABORATIVE PEER PRODUCTION
Digital models, script		grasshopper3d.com, revitcity.com processing.org, openprocesing.org WikiHouse, Opendesk
Drawing, plans (CAD files)	ELEMENTAL	WikiHouse, Opendesk
Technical report	MGA	UNStudio
Marketing material	UNStudio	UNStudio

The examples can also be categorized by the type of online platforms (i.e., website vs. collaborative platform) and the type of licensing agreements they utilize (Table 2).

Table 2. Categorization of open source examples in architecture by online platform and licensing

	TRADITIONAL WEBSITE	COLLABORATIVE PLATFORM
Custom disclaimer	ELEMENTAL, MGA	grasshopper3d.com revitcity.com
CC License (Creative Commons)		UNStudio, WikiHouse, opendesk, processing.org, openprocesing.org

PEDAGOGICAL EXPLORATIONS IN THE DIGITAL DESIGN METHODS STUDIO

Evolving open source tools and communities are relevant to academia and practice on multiple levels, regarding design scholarship, digital design skills and tools. To examine the implications of the open source paradigm, we asked the following questions:

- What are the connections between academic scholarship and open source practices?
- What are the related research skills and information literacy requirements for students?
- What open source strategies can be incorporated into the studio?
- What online platforms are applicable to the design studio?

OPEN SOURCE AND SCHOLARSHIP

Academic research, teaching, and engagement, are defined within the conventions of scholarship. Research practices require training in research methods that acknowledge existing research and contributions of others, define problems, and apply appropriate research methods. Research findings are published through rigorous peer review processes. Open source scholarship poses questions regarding the norms of academic recognition including intellectual ownership, impact factors, protection of human subjects (i.e., institutional review board (IRB) protocols). On the other hand, teaching material including syllabus and assignments are typically the property of the instructor's university and be subject to restrictions of sharing openly. Despite such barriers, some academics share whole or parts of their work. Some choose to share independent teaching material via personal blogs, while others share partial course content in terms of partial video recordings via Vimeo, YouTube, or course material (e.g., course syllabi, assignments, student work) via open courseware (e.g., wikispaces.com, personal blogs, Wordpress).

RESEARCH SKILLS AND INFORMATION LITERACY IN THE DIGITAL DESIGN METHODS STUDIO

Incorporating open source content into the classroom requires students to acquire information literacy skills as content users and contributors. The authors found needs in teaching digital design methods incorporating various digital technologies and methods. While students learn relevant digital

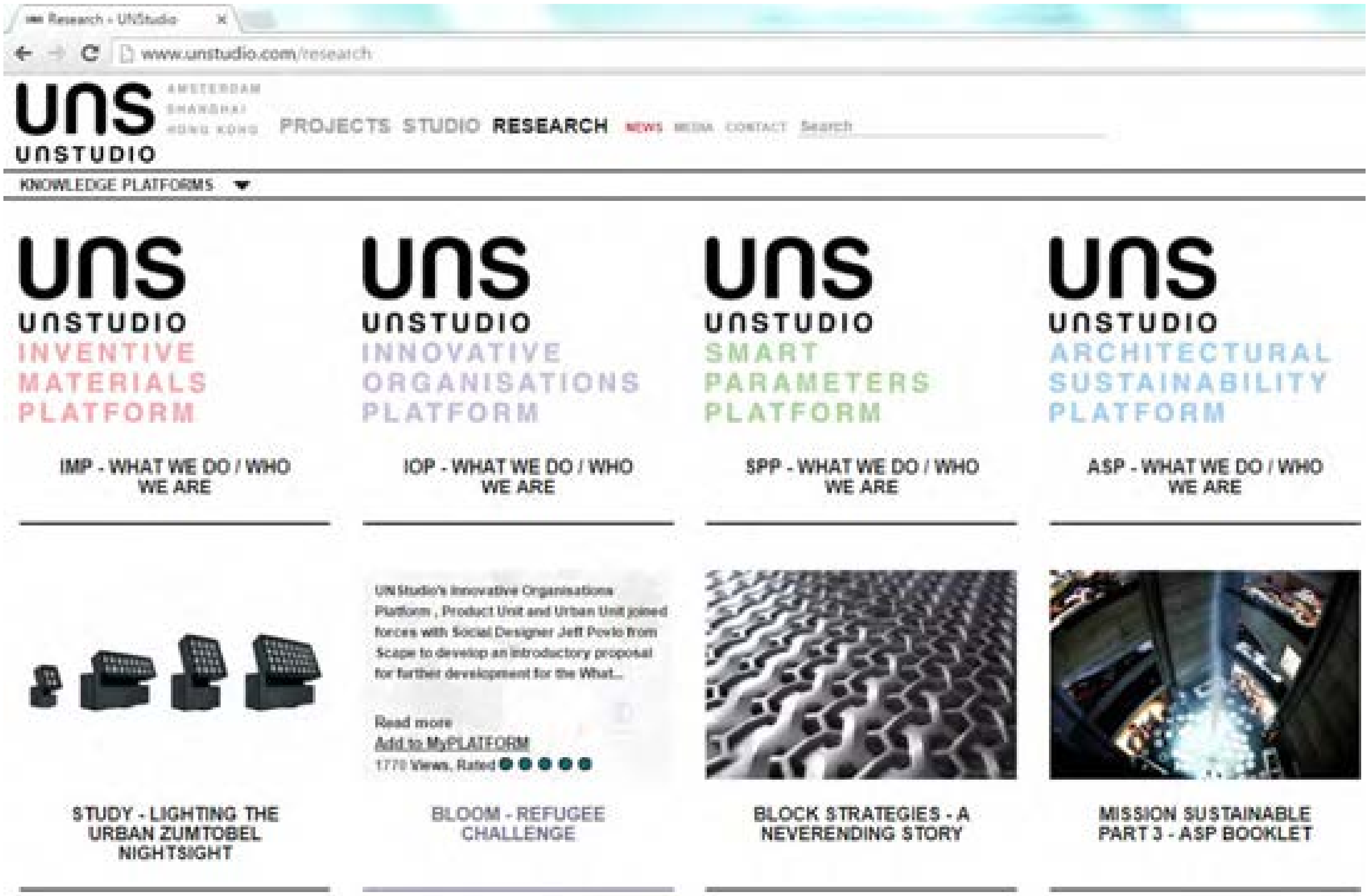

Figure 3. UNStudio Knowledge Platforms. (Source: http://www.unstudio.com/research)

skillsets in support courses, applying those skills on design studio projects often requires advanced skillsets which are not completely achieved in the classroom. In such cases various open online content including tutorials, classroom recordings, examples and Q&A information can be helpful. Open source information literacy starts with the ability to find appropriate sources and evaluating the best sources among the vast material that is accessible.

After being able to identify the right information, students need to apply and refine the information for their own purposes. If the content is an open source digital model or code that can be modified, customized to a student's project, the student and instructor need to determine whether it is acceptable to reuse the content as part of the student's own project, and acknowledge copyright and licensing agreements embedded in the content. After gaining confidence with using open content, students may also be tasked to become contributors of open content that can be accessed and used by external communities. Algorithmic designs are procedural content where the coding or scripting is as important as the resulting model or image. Many examples of such content can be found on various computational design blogs, forums, and course websites. In architectural robotics projects, the use of microcontrollers with real-time sensing and actuating devices, involves algorithms and physical prototypes, which can be replicated if the algorithms, electric circuits, fabrication instructions, digital source files, and assembly and operation instructions are shared. Such examples can be found on DIY communities such as the instructables.com website.

OPEN SOURCE PLATFORMS FOR DIGITAL DESIGN AND PROTOTYPING

The authors have used the Arduino microcontroller, open source hardware, and Processing, an open source software interface, Firefly—a Rhino/Grasshopper visual programming interface for the Arduino, Rhino3D (proprietary software) , Grasshopper and other add-on software for simulation purposes (e.g., Karamba3d, Weaverbird, Galapagos, Octopus, etc.). In the context of the authors' own design explorations and teaching of responsive design studios, open source has proved to be helpful for learning, reusing and customizing common library objects. Subsequently, code, component models, and lessons learned from these earlier classes have been provided to students of future studios.

OPEN DESIGN COMMUNITY PLATFORM

While we observed a large number of open source websites, the authors utilized the university Blackboard courseware and the university internal network server for sharing and posting information, data, document, code, and file sharing. The Blackboard courseware facilitates user content sharing via discussion forums for reading discussions, blogging for seminar and research topic sharing. In parallel, the university server proved to be effective for students posting and sharing source files, digital models of ongoing design work, codes, and all relevant design content. When using the network server it is suggested to provide folder templates and file templates for the students to be followed.

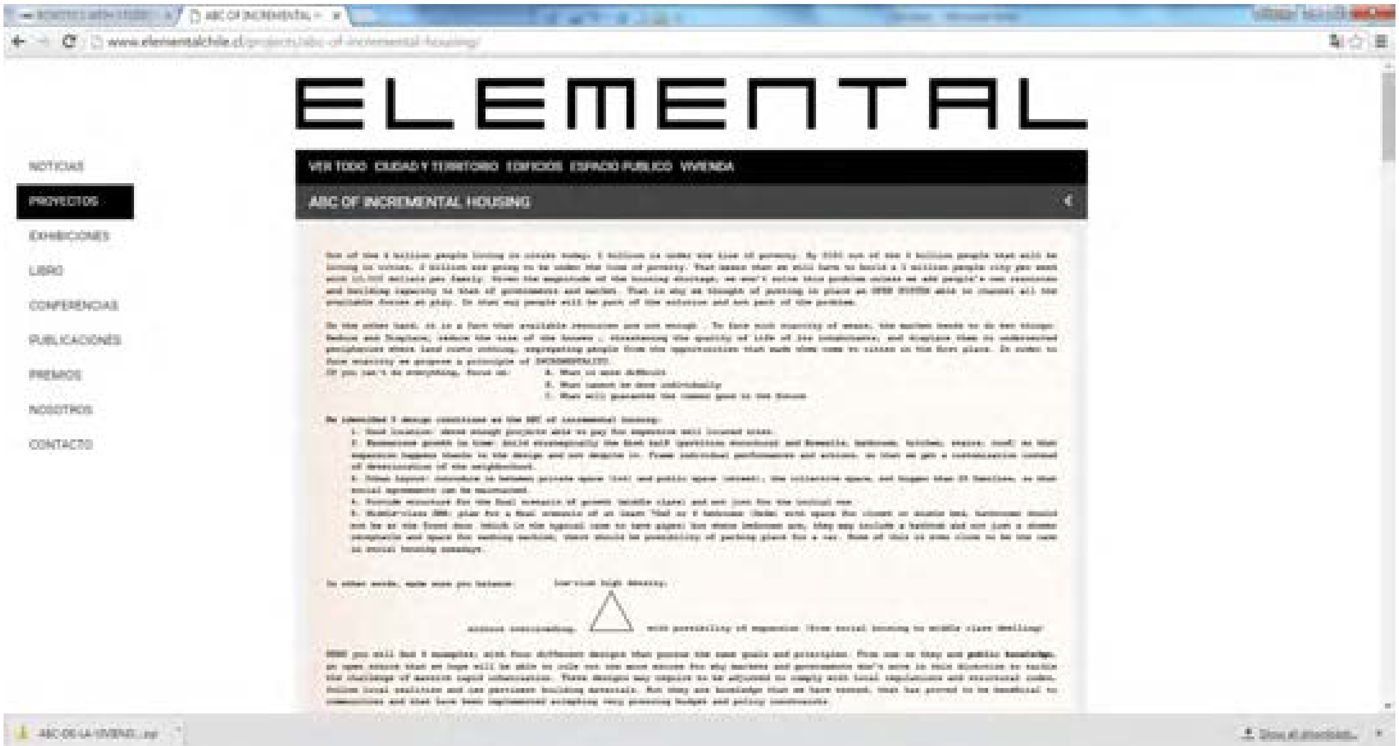

Figure 4. Alejandro Aravena's ABC of Incremental Housing (Source: http://www.elementalchile.cl/projects/abc-of-incremental-housing/)

OPEN SOURCES FOR DIGITAL DESIGN METHODS

The incredible growth of online communities, digital tool tutorial repositories; prove the growing adoption of emerging design technologies by architects. In Table 3, we collected a few examples of (1) online communities that facilitate open information and knowledge sharing; (2) open courseware; (3) tutorial repositories; (4) personal blogs; (5) academic or training providers; and (6) material suppliers and vendors. Within the category of online communities, based on the member types, we included developer-user communities which were initiated by developers and then opened to general users; designer-user communities initiated by users to share visual design and source code; (3) commercial provider initiated communities which engage user communities. These communities share knowledge, information, through tutorials or user forums and downloadable code, 3D models and family objects (e.g., RevitCity), and occasionally relevant information such as job postings and relevant news articles.

Some of the key features of vibrant communities include interactive content, forum settings allowing member posts and rankings. Other online sources such as blogs and websites maintained by academic or commercial training providers offer information of personal research and structured content. In the case of commercial providers, free content previews are offered to attract potential customers for additional fee-based offerings.

From an information consumer standpoint, these online sources can be brought into the design and prototyping process in a number of ways: (1) tutorials, references, guides, are useful to study the basics of the software interfaces and fundamentals of code or electronics to get started; (2) design-share communities such as OpenProcessing.org or DIY communities such as Instructables are helpful to inspire users of the creative potential of the tools, and reuse of source code, CAD files, etc.; (3) various forums are generally useful for troubleshooting issues with code/algorithms and circuitry, although when confronted with novel problems, the drawback is that specific problems may not be resolved because of the lack of expertise in the user base or difficulty of finding the expert (Ku and Grinham 2013); (4) code libraries are generally helpful to simplify coding processes or geometric operations that many users may need; (5) material suppliers offer shopping guides of hardware and provide user feedback; and (6) open creative projects can also be customized and built on by others .

As previously discussed, the benefits of sharing work are worth considering for many creators, and what follows is a brief description of a few instances of leveraging those open source benefits for commercial gain. In February 2008, a 24 year old from Mexico City named Rodrigo Medina launched *designplaygrounds* "an open research design platform" on Google's Blogspot. For two years, Mr. Medina posted open content to the blog sharing everything from his process to original code for digital fabrication of original designs. In 2014, Mr. Medina founded ThinkParametric.com, a paid subscription site providing "Professional training in the leading technologies for the building industry." In six years, Mr. Medina was able to grow a humble open source blog into a viable training site that counts among its clients Snohetta, Grimshaw, Arup, Gensler and AECOM. (www.thinkparametric.com)

Another example is that of Mode Lab, originally founded as Studio Mode in Brooklyn by Ronnie Parsons and Gil Aikos. Studio Mode began as a collection of best practices for parametric and algorithmic design through McNeel's Rhinoceros 3D modeling program. In addition to creating Studio Mode, Mr. Parsons and Mr. Aikos co-authored the openly shared third edition of *Foundations: The Grasshopper Primer* which is the industry standard for learning the Grasshopper parametric design plug-in for McNeel's Rhinoceros 5. Through the history of reliable, innovative shared content, Mode Lab is now recognized as a thought leader in emerging technology in architecture and has been enlisted as a consultant for several large architecture and engineering firms: KPF, Olin, SOM and Arup to name a few. (www.modelab.is)

The final example is how a small architecture firm outside of a major metropolitan area is able to leverage the advantages of social media for its own marketing purposes. PJA Architecture, P.C. is a small architecture firm located outside of Philadelphia, PA. With humble beginnings in 1993, the firm is an established provider of high quality, commercial architecture. The following is a description of how the lean company is leveraging social media to broadcast its message and engage potential clients from the comfort of the office. PJA Architecture has created accounts for Instagram and Twitter. The former serves as a visual catalog of the firm's projects, interests and musings; the latter provides a conduit to the design and development community that otherwise would be inaccessible without a labor intensive marketing drive. By promoting content on social media, PJA is able to identify potential clients based upon project size/scope, location, and design sensibility very quickly. Engaging these contacts on social media affords a company the opportunity to create a relationship, however tenuous, to other people and companies such that an email, phone call or meeting has a shared basis for continued discussion and relationship building.

CONCLUSION

While open source architecture illustrates some similarities to software and cultural production, there are a number of barriers including liability and copyright issues. The complexity of building technologies, design and construction processes, building permit processes, and size of projects, make it difficult to implement open source architecture. Nonetheless, design technologies draw many parallels to open source production in software and cultural goods, and the impact of open source is most obvious in emerging digital technologies. From a pedagogical standpoint it is important to evaluate the opportunities that are offered, and understand the challenges of literacy skillsets and licensing agreements. The profession should continue to assess the impact on design, and continuing and academic education.

ACKNOWLEDGEMENTS

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ENDNOTES

1. Cheliotis, G. (2009) *From Open Source to Open Content: Organization, Licensing and Decision Processes in Open Cultural Production, Decision Support Systems*, 47, pp. 229–244, Elsevier.

2. Ceraso, A., and Pruchnic, J. (2011) *Open source culture and asthetics, Criticism*, Summer 2011, Vol. 53, No. 3, pp. 407–438. Wayne State University Press, Detroit, Michigan 48201-1309 .

3. Ku, K., Frosten, S., and Grinham, J. (2014), *An Open-Source Paradigm in the Responsive Architecture Studio*, ACSA International Conference, June 21-23, 2014, Seoul, Korea.

4. Ku, K. and Grinham, J. (2013) *4D Environments and Design: Prototyping Interactive Architecture, ARCC News and Reports*, http://arccweb.org/newsletter/category/newsletters/37-1-spring-2013/ (accessed March 10, 2014).

5. Hope, J. (2008) *Open Source Revolution in Biotechnology,* Cambridge, MA: Harvard University Press.

6. Van den Bergh, P. (2013). *UNStudio Tried Riding the Open Source Wave, but Failed.* http://www.failedarchitecture.com/unstudio-tried-riding-the-open-source-wave-but-failed/ (accessed May 1, 2016).

7. Voyce, S. (2011). *Toward an open source poetics: Appropriation, collaboration, and the commons, Criticism*, Summer 2011, Vol. 53, No. 3, pp. 337–375. Wayne State University Press, Detroit, Michigan 48201-1309.

CATEGORY	NAME	COMPONENTS	PARTICIPANT TYPE
Online communities	Processing.org	Download Examples Tutorials References Forum/Support Shop/Buy	Open source software developer and user community
	Openprocessing.org	Examples Course examples Collections Shop/Buy	Open source design share-user community
	Arduino.org	Download Shop/Buy Tutorial Examples References Support/Forum Blog	Open source hardware developer-user community
	RevitCity.com	Forum Downloads Gallery New/Articles Resources Jobs FAQ	Commercial software user community
	Designbymany.com Case Consulting	Community Consulting	Commercial training provider on various tools
	Instructables.com	Explore Create Contests Forums	DIY user community
Courseware	http://www.wikispaces.com/ https://realtimecities.wikispaces.com/	Online classrooms	Academic classrooms
Tutorial repository	http://digitaltoolbox.info/	Tutorials Workshop recordings	Academic instructor/ Consultant
	http://designalyze.com/	Tutorials Workshop recordings	Academic instructor/ Consultant
	Designreform.net	Publication/ tutorials	
Blog	http://shiffman.net/	Books Teaching Blog Download	Educational provider on open source tools
	http://www.jeremyblum.com/	Blog Tutorials/Books Portfolio examples	Educational provider on various software/ hardware tools
	http://www.plethora-project.com/	Video tutorials Portfolio examples Blog Code library	Educational provider on various design tools

Table 3. Categories of Open Source Platforms related to Architecture
(modified from Ku et al., 2014)

Academic or Training provider	http://lab.modecollective.nu/	Online tutorials Workshop arrangements	Commercial training provider on various tools
	http://www.fabfoundation.org/fab-labs/what-is-a-fab-lab/	Technical prototyping platform Knowledge sharing network	Digital fabrication and computation platform
	http://elsewarecollective.com/teaching/studio-air/ http://elsewarecollective.com/AIR/Tutorial%20Videos/AIR_TutorialVideoList.pdf	Tutorials Webinar	Academic instructor
	http://www.nycctfab.com/	Tutorials Academic courses Digital fabrication	Academic instructor/ Training provider
	https://www.youtube.com/user/nsenske	Course recording	Academic instructor
Material vendors	https://www.sparkfun.com/	Products Blog Tutorials Videos Classes Support	Commercial electronics supplier with tutorials and user discussion board and support
	http://www.adafruit.com/	Shop Blog Learn Forum	Commercial electronics supplier with tutorials and user discussion board and support

Table 3 (continued). Categories of Open Source Platforms related to Architecture (modified from Ku et al., 2014)

Digitally-driven Fabrication of Fiber-reinforced Composite Panels for Complex Shaped Envelopes

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Composite materials have been explored in architecture for their high performance characteristics that allow customization of functional properties of lightness, strength, stiffness and fracture toughness. Particularly, engineering advancements and better understanding of fiber composites have resulted in growing applications for architectural structures and envelopes. As most new developments in material fabrication start outside the realm of architecture such as in automobile and aeronautical industries, there is need to advance knowledge in architectural design to take advantage of new fabrication technologies. The authors introduce results of new digitally driven fabrication methods for fiber-reinforced composite sandwich panels for complex shaped buildings. This presentation discussed the material properties, manufacturing methods and fabrication techniques needed to develop a proof of concept system using off-the-shelf production technology that ultimately can be packaged into a mobile containerized facility for on-site panel production. The researchers conducted experiments focusing on developing a digitally controlled deformable mold to create composite relief structures for highly customized geometrical façade components. Research findings of production materials, fabrication methods and assembly techniques, are discussed to offer insights into novel opportunities for architectural composite panel fabrication and commercialization.

1. INTRODUCTION

The demand for large scale free form shapes in architecture and the push for high performance building materials and systems has brought evident changes in the building industry. The completion of the Bilbao Guggenheim Museum in 1997 marked an important accomplishment in the implementation of digital design and manufacturing tools (Kolarevik, 2003). With the availability and precision of 3D modelling tools and direct control of fabrication via CNC equipment, free form architectural projects have become more affordable. Such digital tools have broad implications on production and design processes involving changes in the roles and arrangement to generate and control design (Ku et al., 2008). In case of complex shaped envelopes, designers have focused on rationalizing surface geometries to optimize and maximize standardized components reducing the high cost of fabricating and installing non-standard components (Glymph et al., 2004; Whitehead, 2003).

Alternatively, designers and researchers have turned to technological advancements in materials and fabrication techniques used in the automobile, shipping, and aerospace industries for innovation. Addressing the inefficiencies of constructing continuously changing curved forms with traditional structural systems (Yun and Schodek, 2003) and layered systems for enclosure (Lynn, 2010); there have been attempts to adapt fiber reinforced polymer materials. Instead of using conventional systems composed of primary load-bearing structural members, secondary structure and connecting systems that support layers of insulation, waterproofing, and exterior finishes, some designers are exploring new methods of applying laminated composites with integrated structure.

There are a number of challenges to adopting composites such as the lack of standards for assessing the structural performance under various loading conditions and understanding long term impacts of aging and durability (Fernandez, 2006). While there are a number of architectural composites manufacturers (e.g., Kreysler & Associates, CA, USA; Trespa International BV, Netherlands; Acell, Milan, Italy; PCT, Dubai, UAE), cost is typically higher than common building materials[1]. Composites are functionally customizable but for the majority of building applications such levels of customization are unnecessary and costly. Thus it is necessary to understand how to best take advantage of the customizable characteristics of composites with economically feasible means of production. Future complex shaped envelope production will benefit from a better understanding of state-of-the-art fabrication methods. This is gained through a literature review of current panel fabrication methods and experimental design research involving hands-on prototyping of composites panels. In this article, investigations of the impact of digitally driven composites production processes are described to contribute to the growing knowledge base of architectural composites.

2. RESEARCH GOAL AND APPROACH

The ultimate goal of this research is to develop a framework for a digitally driven mobile containerized factory of architectural composites for complex shaped building cladding systems. The objective for this paper is to document the initial explorations of developing a composites panelling and production strategy involving a deformable mold prototype. This project targets the production of cost effective composites cladding systems which can efficiently enclose space while also producing complex envelope geometries (Chudley and Roger, 2010).

The background section explains the geometric rationalization of complex shaped building envelopes and relevant composite production approaches. The next section discusses composites panelization strategies and the following section elaborates on the prototype development process. The conclusion discusses the findings and future steps.

3. BACKGROUND

3.1. GEOMETRIC RATIONALIZATION OF FREE FORM SURFACES

Large scale free form building shapes have direct cost impacts. Design of complex shaped buildings often involves rationalization of project geometry to increase the number of identical components, flat units, and consequently reduce the number of unique curved panels.

For construction, curved surfaces are generally more difficult to produce than flat ones and ruled surfaces are easier to produce than complex parametric surfaces (e.g., NURBS curves or B-splines). Ruled surfaces can be generated by the rotation or translation of straight lines and include developable surfaces (e.g., cylinders, cones) which can be flattened without cutting or stretching the original surface and non-developable surfaces (e.g., hyperboloids, spheres, and hyperbolic paraboloids) which require cutting and stretching to be transformed into planar sheets (Schodek et al., 2005).

In general, these strategies for creating large complex shapes via panelization can be grouped into three categories. First and least expensive for the panel fabrication is dividing the complex shape into a series of facets, often triangles or polygons that allow the panels to be flat. Second is the geometric division of the complex shape into flat and single curve panels. Sheet metal panels can be readily roll formed into single curves without the use of expensive forms. Third is the use of multi-curved panels. (Schodek et al., 2005). These tend to be the most expensive and have often required the most amount of time to produce. Generally, the larger the rate of change and the greater the number of curves the more difficult it becomes to fabricate the panel.

Design rationalization strategies include simplification of NURBS geometries to arc-based geometries (Whitehead, 2003), modification of design geometry to conform to the physical constraints of planar quadrilateral panels (Glymph et al., 2003), or adjustment of the inter-panel distances between adjacent panels within positional and normal continuity (Eigensatz et al., 2010).

As such it is important to understand the significance of geometry in design for manufacturing. Digital design tools offer guidance in analysing manufacturability by supporting Gaussian and mean curvature interpretations to analyse isotropic materials such as metals, or normal curvature evaluation of non-isotropic materials such as wood and reinforced plastic materials (Schodek et al., 2005).

3.2. RELEVANT COMPOSITES APPROACHES

Composites offer opportunities to produce curved components observed in products from the automobile, shipbuilding and aerospace industries[1] such as the fuselage of Boeing airplanes (Lynn, 2010). Pearson (2010) describes the process of producing high performance race boats sails which involves lamination of PET film, thermoplastic resin, and structural yarn (custom patterned with carbon, aramid, UHMWP fibers), and another layer of film. The process relies on an adjustable 3D male mold which matches the custom sail curvature imported from a 3D CAD/CAE file. Composites can offer greater formal freedom than metals and deformed sheet materials to designers because they can be configured into highly complex geometries through molding processes.

Fiber reinforced plastics can be made from a variety of fibers (e.g., polyehtylene, polypropylene, aramid (AFRP), glass (GRRP), carbon (CRFR), etc.) (Fernandez, 2006). Combined with flexible formal possibilities, composites can be functionally customized to serve a variety of architectural applications.

4. COMPOSITES PANELIZATION STRATEGIES

4.1. SANDWICH CONSTRUCTION

Building envelope cladding systems often need to be waterproofed, insulated, structurally engineered for gravity and lateral loads, and accommodate movement within the panels and between adjacent panels. To accommodate these functionalities, architectural composite panels often require sandwiching a thermal foam core between thin sheets of composite material. The foam core provides both thermal resistance and shear stiffness and can be bonded rigidly to the face sheets. While high density foams are typically better structurally, their thermal insulation value is less favourable then other foams. This can be addressed by introducing shear resistant spacers combined with lower density foams which exhibit higher thermal resistance (Bechthold, 2008).

5. PROTOTYPE DEVELOPMENT PROCESS

The development process considered a design to manufacturing process (Figure 1). During the design process cost implications of applying composite panels were assessed through parametric modelling and optimization tools that can help to identify tolerances and curvature, identifying the scope of custom panelization areas and analysis of performance objectives. The material process involves a hybrid process of automated and manual processes to fabricate the mold, laminate fibers, structural and thermal layers. The design curvatures of the final panels are achieved through various forming processes using a digitally controlled reusable deformable bed as a casting surface.

5.1. FABRICATION PROCESSES

This research accommodated a variety of existing digital fabrication processes.

5.1.1. MATERIAL AND FORMING

Potential materials for architectural surfaces are based on the matrix materials (e.g, metal, polymer, ceramic) and fiber for structural or non-structural applications. While a concrete based ceramic matrix of cement is the most common building material for complex shaped panel construction. This research examined examples of composites including polymer matrix composites (PMC), glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), pultrusions, metal matrix composites (MMC), ceramic matrix composites (CMC), and carbon-carbon composites (CCC).

Those materials can be pre-formed (forming and casting) or post-formed (deforming). Currently the majority of large scale architectural projects using complex panel shapes have been produced using pre-formed concrete panels and post-formed metal sheet panels. Composites such as fiber reinforced polymers have also been used to create complex shaped panels. In most of these cases pre-formed single-use molds have been used to create the FRP panels (Blonder & Grobman, 2015).

5.1.2. ADDITIVE TECHNIQUES

Additive techniques for complex shaped components often utilize 3D printing techniques. A small scale example is a fiber 3D printer (MARKFORG3D[2]) which incrementally deposits fiber to create surfaces and solid components. While size limitations prohibit large scale applications of 3D printing techniques, CNC fiber placement heads are utilized in the production process of large complex shaped sail products, adopting additive techniques. This technique is intended to be applied subsequently in this research to automate the fiber layering during the laminating process for the proposed prototype.

Non-fiber additive techniques such as stereolithography, laser sintering, fused deposition modelling, polyjet and 3d-printing have been used in commercial manufacturing to produce plastic prototypes and machine components (Strauss, 2012). These techniques primarily utilize plastics or resins that are heated or cured to create bonded layers. These bonded or fused layers of plastic although relatively strong for smaller components generally lack the stiffness and bending resistance needed to perform as a building scale architectural panel.

Direct metal fabrication (DMF) additive techniques such as power feed process, laser engineered net shaping, direct metal deposition, power bed process and electron beam melting utilize lasers or electron beams to melt deposited metal particles to create prototypes for complex shaped machine parts (Strauss, 2012). Both plastic and metal additive methods have not found commercial success in producing large scale architectural panels. This is primarily due to the issues of build volume, speed and cost. Most of the tools for additive techniques have build volumes that are unable to accommodate a large scale building panel such as a 1.5m x 3m panel. Although some newer equipment such as the VX4000 by Voxeljet have the build volume to create a large scale building panel the type of plastic materials available for use still are not well suited for thin large scale exterior panels. Speed in additive techniques has also been a challenge especially for larger objects that still require high resolution (Castaneda, Lauret, Lirola, & Ovando, 2015). When comparing the set up and production time for additive techniques versus deformation techniques such as roll forming for metal sheet goods used in building panels, additive techniques require at least an order of magnitude greater time to complete production.

5.1.3. SUBTRACTIVE TECHNIQUES

Subtractive methods used during milling and routing parts from larger material blocks are often applied to create desired complex surfaces for mold surfaces or sandwich core material (foam or honeycomb). This process relies on computer-numerically-controlled (CNC) equipment. Subtractive techniques such as laser cutting, water-jet, hot-wire, and multi-axis milling have often developed from automating the manual process of two-dimensional production techniques (Castaneda et al., 2015). In general contouring of complex three-dimensional surfaces is geometrically reduced to a stacked series of two dimensional subtraction operations that can be procedurally burned, carved or cut by a computer controlled tool arm. The inherent draw back to this method is the waste of material and the time needed to cut through each layer. Materials with greater hardness, density and strength typically require more time to slowly subtract the material. CNC milling techniques have been extensively used for large stone fabrication, especially for countertops and decorative relief panels. Subtractive techniques to directly produce complex double curved panels though have had very limited commercial application due to time required to mill large depth panels and the associated material waste (often directly impacting cost) of large panels with significant depth change.

5.1.4. PRE-FORMING TECHNIQUES

Preforming techniques utilize subtractive methods to create the formwork or casting beds for curved surfaces. These processes are often used to cast concrete into complex shapes. Often the process starts with CNC routing a foam bed to create the negative mold shape and is followed by casting cementitious fiber reinforced material into the negative mold to create the desired positive surface.

Because the process of creating and molding uniquely shaped components is highly time and labor intensive, this process would only be viable if there are large numbers of repetitive components that can be repeatedly cast to reach economies of scale.

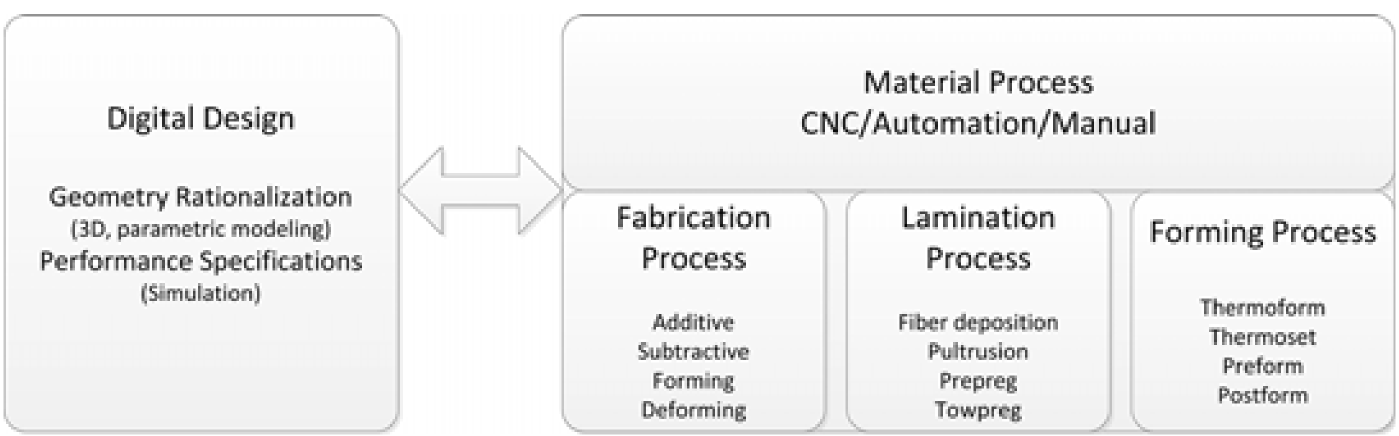

Figure 1. Digital design and manufacturing process of architectural composite panels.

5.1.5. POST-FORMING TECHNIQUES

Post-forming processes often utilize heating methods to plastically deforming sheet materials by pressing them against another object to create a three dimensional surface. Thermoforming and vacuum forming have been used to create architectural surfaces primarily out of plastics. The benefit of this technique is that it reduces fabrication time by removing the curing process typical of forming techniques. The same limitation of creating a formable bed or negative surface used in forming techniques is required in this process. Large local depth variations and sharp changes in surface direction may also not be well resolved using deformation techniques due to uneven plastic deformation of the sheet product causing local tearing or thinning which may result in unacceptable panel weaknesses.

In the last decade recent improvements in sheet metal fabrication techniques offer insight into possible strategies for composite architectural panels. Roll forming has long been used to create metal panel products such as corrugated steel. The ridges and deformations created through roll forming have generally been used to add rigidity by imparting an improved cross-sectional geometry to a linear product whether being a sheet good or cold rolled structural section. Roll forming has also long been used to create single curved metal sheet goods that have been used in building cladding.

For more complex three dimensional shapes requiring non-uniform radii or double curved surfaces metal sheet fabrication has required the creation of die or CNC milled upper and lower forms and often hydraulic presses to provide uniform pressure on the sheet. These forms are expensive and time consuming to create and are traditionally only utilized for mass producing a repeatable product such as an automotive body part (Alonso-Pastor, Lauret-Aguirregabiria, Castañeda-Vergara, Domínguez-García, & Ovando-Vacarezza, 2014). Thus most metal cladding of complex three dimensional shapes have typically relied on geometric panelization that limits the panels to single curved and flat tessellated pieces.

Recently sheet metal fabricators have created two and three roller processes that utilize a flexible set of curved rollers that can create double curvature sheet metal surfaces such as saddle and torus shapes. The drawback to this is that these techniques currently have relatively small maximum deformation capacity perpendicular to the length of the material due to the roller design. The state-of-the-art in complex geometry metal sheet fabrication is multipoint stretch forming. The term multi-point denotes that the forming surfaces are actually a grid array of computer controlled points that can be raised and lowered as needed to create a surface shape (Lee & Kim, 2012). This technique utilizes two multi-point beds (one below and one above the metal sheet) to press the sheet. At the same time to reduce wrinkling and dimpling the sheet is stretched by clamps on two ends to maintain the desired geometric boundaries (Cai, Li, & Lan, 2012; Wang, Li, & Cai, 2014).

5.1.6. RESEARCH NEEDS FOR FORM BEDS

The dimensional and cost limitations of current additive and subtractive digitally driven fabrication techniques indicated the need of research for improved forming techniques of composites. The cost of creating custom molds for negative surfaces poses significant limitations during the forming process. Thus making fiber composites a less attractive product for architectural projects as it increases the overall cost including lead times, packaging and shipping of finished products to job sites.

To address the shortcoming of single-use custom molds, investigations focused on developing a reusable rapidly deformable bed for pre-forming and post-forming operations which could reduce the material and fabrication time needed to make the surface negatives. This is similar in essence to the multi-point method to create a deformation bed used in sheet metal fabrication.

5.2. PROTOTYPING

5.2.1. VACUUM FORMING STUDY

Initial experimental studies were conducted to explore vacuuming forming with 1/16” sheets of Plexiglas over a laminated cardboard forming bed. Cross sections of cardboard were laser cut to create a three dimensional surface with each layer of cardboard standing vertically on its edge to allow for air to be pulled through the assembly. The cardboard pieces were mechanically held together to form the bed. It was identified that vacuum forming requires large forces to be exerted on the forming bed and accordingly require high strength resistive capabilities to support the forces generated during the vacuum forming. High strength resistance in a deformable bed can be achieved through a mechanical lock system or pneumatic actuators. Forming large

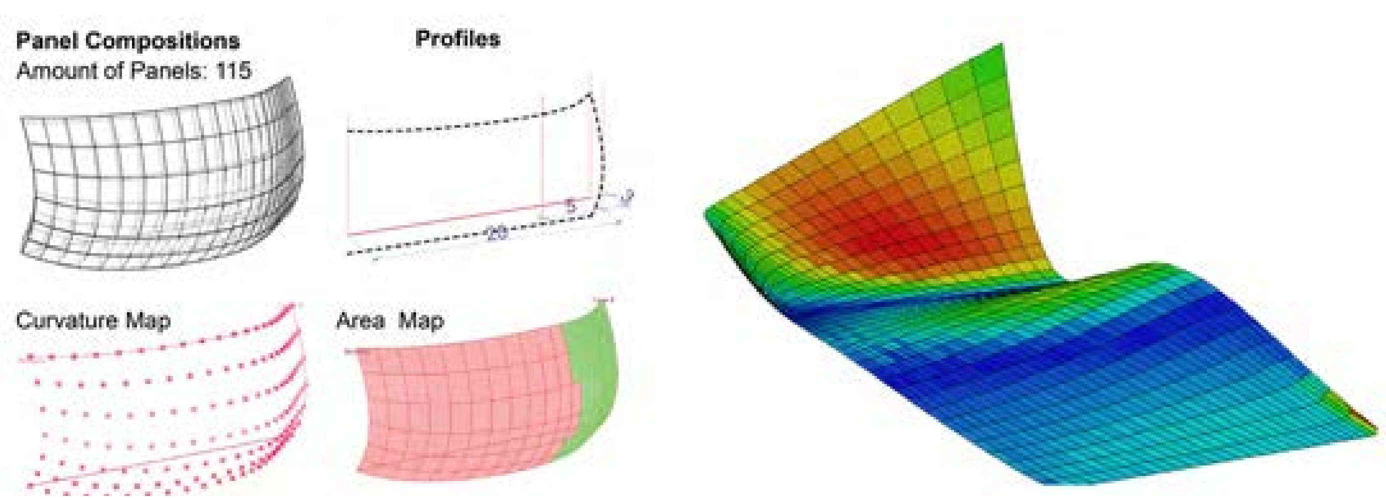

Figure 2. Double-curved panelization model and planarity analysis.

sheets via vacuum forming techniques may require large sacrificial molds which may be costly and challenging to produce.

However, on a larger scale vacuum bags are used to laminate large scale sheets instead of molding composite sheets into desired geometry. To laminate using vacuum bags, the sheet material would be tension stretched over a mold and vacuum compressed with fibers that are laid on top of the membrane material. Creating the required vacuum force and heat while maintaining control over the product quality may be achieved at larger scale for up to 500 square meters as seen in the production of sails (Pearson, 2010).

As a next step the team started to investigate mechanisms for an adjustable form bed for resins, epoxies and fiber reinforcement placement.

5.2.2. GEOMETRIC STUDIES

3D models of double- and single-curved panels' geometries were generated to study panelization strategies from larger architectural surface applications. The left portion of Figure 2 shows a model of a double curved surface made from 115 panels. The highlighted areas in green were calculated to identify target areas with larger deformation curvatures that would be adequate for custom composite panel production. Curvature analyses can be used to evaluate and plan for composite fabrication to maximize time and production advantages. Using geometry rationalization and planarity analysis tools such as Evolute, a Rhino 3D plugin, double curved surfaces can be panelized using parametric rules to limit maximum slope and deformation within panels to improve ease of fabrication. The right side of figure 2 shows and example of planarity analysis.

5.2.3. MOLD BED USING MUSCLE WIRE

The research explored two digitally driven deformable bed techniques to replace the standard disposable CNC cut foam beds. The first alternative utilized shape memory alloy (Nickel Titanium or nitinol wire) – muscle wire. Nitinol has the unusual ability to perform a solid-state transformation (known as a martensitic transformation) between two defined states as a result of changes in temperature which can be incurred through an electric current. At lower temperature the wire elongates and at higher temperature the wire shortens returning to its original shape.

The team explored various nitinol weave patterns (i.e., rectilinear, circular) to study deformations to be used in a deformable bed. Results proved to be unsuccessful because of the small amount of displacement they created to achieve a desired form. Relating specific weave pattern with desired shapes also turned out to be challenging and this approach was abandoned.

5.2.4. MOLD BED USING MECHANICAL ACTUATORS

A mold bed with high surface variation for the resin, fiber, and foam core, was developed adopting a mechanically driven solution using solenoid actuators controlled through a microprocessor (currently the team has adopted the use of an Ardunio microcontroller) with a relay array.

This allows for a surface resolution determined by the number of actuators and the stepping height of each actuator. For the initial prototype attempt simple push pull actuators are being used to create a three height actuator array with each actuator being able to be addressed individually. Figure 3 shows the actuator array. The array is designed to be covered with a plastic or silicone membrane that holds the resin or epoxy matrix. Preliminary tests have shown that these actuators have ample load capacity for supporting our expected casting activities. The interface control is achieved through a Rhino 3D/Grasshopper Firefly plugin which allows direct control of the actuators from an interactive digital surface geometry.

5.2.5. FIBER COMPOSITE LAYERING AND FORMING

The team experimented with glass fiber fabric and epoxy resin to create fiber reinforced composite sheets which would be formed on the mechanically deformable bed. The vacuum lamination process requires a tight seal around the perimeter of the bagging film which informed the geometry and design of the deformation bed apparatus.

6. CONCLUSION

This paper discussed the development of a digitally driven fabrication framework for complex-shaped architectural composite panels. Results from preliminary explorations of a deformable bed for forming composite panels were presented. Literature review showed growing interest for composites use in architectural envelope panel applications, particularly in complex shaped projects, and the need for design research of associated production systems, dynamic mold processes and materials. Prototyping efforts helped to understand core aspects of fiber composites, molding processes and tertiary aspects including electric circuits and actuation mechanisms.

Future work will focus on refining the mold bed platform involving curvature resolution control, mold bed attachment details, and in-depth explorations of various fiber composite material properties and applicability of pre-forming and post-forming techniques. The prototyping research of the deformation bed will be expanded to include design criteria of a fabrication space and examine the work flow from raw fiber materials to finalized products that can be fabricated onsite in a mobile containerized facility.

Recommendations for future research and a roadmap for commercialization will be established. This research project is scheduled to continue through the remainder of the 2015-2016 academic year with early trials of casting materials for panel creation currently in progress.

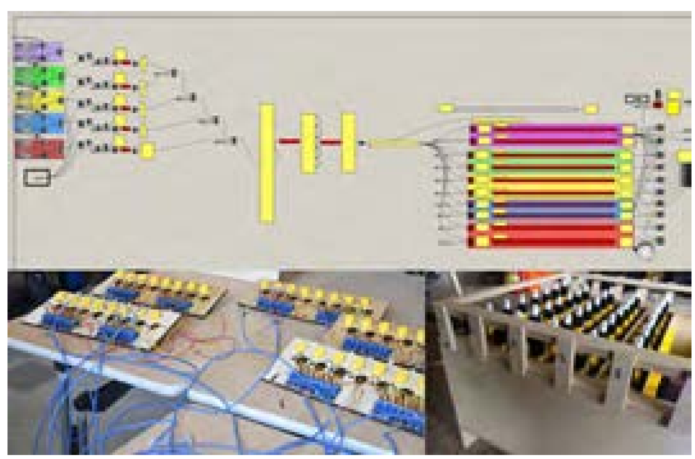

Figure 3. Digital control of solenoid actuator array for deformable bed experiments

Figure 4. Flexible, reconfigurable deformable bed mold

Figure 5. Fiber composite sample

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ENDNOTES

1. http://www.compositesworld.com/articles/composites-and-architecture-blog
2. https://markforged.com/.

REFERENCES

Alonso-Pastor, L., Lauret-Aguirregabiria, B., Castañeda-Vergara, E., Domínguez-García, D., & Ovando-Vacarezza, G. (2014). Free-Form Architectural Façade Panels: An Overview of Available Mass-Production Methods for Free-Form External Envelopes *Construction and Building Research* (pp. 149-156): Springer.

Bechthold, M.: 2008, *Innovative Surface Structures: Technologies and Applications*, Taylor & Francis.

Blonder, A., & Grobman, Y. J. (2015). Design and fabrication with fibre-reinforced polymers in architecture: a case for complex geometry. *Architectural Science Review* (ahead-of-print), 1-12.

Cai, Z.-Y., Li, M.-Z., & Lan, Y.-W. (2012). Three-dimensional sheet metal continuous forming process based on flexible roll bending: principle and experiments. *Journal of Materials Processing Technology*, 212(1), 120-127.

Castaneda, E., Lauret, B., Lirola, J., & Ovando, G. (2015). Free-form architectural envelopes: Digital processes opportunities of industrial production at a reasonable price. *Journal of Facade Design and Engineering,* 3(1), 1-13.

Chudley, R. G., Roger. 2010. *Building Construction Handbook - Incorporating Current Building and Construction Regulations* (8th Edition).

Eigensatz, M., Kilian, M., Schiftner, A., Mitra, N., Pottmann, H., and Pauly, M.: 2010, Paneling architectural freeform surfaces, *ACM SIGGRAPH Tansaction on Graphics*, 29 (3), Available from: < http://graphics.stanford.edu/~niloy/research/paneling/paneling_sig_10.html> (accessed 1 December 2015).

Fernandez, J.: 2006, *Material Architecture*, Architectural Press.

Glymph, J., Shelden, D., Ceccato, C., Mussela, J., and Schober, H.: 2004, A parametric strategy for free-form glass structures using quadrilateral planar facets, *Automation in Construction*, 13, 187–202.

Kolarevik, B.:2003, *Architecture in the Digital Age: Design and Manufacturing*, Kolarevik, B. (eds.), Taylor & Francis.

Ku, K., Pollalis, S., Fischer, M., Shelden, D.: 2008, 3D model-based collaboration in design development and construction of complex-shaped buildings, *ITcon* 13, Special Issue Case Studies on BIM Use, 258-285.

Lee, G., & Kim, S. (2012). Case study of mass customization of double-curved metal façade panels using a new hybrid sheet metal processing technique. *Journal of Construction Engineering and Management*, 138(11), 1322-1330.

Lynn, G. and Gage, M.: 2010, *Composites, Surfaces, and Software*, Yale School of Architecture.

Pearson, W.: 2010, North Sails Three-Dimensional Laminates: The shrinking Space between Composites and Textiles, *Composites, Surfaces, and Software*, Lynn, G. and Gage, M.: (eds.), Yale School of Architecture.

Schodek D. L., Bechthold M., Griggs K., Kao K. M., and Steinberg M.: 2005, *Digital design and manufacturing : CAD/CAM applications in architecture and design*. John Wiley & Sons, Hoboken.

Strauss, H. (2012). *AM Envelope: The Potential of Additive Manufacturing for Façade Construction* (Vol. 1): TU Delft.

Wang, D., Li, M., & Cai, Z. (2014). Continuous-forming method for three-dimensional surface parts combining rolling process with multipoint-forming technology. *The International Journal of Advanced Manufacturing Technology*, 72(1-4), 201-207.

Whitehead, H.: 2003, Lays of form, *Architecture in the Digital Age: Design and Manufacturing*, Kolarevik, B. (eds.), Taylor & Francis.

Yun, Y. and Schodek, D.: 2003, Development of boundary structures for complex-shaped buildings, *Journal of Architectural Engineering*, 9 (1), 18-25.

The Future of Architectural Design in the Post-Digital Era

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Our presentation at the 2016 AIA Intersections Symposium described a multi-disciplinary research agenda that ponders where architecture, as a discipline and a practice, sits with respect to the age of ubiquitous data. That presentation and the synopsis that follows is focused on our on-going development of novel tools and frameworks to advance decision support for building design and construction in this context. Apropos to the workshop theme, ***Innovative Technologies in Design and Delivery,*** our work is motivated by emerging technologies in computational and data science that may revolutionize the way the built environment is conceived and produced and, consequently, what that means for the Future of Design in a Post-Digital Era.

BACKGROUND AND MOTIVATION:

First, to establish what we mean by **Post-Digital Era**. Several years ago, pioneering computer scientist Jim Gray offered that we are moving into a wholly new era in scientific discovery, what he termed to be **The Fourth Paradigm** (Hey). Whereas previous eras of scientific discovery were marked by advances in observation, theory, and then observation and theory supported by computational analysis, we have entered yet another revolution – The Fourth Paradigm – wherein altogether new ways of conducting research through Data analysis are being discovered. The Fourth Paradigm*, which exists beyond the Computational Era,* marks newfound ability to access large amounts of heterogeneous data in order to make discoveries that would not be possible in a single view of the data from a single data set. Furthermore, Fourth Paradigm technologies transform our ability to make decisions *using* that data; in ways that would be virtually impossible previously. Unlike preceding paradigms in discovery and research, which were marked by advances in observation and the generation and use of data, The Fourth Paradigm signifies our ability to comprehend data in completely new and useful ways [Figure 1].

WHAT DOES THIS MEAN?:

Today, we have access to data from around the world and we have technologies that allow us to gather this information into manageable, semantically-compatible formats such that the data can be made useful in an architectural design process. Where data is needed, missing, inconsistent, or incomplete, we have technologies to help us "fill in the blanks". Our design decisions can be influenced by myriad design tools and analysis approaches because of the increased interoperability afforded by modern technologies. And, perhaps most critically, because of these new technologies, we can begin to incorporate data from outside the immediate domain of architecture into the decision-making process; meaning, we can use data from domains that directly affect our design choices and design outcomes, but was previously incompatible with tools and processes without manual and unreliable human intervention.

ARCHITECTURE, BIG DATA, AND A POTENTIALLY TRANSFORMATIVE APPROACH

Given current methods and approaches for incorporating building design information and data into a holistic design process – generating, storing, and communicating via BIM – the focus of our research is on the challenges and areas of weakness in the state-of-the-art, and the intersection of architecture with non-domain-specific methods, tools, and frameworks that already exist – *and that architecture could better exploit* – in the design and execution of buildings. Among them, concepts with origins in Big Data that have the potential to help architects, among many other disciplines, "harness information in (new and) novel ways (in order) to produce useful insights or goods and services of significant value." (Cukier). The concepts behind the Big Data revolution are tightly tethered to another fundamental, yet potentially revolutionary idea: that *all things* that are discoverable are also linked (Barabasi). So, in addition to achieving better access to and utility of data, our understanding of networks *and the relationships between things* may very

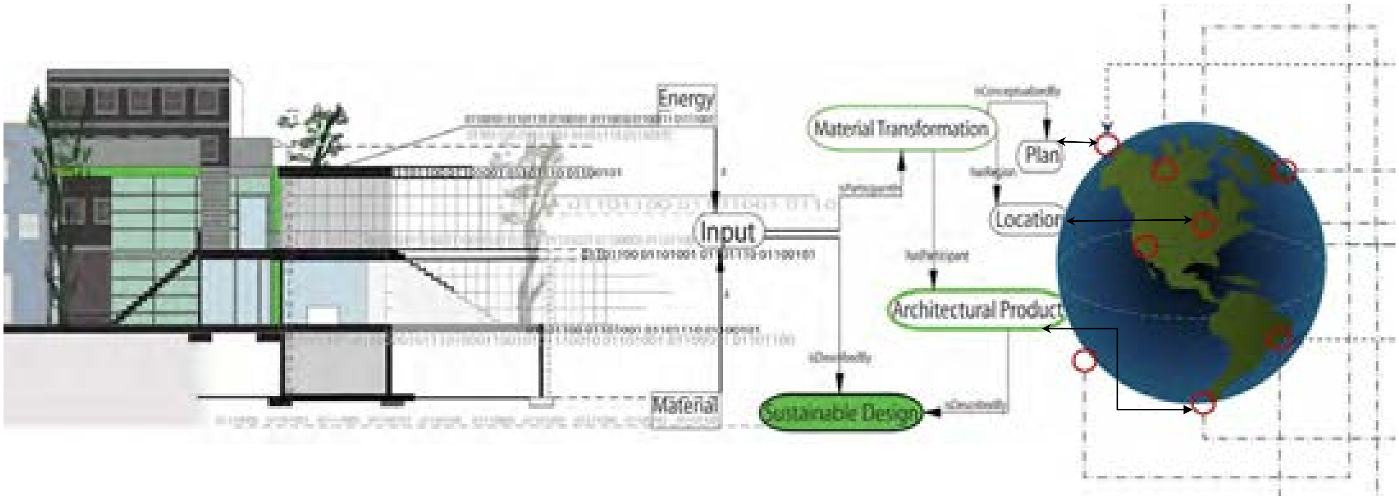


Figure 1. Development of Design from Base Material Observations to Computational Analysis to Modern Data Accessibility/Us

well transform the way we approach design, from the design of businesses, to vaccines, to buildings, to cities [Figure 2].

How, practically, will this transformation occur? How will we gain the necessary understanding? What can we possibly do with all of this data? Nearly every discipline is grappling with these questions. Our research is interested in determining how tools and concepts being ushered in by the Era of Big Data might be useful to and influential in the practice of architecture, along the following general themes:

First, how can we, the architecture community, more effectively use data and metadata to drive innovation in design and project delivery? Although recognized by industry, the ability to rapidly derive alternate, information-rich views of building models is touted by BIM applications as "critical for making quantitatively-informed design decisions" (Levy), and yet, we cannot always determine the origin of the source data or even the mathematical models behind the analysis and simulation conducted in these tools. Which means architects must not only understand the outputs of prevailing tools, but also *how* the models behind those tools work and generate insight, and, importantly, according to what data. Because ultimately, regardless of the interface, transparency, and interoperability, "good quality data is essential for architects to make more intelligent choices about how they design *all* projects". (Levy)

Next, how can we meaningfully advance collaborative practices in architecture in the age of ubiquitous data, information-rich drawings, and smart buildings? And, finally, what might happen if we are able to harness the knowledge of our broader community to grow and sustain new networks of information? For example, advanced computational models and methods that will help us explore the vast amount of building information and data that already exists and that is being generated, daily, by industry, by architects and allied experts, and by the buildings themselves.

In response, our research ponders the following topics and questions:

1. Understanding Structured Data and how our architecture, like others, can benefit from the generation, curation, and use of structured data in practice
2. Why is data access hard? And how does data access (and reliability) influence the practice of architecture, the decisions that architects make, and the impact of the buildings that we create?
3. Once we can achieve better access to data and more reliable data, what more powerful ways exist for harnessing it and using it? Can we utilize pattern-based approaches, like other disciplines?
4. Once more reliable data can be more efficiently and effectively accessed, how might advanced computational tools further support the architect in decision-making?

When thinking about answers to those questions, the kinds of methods and tools that we are developing fall into three main areas:

1. Novel multi-criteria decision support tools that
2. Use and leverage web-based strategies to streamline the creation and discovery of building information and design data, and
3. Enhanced decision support via rules engines and machine learning

HOW DID WE GET "HERE"? DATA KNOWLEDGE EVOLUTION

Several years ago, while pursuing a very specific question related to material property research, we discovered large **gaps in both tools and data** for accurately evaluating and comparing the broader impacts of the way we make and operate buildings, particularly with respect to the usefulness of these evaluation tools to the average student and practitioner and the availability of source data. Over the course of this inquiry, we discovered that the data we use – and that is used by prevailing design and analysis tools – is largely siloed and non-localized. Data existing in fragments and pieces, of varying quality and accessibility. And, yet, in spite of the fidelity of the data and the tools – or lack thereof – today's design and analysis tools – and the data they use – have a substantial influence over design decision-making. And this is the data that already exists -- some of it in databases, some open, some proprietary. What of the data being generated each day, by researchers of buildings, building materials, and the buildings themselves?

We began to ask ourselves and, eventually, our colleagues across and allied to our discipline (Buccellato):

1. How do we currently access and building design information and data?
2. What are the barriers to it -- the data?
3. What data is missing?
4. How do we tap into the explicit and tacit knowledge of the built environment, data that's embedded and available, but NOT yet accessible, reliable, and usable?

GIVEN ALL OF THESE CHALLENGES, HOW DO WE SOLVE THEM?

1. How do we *accelerate* access to the data that we have and the data that we need?
2. What kind of model frameworks exist for data and knowledge acquisition, discovery, and sharing?

How are other disciplines approaching – and advancing – in the age of ubiquitous data? And what can WE learn from them? How do WE similarly tap into the potential in Big Data?

Although this is a non-trivial task, gaining broader access to building design data and related information presents myriad new challenges as well as timely opportunities to influence the future conception and execution of the built environment. So, how do we do it? Everyone could remain focused on building more robust tools and individual applications, simulation models, and databases, etc., but the broader data challenge would remain. Our strategy is to make the data smarter, make that data accessible and then create frameworks that use smart data, which will ultimately make everyone's applications smarter.

NOW, WHERE DO WE "GO"? INTERDISCIPLINARY OPPORTUNITY:

These are big challenges and therefore we, the architecture and allied community, need help. This is where we turn to experts in Big Data, Knowledge Engineering, and Decision Theory to expand our current understanding and ability to effectively harness data and information in a data-enabled design

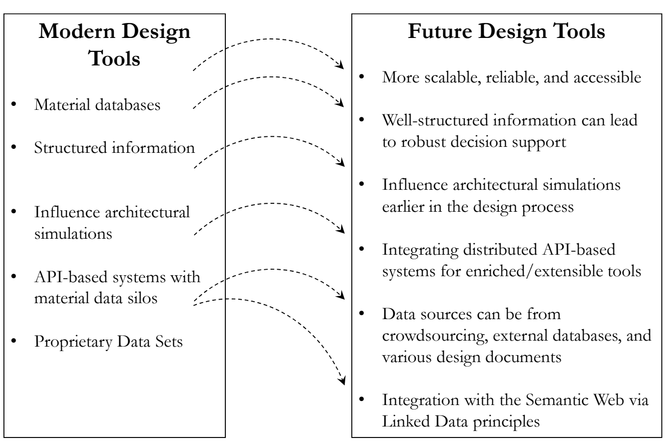


Figure 2. Comparison of Data in Modern Design Tools versus Future Design Tools

> "A major paradigm shifts introduced by the Semantic Web is to focus on the creation of smart data instead of smart applications. The rationale behind this shift is the insight that smart data will make future applications more (re)usable, flexible, and robust, while smarter applications fail to improve data along the same dimensions..."
>
> Source: Krzysztof Janowicz, Frank van Harmelen, James A. Hendler, and Pascal Hitzler. "Why the Data Train Needs Semantic Rails." AI Magazine, 2014. http://corescholar.libraries.wright.edu/cse/169/.

process. Fundamental concepts that are changing the face of many data-aware and data-dependent disciplines that can also be used to mitigate the (data) challenges we face in architecture. These concepts, some of which are described below, include the Semantic Web[1] (which introduces relationships to concepts as opposed to just definitions), pattern languages (which are used to computationally construct relationships and context between ideas and data), and specific ways that we are exploring the intersection of architecture and A.I. – or artificial intelligence – and the potential for architects to meaningfully leverage AI methods and tools in their work.

COMPUTATIONAL MODELS AND METHODS TO EXPLORE BIG DATA: THE SEMANTIC WEB AND STRUCTURED INFORMATION

This idea of making "smart data" instead of smart applications coincides with a major paradigm shift introduced by the Semantic Web. The World Wide Web (WWW) "invented" by Tim Berners-Lee was intended to be a web of connected data, not simply a web of connected documents; what most web users are familiar with in the form of hyperlinks and hypertext. In Berners-Lee's vision (Tim Berners-Lee), the web is an ecosystem of smart agents that can process smart data directly without human intervention. The WWW standards organization, the World Wide Web Consortium (W3C), has already developed a set of technologies and standards that enable this vision including graph representations of data (RDF)[2] and standards for encoding formal logic in RDF, like OWL.[3]

These tools are powerful because they allow the formal representation of a human conceptualization in a structure that is understandable by machines. This is called an ontology. However, in order for an ontology to function and support a human-posed question, the data must be formatted a certain way (or be "query-able"). Linked Data is a set of principles that have been developed in the Computer Science fields to guide the publication of data on the World Wide Web to meet this formatting style. It is intended to accelerate and enable, really, the adoption of Semantic Web technologies, like the use of ontologies. Some of the rationale behind this shift is "… the insight that smart data will make future applications more reusable, flexible, and robust, leaving smarter applications to fail to improve data along the same dimensions" (K. Janowicz). The primary thrust being: most modern tools, design-centered or otherwise, do not (yet) integrate how human beings think, work, or find useful information in their daily lives, let alone enable us to connect various types of data for simultaneous consideration and use.

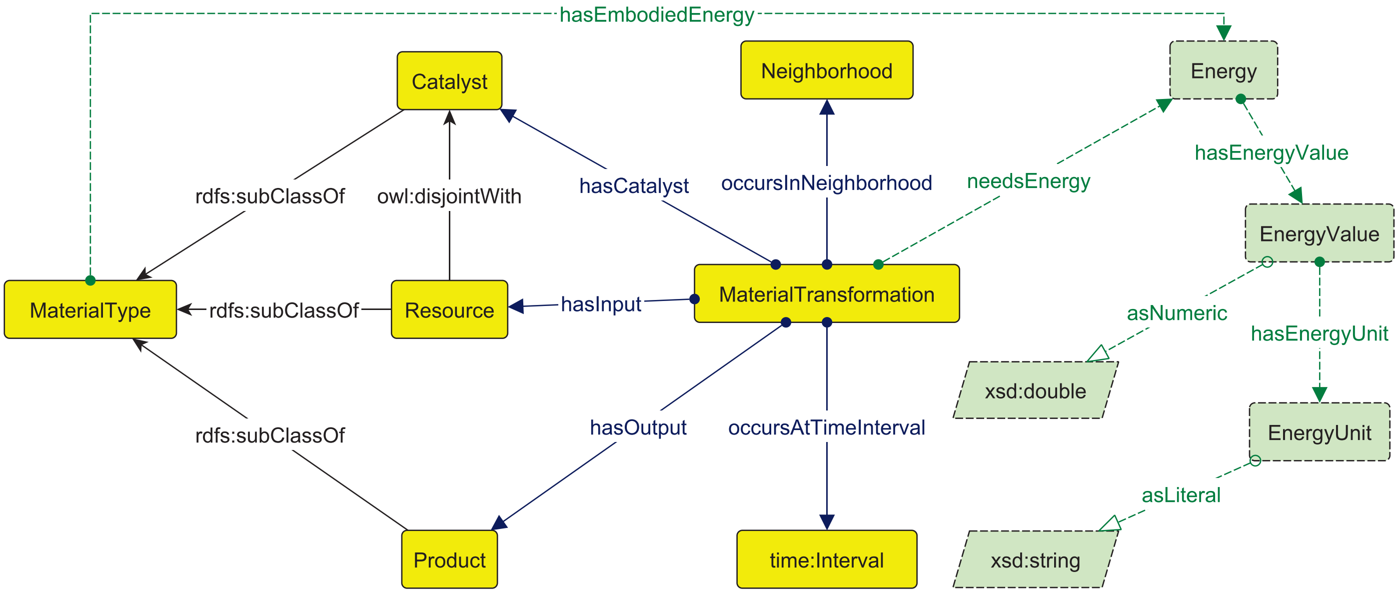


Figure 3. Example Data Patern: Material Transformation Pattern (To read more about these please visit: http://ontologydesignpatterns.org/wiki/Submissions:ContentOPs)

If properly structured, Semantic Web technologies could transform the way that architects access building design information and data and, in turn, architects could exploit the assistance of machine agents in decision support, including the potential to use and manipulate distributed knowledge bases called Knowledge Graphs. A knowledge graph structure provides the basis for contextual information. An example of this is the additional information – dates, history, related events – that are returned in many Google searches of the WWW.[4] If Google can provide useful, contextual information about a simple term lookup, imagine the opportunities for harnessing information about something as complex as the elements of building design. Our efforts are particularly focused on ways that these techniques and technologies could enhance and expand the data used during architectural analysis and thus advance our capacity to make sustainable and resilient design choices. A similar structure is used in

LinkedIn and Facebook, which is a type of AI used to determine suggested acquaintances. In lieu of the author/user expending all of the effort of searching, the smart agent connects pertinent information related to the data. Importantly, the decision to be connected is not made for us, but all of the information available is presented for human consumption and human action.

LINKED OPEN DATA AND ONTOLOGY DESIGN PATTERNS

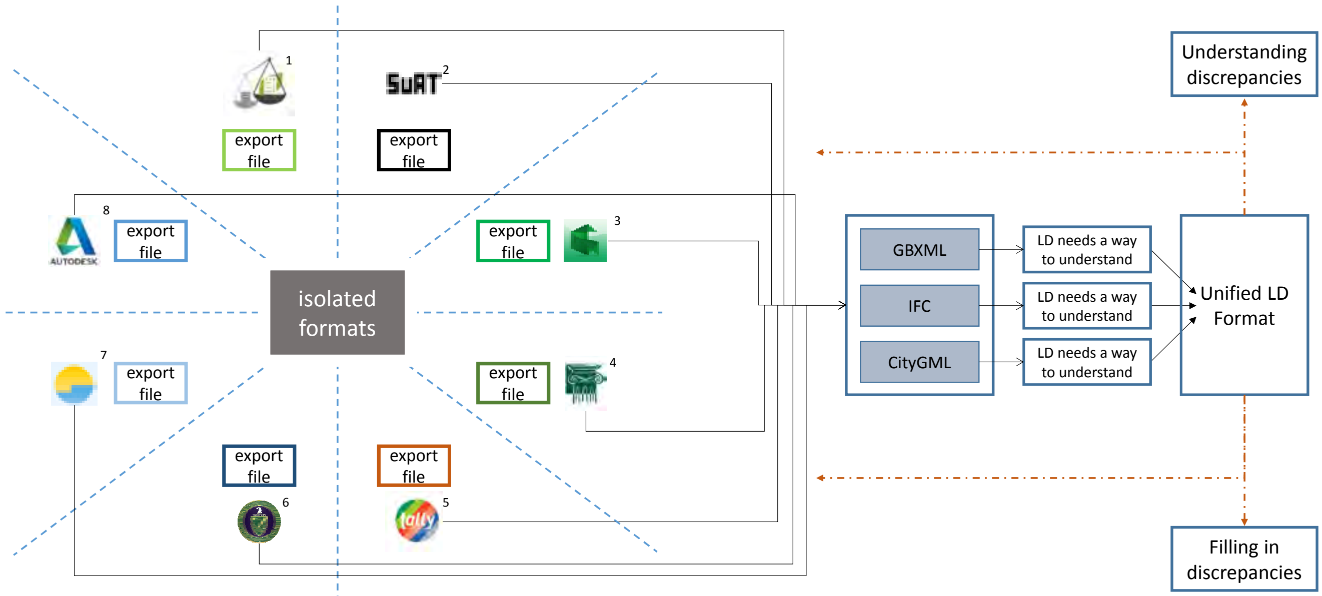
What does it mean for data to be structured in a re-useable way that machines can understand within the Semantic Web? This process is essential to integrating these technologies with architectural design. The interoperable structures that make this all possible are called Ontology Design Patterns and are a type of Linked Data that not only connect data but also establish relationships between different data elements with formal logics.

A pattern-based approach of re-usable solutions makes it possible draw equalities and mappings between all of the different sets of data that we may encounter and use in modern tools.

For example, imagine that you would like to capture the motion or trajectory of a building material from raw material to installation at a construction site. You may be a construction manager or an architect concerned about the transportation impact of materials on embodied carbon. How would you describe the trajectory in a way that a computer could understand? Today, there are reusable patterns that allow us to track and record location-specific, GPS, and other information that can be queried during analyses that track a “Semantic Trajectory” (Y. Hu) through space and time. For our more specific use-case, we have constructed a new pattern called a “Material Transformation” pattern [Figure 3] (Vardeman II) that “tells” a machine that something has changed identity in, say, a manufacturing process. In this pattern, a set of material inputs and outputs exist to the transformation and something must change between the inputs and outputs for a transformation to exist. This logic is enforced though machine readable axioms expressed in formal logic. Together, these two patterns, the existing Semantic Trajectory pattern and our new, Material Transformation pattern, enable a computer to understand how a building material moves from place to place and how to identify if a material has changed identity. The influence of these patterns on the collection of life-cycle inventory data, for example, could be significant.

LINKED OPEN DATA AIDING DECISION SUPPORT

Beyond the ability to structure data in an interoperable way to make it more easily discoverable and accessible, there are opportunities to computationally-support the analysis and use of information in new and potentially transformative ways. Current methods of analysis in architecture typically involve techniques that consider the information available compared with the preferences of the user (one example of this is the selection of preferred building materials or preferred manufacturers). In the realm of computer science, Decision Support techniques and technologies are developed to assist



1 http://www.greenscale.org/
2 http://www.suat.arch.ethz. ch/en/research/design-performance
3 http://usa.autodesk.com/ecotect-analysis/
4 http://www.athenasmi.org/
5 http://www.kierantimberlake.com/pages/view/95/tally/
6 http://energy.gov/
7 http://www.gabi-software.com/international/index/
8 http://www.autodesk.com/products/revit-family/overview

Figure 4. Extracting and Formatting Data that is Semantic Web Compatible

users in processing information, which is becoming increasingly essential in the Era of Big Data, in order to process the immense amount of information available or even to be able to ask our modern, multidisciplinary questions.

A foundational component for Decision Support now and in the future is smarter data, made possible by standards called Linked Data. With properly structured Linked Data, Decision Support can be orders of magnitude more accurate and comprehensive than what is currently used in individual design tools. For example, smart data-enabled Decision Support in building design could mean the ability to compare anticipated building energy use with embodied energy/ carbon for the entire lifespan of the building, competitive trade-off analysis of those choices, including degradation and replacement costs, and resilience-based concerns, including climate, hazard risk, and so on.

This level of analysis is clearly needed in the building industry, though it requires data and processing capabilities beyond what our current tools can perform. However, Semantic Web technologies can be combined with distributed cloud based data platforms, technologies which do already exist, in order to enable users to access remotely-located resources for Decision Support. The Cloud, when combined with Linked Data, already has powerful enough processing capabilities to advance Decision Support in the manner we are suggesting, all of which is needed in order to more fully support and enable data-aware architectural design. Meanwhile, it is important to acknowledge that Decision Support is a major part of our everyday lives, in the form of our smart phones and machine agents that already assist in controlling parts of the build environment, such as in smart homes. At minimum, shouldn't these existing technologies be informed with the most robust and complete data?

ARTIFICIAL INTELLIGENCE: BENEFITING THE CREATIVE PROCESS

Artificial Intelligence, or the ability of machines to exhibit intelligent behavior can benefit the human-centered, creative design process – as opposed to replacing it. If machines such as Watson5 can "learn" to play competitive chess and comprehend trends in recipes and preferred flavor combinations in order to propose new, improved cooking ideas, then perhaps it is not too far-fetched to suggest that we could use the same tools to learn something useful about trends in building construction and performance that would provide insight for the design of new buildings. Thomas Malone, founding director of MIT's Center for Collective Intelligence, said that the "future lies in building systems that can best leverage the capabilities of humans and computers. A growing body of research is finding that answers gleaned from a combination of humans and computers are more accurate than those generated by either group alone."[6]

Instead of hindering creativity, better data processing mechanisms can conserve design time previously spent manually sourcing and aligning data, leaving more time for actual creative design pursuits. Additionally, many of the simulations used for resilience calculations are able to utilize real-time and sensor-based data. The efficient and effective collection of this type of information for use in the creative process is not typically feasible without computational intervention without unreasonably burdening the creative process. Instead, data platforms using Semantic Web technologies can make sense of sensor data, for example, and draw conclusions computationally that will support architects with data analysis that is too complex to be done by humans in an efficient manner.

CONCEPTS APPLIED: OUR CURRENT MULTIDISCIPLINARY RESEARCH PROJECTS AND FUTURE WORK

As we assess and align our research with normative design processes and workflows, we design data patterns to extract information from building design models and filter it into a common and unifying format whose intelligence can be expanded as our Linked Data Platform (LDP) infrastructure grows. LDP is already a W3C standard and the patterns themselves are also already Linked Data. Therefore, data can be used in different simulations and serialized into a variety of formats. By virtue of using Linked Data-compatible formats, these technologies virtually eliminate the need to create "patch" solutions, in the form of individual tools or translators, for translating data between file formats. Communications within the LDP are designed specifically to promote the exchange of structured data and translation mechanisms and meanwhile provide passageways for the automated searching of additional data on the web to fill in the missing data, automatically correct the inconsistent data, and place information where data is otherwise incomplete. Additionally, these tools can be expanded in a "build-as-you-go" manner.

In prevailing 3-D modelling programs, BIM is what a computer uses to describe and understand what a particular design is. To use building information of this kind in a LDP environment means developing methods to automatically provide context between different data types, and as an extension, make BIM and related tools more interoperable. In other words we work on ways to translate data for use in several simulation types without the necessity of manual intervention, which is useful for improving predictive modelling, and for tracking data provenance information. This part of our research focuses on building linked-data compatible translation methods between the industry common data formats: IFC, GBXML, and CityGML, so that we can test and expand the capability of our data models to more effectively harness data and enable greater insight during the design process [Figure 4].

The development of these tools and technologies is extremely prescient and timely for the domains of architecture and engineering and the creation of the built environment, as the influence of our design decisions on the environment and human health are acknowledged to be significant. When we think back to the very earliest practitioners and theorists on architecture, there were a relative few types of materials suitable for the construction of buildings. Simply those, as Vitruvius observed, containing or made by the "primordial substances": earth, air, fire, water. Not so today: when compared to the sheer number of materials and methods that can be used to construct a building; and the growing expectations on architects and engineers to predict how their design decisions related to the combination of those many materials and methods will ultimately perform when constructed.

Ultimately, buildings are more complicated than ever before and we must design and make them faster. Owners, their representatives, banks, and building operators ask design teams to predict how those buildings can be expected to perform – on time, over time – in terms of energy consumption, long term durability of systems and assemblies, under normal conditions of degradation and even resilience against failure due to natural or man-made hazard. We are generating more data and information about our buildings – and by our buildings – than ever before. So, there are challenges surrounding data-enabled design, <u>*even in its current state*</u>. Foremost among them:

1. Where is the data? And how much can we move to the open?
2. Can we get businesses and people to share their data and information for the common good?
3. If the will is there, for sharing, what are the mechanics?
4. Of the barriers to adoption of data-enabled practices – authorship, intellectual property, data quality, data validation – which are the biggest threats?

When advancing to the frontier of discovery, we need tools to prepare us to perform once we get there. We are not suggesting that these tools or methods – these cognitive agents -- will replace the human agent in design. What we are suggesting is the Future of Design in the Post-Digital Era lies in tools and cyberinfrastructure that will advance ***design*** and practice, enabling, as the legendary computer scientist Steve Jobs suggested, the machines to do the mundane, while empowering people to do the extraordinary.[7]

ACKNOWLEDGEMENTS:

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ENDNOTES

1. https://www.w3.org/standards/semanticweb/
2. https://www.w3.org/TR/rdf11-concepts/
3. https://www.w3.org/TR/owl2-primer/
4. https://googleblog.blogspot.com/2012/05/introducing-knowledge-graph-things-not.html
5. http://www.ibm.com/watson/
6. https://www.technologyreview.com/s/519831/new-answer-from-ibms-watson-a-recipe-for-swiss-thai-fusion-quiche/
7. https://www.youtube.com/watch?v=ob_GX50Za6c

REFERENCES:

Barabasi, Albert-laszlo. *Linked: How Everything Is Connected to Everything Else and What It Means for Business, Science, and Everyday Life*. Basic Books, 2014.

Buccellato, A. P, et al. "Sustainability Data Community Forum." Chicago, 18-19 July 2013. Workshop.

Cukier, Viktor Mayer-Schönberger and Kenneth. *Big Data: A Revolution That Will Transform How We Live, Work, and Think.* Eamon Dolan/Mariner Books, 2014.

Hey, Tony. The Fourth Paradigm: Data-Intensive Scientific Discovery. Vol. 1. *Microsoft Research*, 2009.

K. Janowicz, F. van Harmelen, J. A. Hendler, and P. Hitzler. ""Why the Data Train Needs Semantic Rails"." *AI Magazine* 2016.

Tim Berners-Lee, James Hendler, and Ora Lassila. ""The Semantic Web"." *Scientific American* 2001: 28-37.

Vardeman II, C. F., Krishnadi, A. A., Cheatham, M., Janowicz, K., Ferguson, H., Hitzler, P., and Buccellato, A. P. "An Ontology Design Pattern and Its Use Case for Modeling Material Transformation." *Semantic Web* (2016).

Y. Hu, K. Janowicz, D. Carral, S. Scheider, W. Kuhn, G. Berg-Cross, P. Hitzler, M. Dean and D. Kolas. "A Geo-ontology Design Pattern for Semantic Trajectories." T. Tenbrink, J. Stell, A. Galton, Z. Woods, Eds. *Spatial Information Theory*. Springer International Publishing, 2013. 438-456.

Optimizing Early Design Process Decision Making Through Effective Problem Framing

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Temple University

Building design and delivery activities, from programming to commissioning, draw on different strengths of architects including a unique form of problem solving that appears mysterious and personal. More common early in the design process, an intuitive approach, and a paucity of arguments connected to the financial interests of owners, masks the capacity of architects to provide valued adding integral sustainable design solutions which others can't effectively provide. An inclination toward intuition, and simulating early phase design problem solving, is consistent with how architecture schools teach, supplementing core studio curriculum with course work structured to introduce detailed knowledge. Within schools, this division is supported by the perception that numerical, and technical considerations, inhibit creativity and fluid output.

The degree to which this model fails to lead to rapid productivity of recent graduates has been a source of criticism from practitioners. Academics typically counter that they are interested in longer term critical thinking skills, and that it would be irresponsible to privilege the short term concerns of practitioners. This paper looks beyond the skills vs. thinking debate by relating core aspects of design thinking to opportunities available to optimize sustainable design earlier than later in the design process. It traces an experiment in introducing analytical tools to an undergraduate design studio course which demonstrates that objective feedback can co-exist with creative action, and points to the power of design at the schematic level when significant opportunities for sustainable design are cemented.

PROBLEM SOLVING

The building design process presents distinct challenges which influence the unique nature of architectural design education and practice. Other professionals are able to determine with relative effectiveness the objective of their design efforts by clearly identifying a range of acceptable outcomes which can be codified in explicit criteria and physical parameters. With clear parameters, they can anticipate what they will need to learn through analytical activity, consistent with the scientific model of gaining knowledge [Fig. 1]. A notion of problem identification as a discrete component of architectural design thinking is central to William Pena's book Problem Seeking which formalized the activity of programming. Because of the type of mindset necessary to ask adequate questions Pena argued that programming was best accomplished separately from design because it was methodical, and design is intuitive, although he acknowledge that a designer could program if of the correct mindset.[1] Prior to Pena, architects including Christopher Alexander distinguished formal analysis and design activity with the aim of bolstering the efficacy of architects within a climate of increased confidence in science in the decades immediately following the Second World War.[2]

A scientific model of analysis and synthesis did not translate as well as promised to architectural design for several reasons. The first involved the amount of time that owners and architects had to develop a detailed program that identified comprehensive clear objectives. Second, although a detailed program could be developed, it was not possible to come to complete terms with the nature of a design problem before commencing design since building problems presented too many possible situations to analyze. A third reason involved the culture of architecture, where analytical activity that would lead to clear findings has been peripheral to alternative priorities in architectural studio education and practice.

Although counter to scientifically grounded thinking of engineers, de-emphasis of analysis by architects is not completely irrational since ridged criteria can be a liability when seeking a wide range of potential outcomes. Architects are able to explore a wide range of potential solutions because analysis of problems does not preclude them from testing solutions that do not directly correspond to initial understandings of problems. More importantly, architects need to be able to learn about problems through posing solutions which contributes to a model of design thinking that advances on the analysis-synthesis model of design thinking [Fig. 2]. The notion of learning through solution reflection, as a method of addressing wicked problems which are disorderly, is credited to Donald Schon.[3]

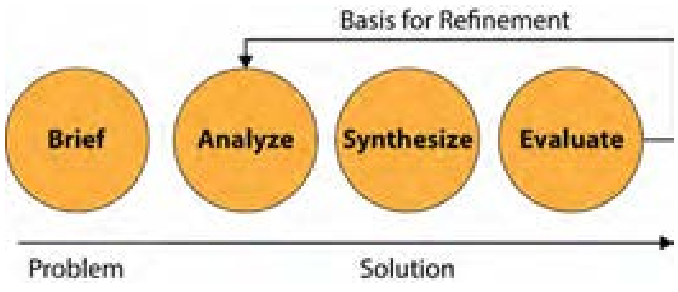

Figure 1: Analysis and synthesis model of problem solving.

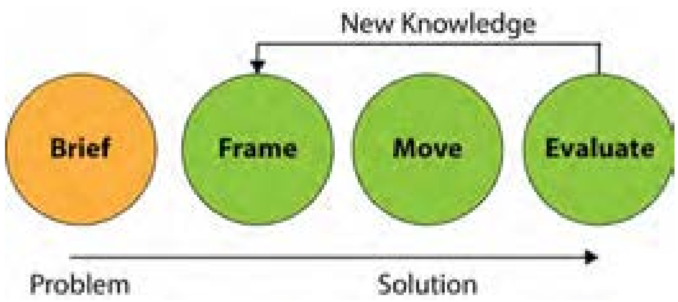

Figure 2. Learning through framing, solution posing, and evaluation model of problem solving.

In order to avoid paralysis and cut through almost unlimited problems and potentials, architects act intuitively by identifying issues to frame, and posing solutions that directly, or indirectly come from the territory framed. They can also import solutions external to the problem, which is a technique specific to architecture that plays a significant role in architecture school studio exercises.4 External solutions in the form of metaphors, typologies, or previous works, allow designers to cut across uncertainty and generate solutions by which problems can be better understood. Learning by doing, as opposed to learning by analysis, is particularly effective in the beginning stages of design when possibilities are vast, but less rewarding later in the design process when paths have been committed to, and specific problems become clearer and more technically demanding.

Broad gestural design moves need to occur within the realm of responsible solution posing. Experienced designers have accumulated knowledge that feeds intuitive abilities, can recognize situations, and determine when creative leaps are warranted. If a designer has not accumulated enough knowledge to assess situations, cannot make creative leaps, becomes paralyzed, is not critical, and can't learn from solutions, potential for effectiveness is limited. Beginning designers are presented with having to make intuitive decisions before they understand the implications of the design situations they are expected to sort through, and before they can effectively assess the decisions they make. The process of design education guides students to issues, and forms framing habits by which see design problems, and question results.[5]

The way architectural problem solving is introduced in the academy has implications for practice. Although architects have historically relied on learning in practice settings, the ramifications of design education are greater now, than in the past, since buildings are more technically complex and performance expectations are greater. Within individual building spaces, lighting, acoustic, and interior climate expectations have risen, and spaces accommodate demanding equipment, oftentimes suppressed in the building fabric. This requires architects as coordinators to evaluate disparate systems within a context where other actors are approaching the design and building process with knowledge backed by science. More importantly, education establishes future values, and habits.

CONNECTING TO THE BOTTOM LINE OF OWNERS

Even though architects' responsibilities prior to the twentieth century included those of the modern general contractor, they currently have less credibility than general contractors and owner advisors with respect to understanding and controlling building costs. During construction, architects are often in the position of defending intentions which contractors claim were difficult, if not impossible to predict. Because proposed changes are framed as a value proposition, architects are generally forced to rationalize aesthetic decisions in the face of hard numbers from contractors. Often pressures to control construction costs eclipse perspective on long term benefits derived from quality designs that are sustainable, and contribute to a long building life.

Within a context of deliberation tied to building costs, architects who stubbornly defend higher costs without firm support for decisions, risk being perceived as frivolous or working counter to owner interests. A response to this dynamic includes communicating more pragmatically about construction, and cost issues, as well as linking design decisions to positive financial outcomes. Another avenue to more influence is to provide compelling reasons why form, material, systems, and finish expectations made early in the design process should not be compromised later. Many changes made under the guise of value engineering reduce the quality of buildings, and incur additional change charges. Potential additional construction charges garner exceptional attention eclipsing other issues.[6]

Labor expenditures during schematic design, which approximates studio design, are a fraction of those for design development, and construction documentation. After schematic design, the form of a building proposal is typically fixed and can only be slightly molded without upsetting schedule and work flows. Cost implications of making significant design changes late in the design process, is effectively captured in the MacLeamy Curve [Fig. 3]. Inherent in escalated costs for later changes is additional design work, but more importantly the cost of construction changes, both logistical and material. As a result opportunities to tweak a design to enhance its sustainability diminish throughout construction. Energy analysis, typically executed by engineers, generally occurs late in the design process after they have contributed the bulk of their labor.

When performance feedback is gained late in the design process, there is little chance to revisit early form decisions which could increase building performance. In this light, energy analysis typically acts as verification, as opposed to the basis for fundamental form adjustments, although valuable changes can occur with materials and details. Integral planning strategies, such as those executed at the Arup office building in central England can't be introduced later in the design process. The result is that most sustainable designs are a hybrid between early design process decisions made by architects intuitively, and late design process adjustments made based on hard analysis.[7]

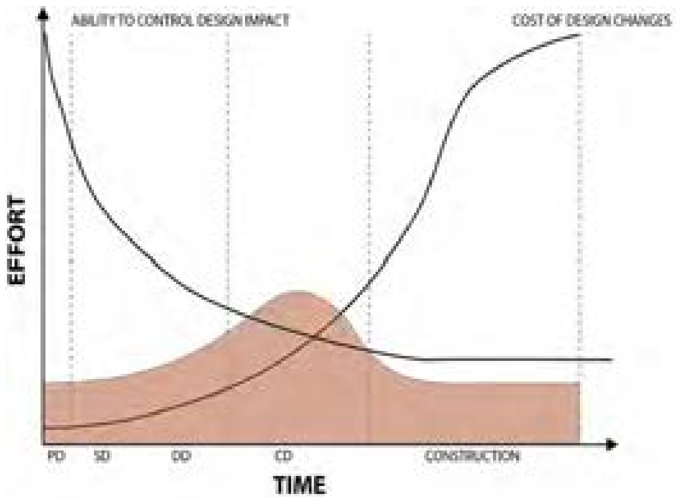

Figure 3. MacLeamy Curve.

SUSTAINABILITY AS A VALUE PROPOSITION

Sustainability has been typically framed against the negative environmental which have broad communal impacts, as opposed to benefits reaped directly by the building owners and users, and contractors. Greater focus of the building owner and occupant's interests broadens the appeal of sustainable design, and helps justify higher design and construction costs. Economic benefits include better energy performance, lower maintenance costs, greater user satisfaction and increased productivity; all of which can be tied to how well the building supports activity, comfort, and well-being. A less common sustainability concept points to a building's long term life being linked to its physical attractiveness motivating building owners and users to care for, and advocate for, a building that they consider beautiful.[8]

Finding increased value in form created early in the design process will increase understanding of architects' capabilities and value across projects of different building price points. Currently core architect talents are realized most fluidly in expensive expressive projects. Sustainably brings value, but it is rarely connected to early design decision making in a way that distinguishes benefits derived earlier than later in the design process. Utilizing software that provides early feedback supports sustainable building forms which are architect driven, permits integration of sustainability and form, and demonstrates that form is essential to building optimization.

Characteristics of vernacular buildings that work in harmony with local climate have been incorporated into architectural theory, and are integral to the thinking of many architects. Similarly non-vernacular concepts of solar design became part of the collective knowledge in the nineteen-fifties largely through the work of Aladar and Victor Olgyay, brothers who analyzed environmental forces in relation to what at the time were contemporary design strategies. By distilling solar design techniques and developing a language of visualizing the performance of buildings, the Olgyay brothers paved a path for architects to underpin solar design.

The Olgyay's research utilized scientific techniques including extensive mathematical calculations to support the principals they conveyed. These calculations were too cumbersome for most architects to apply to particular problems considering the fluid nature of design, and limits on time.

Figure 4. Student model at mid-term.

Figure 5. Discussion of design options using analysis printouts.

Alternatively, designers could utilize analogue tools including solar path diagrams, climate charts, and shaded design drawings; although it was more likely solar design would be intuitively applied and not explicitly demonstrated. Standard compensation models did not adapt to acknowledge additional time needed for calculations and drawings linked to solar design.

Strategically pointing to appealing forms helped the Olgyay brothers justify extra construction costs associated with solar shading strategies. In their book Solar Control and Shading Devices, the emphasis was on fenestration techniques, not building massing. In Victor Olgyay's later book Design with Climate: Bioclimatic Approach to Architectural Regionalism, massing and ventilation strategies are emphasized with few examples of appealing forms. Because principles and examples were more diagrammatic in the later book, architects were provided fewer familiar ways to justify design moves. Although style and recognition can move individuals to face costs, analyses complements judgment when emotion alone in not adequate to justify design.

UNDERGRADUATE SUSTAINABILITY STUDIO

Hurdles exist to introducing learning objectives that include building performance in early level design studio curriculum. Students have yet to develop

Figure 6. Section illustrating shading effects..

a personal design approach that they can confidently apply to different types of design problems. In most cases, they need guidance identifying design situations, recognizing key criteria, and generating concepts. Because of potential distractions, and limited knowledge of specific building requirements including egress, such factors are often omitted in studio projects to channel efforts towards more conceptual factors, and to allow for fluidity of form. Knowledge deemed important to architectural education, but is difficult to impart in studio settings, has traditionally been conveyed in support courses which are administered concurrently with studio courses, but seldom integrated until after graduation.

Learning objectives in the spring third year undergraduate studio at Temple University acknowledged challenges of integrating objective knowledge into studio exercises while addressing fundamental pragmatics including program and site. This semester the program was a Jazz Institute to include performance, practice, and exhibit space located on South Broad Street in Philadelphia. The public nature of the Jazz Institute program, and urban setting, engaged students in a design process that accounted for contextual site conditions including how the different program elements relate to the site, circulation, and views. Context also played a role in understanding the building in relation to sunlight, so factoring out site conditions was not an option. Students would also continue developing their ability to use abstract conceptual ideas to advance their proposals, a primary objective of the prior semester studio.

PRELIMINARY EXERCISES TO MID-TERM

Prior to engaging in building design students were asked to design a mobile performance pavilion. The week and-a-half project allowed critics to quickly gauge what the students have retained from the prior semester, and to have them to think quickly with limited dimensional constraints. After the sketch project, students were immersed in the history of jazz through documentaries, and individual research of seminal jazz artists. In order to provide additional visual material to bring to their design proposals, students were ask to associate found abstract images with qualities of music, instruments, and performance. Site research involved photographing and surveying the site, resulting in a digital base model and an eighth-scale physical site model. From the digital model, they developed photomontages, contextual street wall elevations, and two-dimensional site sections that included seasonal sun paths.   Students were also asked to submit a notebook of key observations made at the site.

After research and concept mining activities, students were issued a detailed building program with area requirements. During the next three weeks excluding spring break, the students were tasked with translating the building program in to two dimensional relationship diagrams, a three dimensional conceptual collage model, plans, and building sections. Development of individual building design proposals necessitated programming instruction including how to interpret, and manage a program. The first building design phase culminated soon after spring break leaving five weeks for design prior to the final review.

POST MIDTERM

The first three weeks of building design allowed students to develop a rough proposal [Fig. 4] that would provide the basis of further development over the following five weeks to include energy analysis. Introducing energy modeling as a means of providing feedback during the design process necessitated software instruction, which at Temple, is imbedded in studio courses. Prior to the mid-term most of the work was in analogue form with some modeling in Rhino, which is the platform the students have been grounded in, and the program they are comfortable with. Since it was important to have students be able to work fluidly while learning about jazz, and how to work with a complex program and site, students were introduced to new software midway into the semester.

In prior semesters many students were reluctant to learn and use software they perceived as burdensome in light of the challenges they faced dealing with new expectations. Digital instruction in a lab also contributed to the perception they were losing time advancing their designs. For this reason, it was important that the digital sessions not be understood as supplemental, but rather as integral to their design objectives. Rather than acquiesce to student biases, and preconceived notions of what is useful, adjustments included using energy modeling software that was user friendly for schematic design. Sefaira was the chosen analysis platform which necessitated instruction in Revit, a program that is associated with cumbersome detail. A response was to focus on the massing capabilities of Revit, and not get bogged down in features of Revit that would not contribute directly to analysis in Sefaira. Students were taught how to transfer file information between Rhino to Revit, something that would help them to see that their efforts in one platform would not go to waste by building redundant models.

BALANCE BETWEEN PERFORMANCE AND BEAUTY

Lectures and assignments involving principles of sustainable design were interwoven into digital sessions creating fluidity between the studio and lab. Building examples, including notable designs and vernacular, were used to

Figure 7. Interior rendering of final proposal..

make connections between sustainability and form. These efforts helped counter the perception that the lab time was just technical instruction. In addition to diagraming their design process, assignments included precedent analysis of green buildings in where they were asked to question how the examples are sustainable.

After learning how to translate between Rhino and Revit, students constructed simple massing models to see how form changes contributed to different readings in Sefaira. They modeled different iterations of their proposals and produced analytical reports. The results were presented in group pin-ups [Fig. 5] so students could learn from each other's efforts, and could see that evaluating data along with abstract representations of their designs was a compatible method of designing. As a result, students advanced their designs with the understanding that changes to massing, orientation, glazing areas or shading would result in different performance outcomes.

Throughout the semester students were taught that design is about balance between competing criteria including energy performance and aesthetics. Absolute improvements in energy performance without creating pleasing spaces, and sound juxtapositions, would be no more valuable than aesthetic achievements without functional and performance. As designers they would be responsible for coming to terms with tradeoffs, and identifying a proposal that recognized the impacts of decision making. In order to produce compelling designs, and convey their ideas presentation standards including crafted models, and perspective renderings were still emphasized. To assist with conveying their ideas, especially performative, students were provided support with representing building performance diagrammatically.

CONCLUSION

Introducing pragmatic considerations early, as opposed to later in the studio sequence, was seen as more important than deferring integration at a later period in the student's development. With tools such as Sefaira which are fluid and provide quantitative feedback, verifiable sustainable design thinking can be part of the next generation's foundational thinking skills. This studio challenged the belief that scientific principles and data and data could coexist with creativity activity without undermining the development of fundamental design skills. Key to this effort was persistent effort to have the students identify constraints that can contribute to design responses, and to identify external inspiration that they could consciously introduce into proposals.

ENDNOTES

1. Pena, William, *Problem Seeking,* CBI, Boston, 1977, 14-22.
2. See Alexander's book *Notes on the Synthesis of Form* first published in 1964. Alexander breaks down design problems into mathematical modules that can be used to construct solutions.
3. Schon, Donald. *Educating the Reflective Practitioner*, Jossey-Bass, San Francisco, 1990, 3-6.
4. Schon, Donald. *The Design Studio,* RIBA Publications, London, 1985, 15-17.
5. Lawson, Bryan & Dorst, Kees. *Design Expertise,* Architectural Press, Oxford, 2009, 82-104.
6. The field of behavioral economics has contributed greatly to establishing that humans are completely rational actors when approaching economic decisions. Economists have been successful in pointing out that the psychological pain of loss is greater than pleasure gained for the same magnitude.
7. The ARUP campus in Solhill, England is a contemporary building opened in 2005 and designed by the firm. It is shaped to allow for passive cooling and heading.
8. Hosey, Lance, *The Shape of Green,* Island Press, Washington, DC, 2012, 39-47, 98-101.

Visioning Energy: Environmental Simulation, Visualization and the Instrumental Nature of Energy

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"The obvious world that we know on the gorse levels of sight, sound, taste and touch can be connected with the subtle world revealed by our scientific instruments and devices. Seen together, aerial maps of river estuaries and road systems, feathers, fern leaves, branching blood vessels, nerve ganglia, electron micrographs of crystals, and the tree like patterns of electrical discharge-figures are connected, although they are vastly different in place origin and scale. Their similarity of form is by no means accidental. As patterns of energy-gathering and energy-distribution, they are similar graphs by similar processes" (Gyorgy Kepes, *The New Landscape in Art and Science*)

A glance at the recent history of the evolving conceptual relationship between energy and building related disciplines, reveals the coextensive emergence of tools and crisis. Whether economic, environmental, technological or cultural, these conditions are shadowed by an analogous — and exponential — leap in the power of computing along with a reciprocal decline in its cost (Figure 1). Moreover, it is not a coincidence that the progressive growth of computation based tools used in the evaluation of interior atmospheres is paralleled by similar historic benchmarks in twentieth-century environmentalism. First adopted in 1965, the ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy), for example, established a metric for indoor thermal comfort, and arrived during an era which saw the first energy crisis and also began to consider the impact of buildings within ecologies[1].

Embedded within this history are multiple polyvalent and intertwined paradigms in design thinking. Any attempt to comprehensively articulate this lengthy narrative of the relationship between architecture and energy would exceed the scope of this essay, instead we propose to identify a causal link(s) between the abstract instruments used to measure and observe energy, and the cultures of design that they engender. More precisely, this session explores how advances in computation are producing a growing range of virtual tools used in the modeling, simulation and visualization of thermal and environmental flows and how these emerging technologies have given rise to new methods of evaluating building performance, altered the economics of lifecycle and resource management, and problematized the traditional metrics of thermal comfort.

Changes to the performative capacity of traditional representational modalities, such as plan, section and perspective are host to the outward-most expression of the specter of virtually simulating and visualizing complex thermodynamic flows. Underlying this, however, are more universal and far reaching themes. When articulating architectures reciprocity to energy, we necessarily examine how architecture frames its relationship to the natural world through representation, or, how architecture represents and anticipates, uncertainty and indeterminacy. How does it define its real and subjective boundaries?

As the environmental, economic and social impact of building performance has changed, architecture has been thrust into rethinking its now nascent relationship to the natural world through an ecological frame of reference; these new modes of visioning energy have also changed the role of testing and research in the design process. Buildings are now understood as a complex ecosystem of "energy-gathering and energy-distribution" - a soft-boundary mediating the intersection of climate, material, space and structure[2].

While every method of energetic visioning, invariably produces its own subjectivities, expressed as spatial, political or economic biases, this discussion explores how we "see" these energetic subjectivities as intrinsic to Architecture. As well as how the instrumental representation of energy transforms the institutions of architectural and engineering practice. Supported by the collaborative intersection of academic and practice based research, this next generation of thinking in the design of mediated environmental control systems expands on what the architectural historian and critic, Reyner Banham, termed the "well-tempered environment"[3]. Static and steady-state building conditions, which Chris Reed of STOSS described as "classical ecological orders," favored stability, certainty and order, and are endemic of a

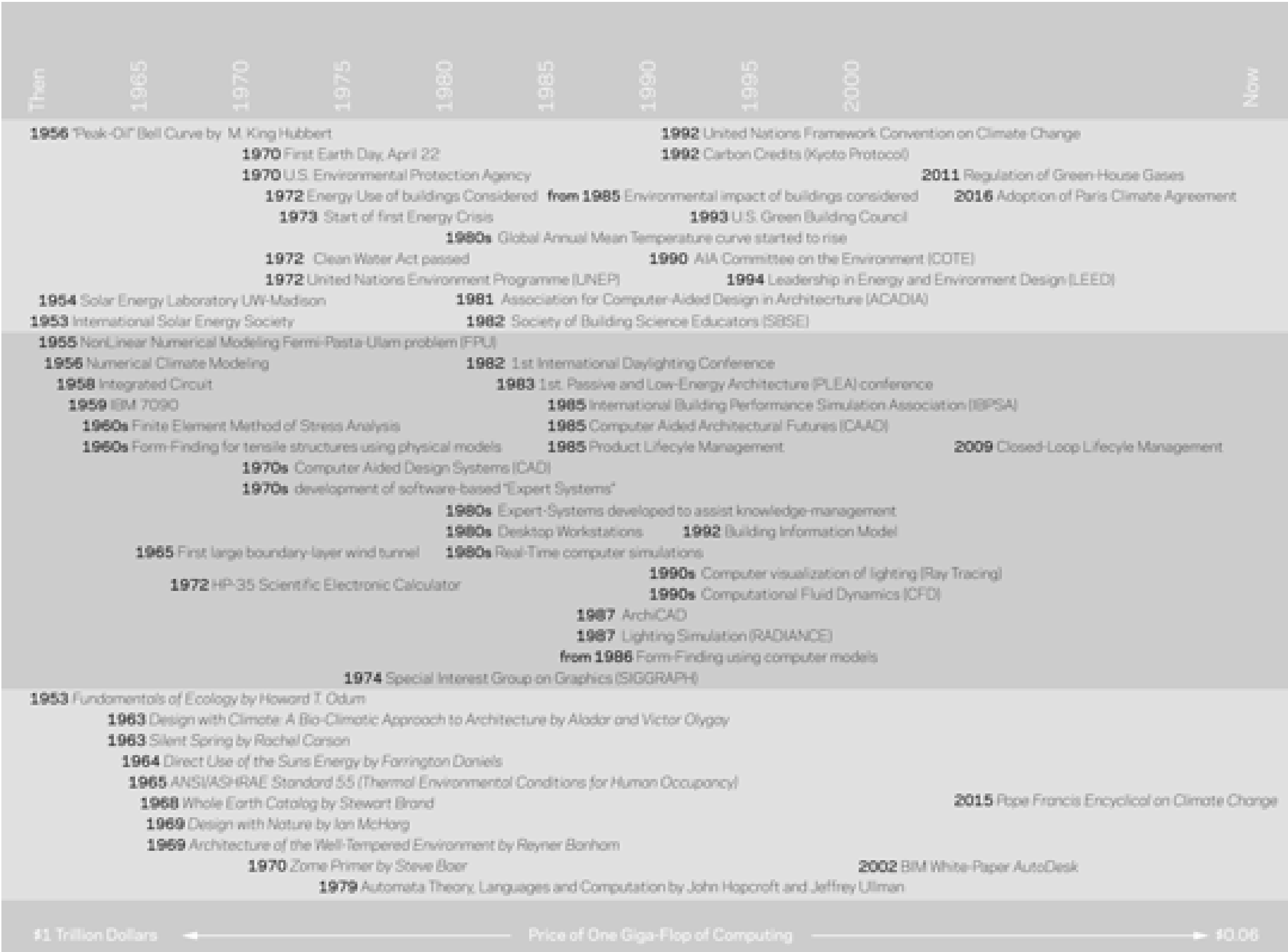

Figure 1. Recent history of the the relationship between energy and building related disciplies.

post-war approach to the design of environments — not to mention at odds with the statistical and probabilistic nature of thermodynamics.[4] Instead, it is dynamic change, adaptability and resilience, that now frame our aspirations.

Ecology, is a perpetual source of reference within this discourse. This is in part an outcome of the comprehensive world-view that it embodies, and by the metrics and quanta that ecology has invented, or adopted since the immediate post-war era - many of which accurately capture and describe the inherent material and thermal conditions of buildings and occupants. Metabolism, mass, power, area and entropy, are expressions of thermodynamic forces in biological systems that are either the same or have analogs in architectural terms.[5]

The fluid mutability of ecologies core concepts is evidenced by their widespread, though diffused, application by disciplines as varied as ecology, economics, geography, landscape architecture, urbanism, architecture, thermodynamics, and others. A majority of which use the concept of energy to denote the material and informational exchange inherent to all mechanical and biological processes. In this regard, energy, as the index of thermodynamic forces, has been and continues to be the general epistemological framework of the 20th and 21st century, structuring a way of knowing the world that is contingent on describing the connections and pathways of things[6].

A map of the pathways that pass between energy and architecture is manifested in a widely divergent and sometimes conflicting ensemble of tools. Models, play a particularly important role as the primary tool in managing the discussion between disciplines because they provide a conceptual scaffold for the deliberation between the metaphors of indexical diagrams, the "sankey", for example, and more complex mathematical models outside of the architects anticipated scope of expertise[7].

While the "Sankey" diagram notates the connections and pathways of energy, it does not image them or retain an indexed record of their exchange. As the biophysicist, Harold Morowitz had outlined in his book, Energy Flow in Biology, "The flow of energy through a system acts to organize that system"[8]. Meaning that the patterns, forms and structures that we observe, whether geological, political, economic or architectural, are shaped in direct reciprocity to the exchange of energy. Any alternate representational model for mapping the reciprocity between architecture and energy would necessarily leverage the "experimentation in contact with the real."[9]

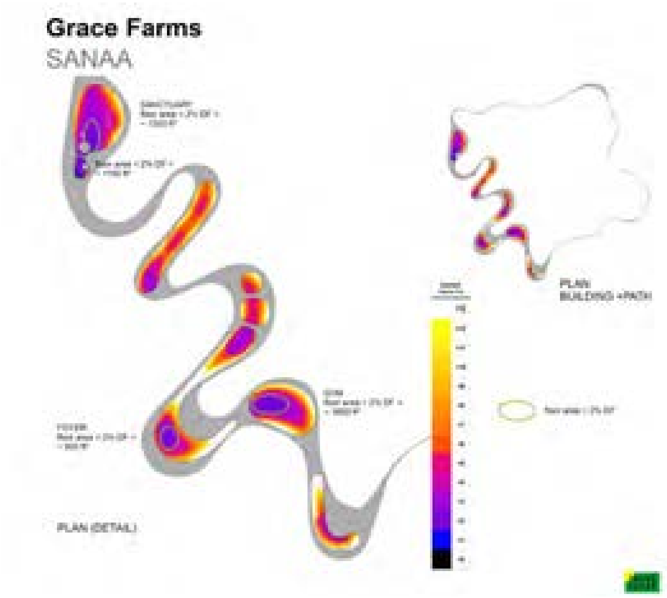

Figure 2. Thermal analysis of roof overhangs for Grace Farms.

Heavily influenced by this paradigm of ecologies, the architectural "systems" diagram, could be construed as a reductive device, capturing just enough of the easily recognizable features of the thermodynamic quotient of space one that domesticates environmental flows and perpetuates the dominance of "steady-state" architectural iconography in the transmission of a powerful image. Rather than obsess over this "temporary" trend of artistic license verging on the pseudoscientific, we propose to examine the productive correlations between the tools and methods currently used by designers and engineers to simulate thermodynamic effects.

Among these new instruments, Infra-Red Thermographic Imaging (IRT) and Computational Fluid Dynamic Simulation/Visualization (CFD), TRNYSYS, and Radiance modelers such as DIVA, are examples of contemporary tools deployed within the profession and related industries. These represent a shift in the conceptual modeling of Energy manifested within the thermodynamic flows present within buildings. Many of these new approaches instrumentalize the role of energy in relationship to structure, form, program and building systems and as a result are implicated at the earliest phases of the design process, providing for the expansion of disciplinary expertise into new material concepts and territories of design agency.

The subject of Tools and methods for the instrumentalized nature of Energy is premised on identifying a new set of collaborative approaches that leverage the unique disciplinary expertise embodied within distinct but often sublimated instruments of representation. Increasingly Architects and Engineers are engaging in a collaborative and creative dialog enabled by the access to these emerging visual tools. This model moves away from architectural (20th century mechanical) engineering as a professional service towards an integrative model. ARUP and Transsolar exemplify this new breed of design consultancies reframing questions of architecture and environment as one of design. This is a question of the dynamic implications of tools and the disciplinary boundaries they represent.

QUESTION AND ANSWER WITH ERIK OLSON / TRANSSOLAR, AND MAHADEV RAMAN / ARUP AND ARUP UNIVERSITY

Lonn Combs and Filip Tejchman: The models that engineers use are primarily mathematical constructs. Perhaps as a function of their intrinsically abstract nature, these models provide a framework that is alternately predictive and immaterial. Describe the relationship between models and nature as it pertains to the methods found in your practice.

Erik Olson: Engineering models are simplified representations of the real physics governing a specific problem or situation. They are not meant to be wholly representative of reality, but only representative enough to capture effects that have a meaningful influence on the parameters being studied. Identifying which parameters are relevant, and which are superfluous, is a key skill in developing models for engineering analysis.

Mahadev Raman: A third factor in the relationship between models and nature is the modeler. Being able to perform a proper 'reality check' on model results based on the modeler's knowledge and experience is vital as there's always the danger of 'garbage in - garbage out'.

LC and FT: Can simulations introduce a new digital materiality into the design process that alters the conversation between architect, engineer and client? How are these tools changing or influencing practice?

EO: Engineering analysis has long had an influence on the design conversation but architect, engineer, and client. Today's performance simulations extend this conversation, allowing a conversation which was often limited to the truly material field of structural design to extend to diverse and more immaterial fields such as climate-responsive thermal design, daylighting design, and acoustic design.

Zaryadye Park is an extreme example, allowing the creation of semi-outdoor space whose environmental performance was unimaginable a generation ago, and with basic governing rules for form generation determined through

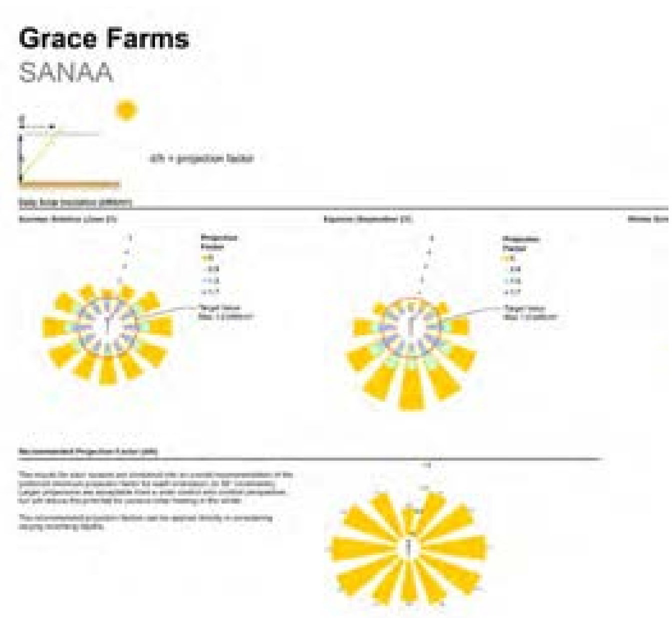

Figure 3. Translation of thermal analysis of Grace Farms into "solar rose."

simulation (Figure 2). Similarly, the sinuous curves of the roof overhangs at Grace Farms are informed by thermal analysis determining the required overhang depths, which were translated into a 'solar rose' which could be used for immediate feedback in the design process(Figure 3).

MR: An important current role for simulations is to provide near real-time feedback on energy performance during the design process to inform the design of net-zero buildings that are essential to meeting future carbon reduction targets.

LC and FT: Can the visualization of simulation data alter the understanding of the underlying model or, reveal inherent liabilities?

EO: Carefully designed visualizations can reveal patterns which might otherwise be invisible. They can also identify unexpected results, and when results are unexpected, the first step is generally to question the model: Have all of the relevant physics been properly understood and represented? If so, does further critical analysis of the physics and the results provide new insight into previously unexpected behavior?

MR: More often than not, the visualizations help to clearly identify areas where the design can be improved or optimized, something that is less easily achievable by scrutinizing pages of numbers.

LC and FT: How do the diagrams used by engineers differ from this used by architects?

MR: During the design process, some of the most useful engineering diagrams and visualizations are those that significantly improve the communication of engineering concepts and phenomena to architects.

EO: Many – if not most – useful engineering diagrams do not include geometric information. A good engineering diagram will still have visual clarity, but doesn't necessarily represent geometry. This is because the topic being studied – particularly in the field of climate-responsive design – often does not have strong sensitivity to architectural geometry. As an example, consider the validation of the natural ventilation design for the new School of Business at Portland State University. The steps necessary to eliminate mechanical cooling are considered in sequence without any need to represent geometry (Figure 4).

LC and FT: Have digital tools and more precisely, advanced modeling and simulation software, changed our expectations of building performance?

MR: There is certainly a growing expectation of predictability in the performance of any given design. There are fewer excuses for results falling short of expectations!

EO: Advanced modeling has changed our expectations of the relationship between performance and design. Increasingly these two topics, traditionally seen as in opposition, are understood as converging. Simulation provides information that allows performance to be studied in relationship to design, meaning both design intent and performance goals be met.

Building performance goals – particularly for energy – have also been becoming more aggressive. However, this is likely a result of increased attention by society to the topic, and not because the simulation tools themselves encourage clients to adopt more aggressive goals.

Lastly, advanced modeling can sometimes allow a new understanding of the definition of performance. For example, thermal comfort

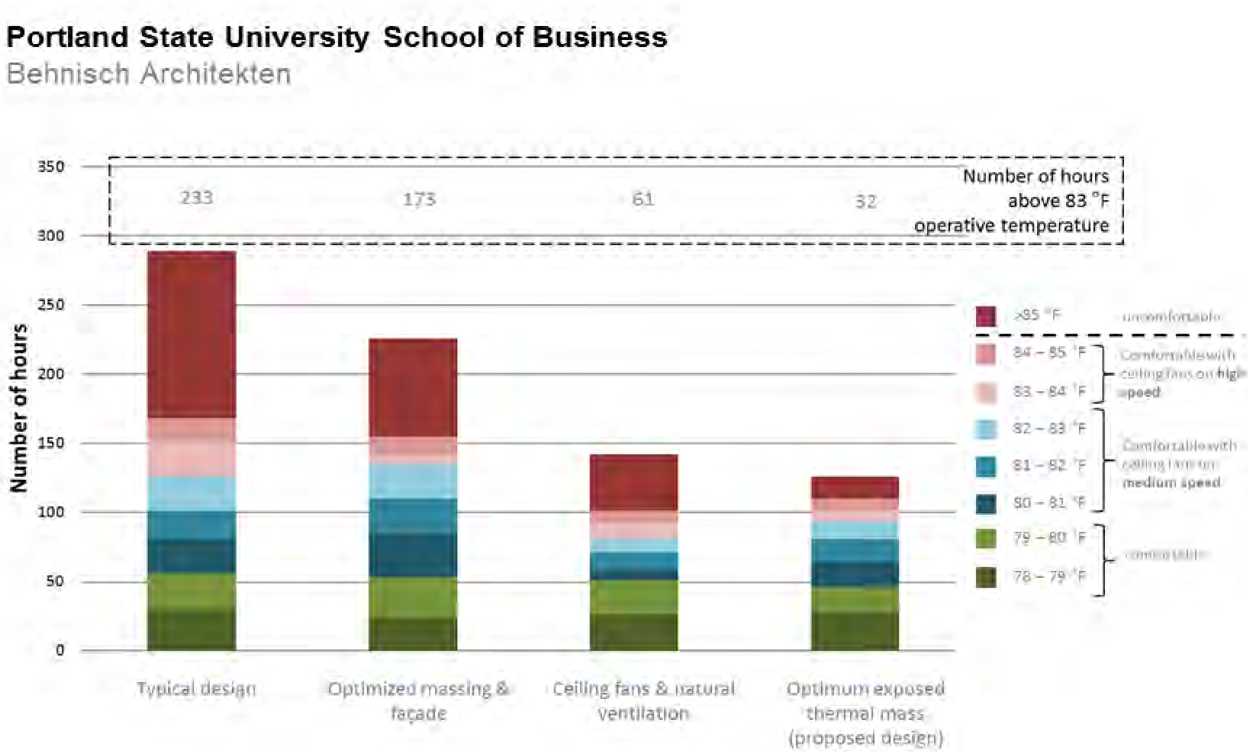

Figure 4. Validation of the natural ventilation design for the new School of Business at Portland State University.

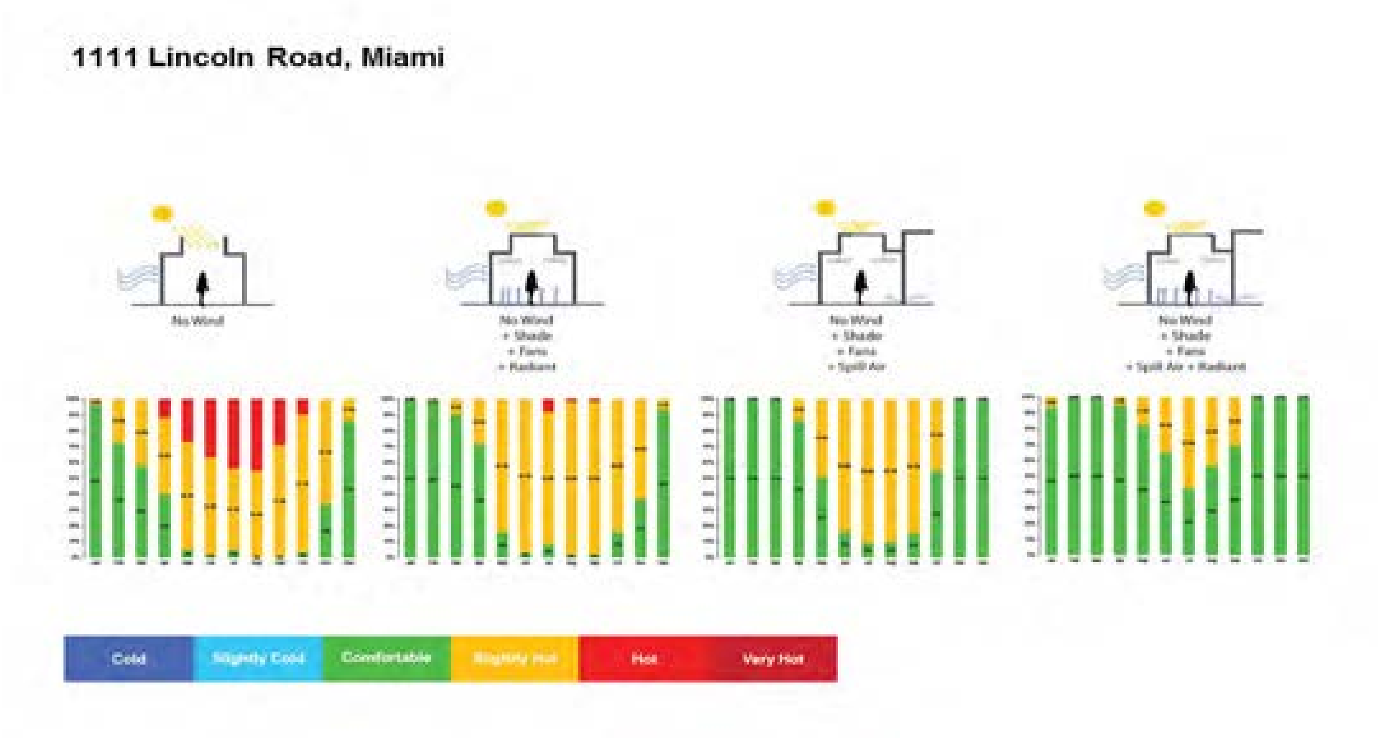

Figure 5. Comfort assessment for 1111 Lincoln Road.

has traditionally been evaluated with air temperature, an incomplete representation of comfort. New tools allow ever-easier calculation of more comprehensive metrics considering all factors affecting comfort – in our practice with increasingly use the Universal Thermal Climate Index (UTCI) for outdoor comfort assessment, such as Lincoln Road in Miami, and Standard Effective Temperature (SET) for indoor comfort assessments (Figure 5).

ENDNOTES

1. Bill Addis, *Building: 3000 Years of Design, Engineering and Construction* (London, UK: Phaeton Press Limited, 2007)

2. Gyorgy Kepes, *The New Landscape in Art an Science* (Chicago, IL: Paul Theobald, 1956)

3. Reyner Banham, *The Architecture of the Well-Tempered Environment*, 2nd. Ed. (Chicago, IL: The University of Chicago Press, 1984)

4. Chris Reed and Nina Marie-Lister, “Parallel Genealogies” in *Projective Ecologies*, (New York, NY: ACTAR Publishers and the Harvard University Graduate School of Design, 2014)

5. Filip Tejchman, from “Beyond the Invisible Rainbow” presented at the 68th Annual Conference of the Society of Architectural Historians, April 13-15, Chicago, IL

6. ibid.

7. Annabel Wharton, “Scaffold, Model, Metaphor” in *ARPA Journal* Issue 04, Instruments of Service ed. by Janette Kim and Jennifer Leong (New York, NY: ARPAJournal.Net, 2016)

8. Harold J. Morowitz, *Energy Flow in Biology* (London, UK: Ox Bow Press, 1979)

9. James Corner, “The Agency of Mapping: Speculation, Critique and Invention” in *Mappings* ed. by Dennis Cosgrove (London, UK: Reaction Books, 1999)