



Title	Integrated modeling agenda for sustainable communities via reconfigurability
Authors(s)	Laefer, Debra F., O'Brien, William J., Steiner, Ruth Lorraine
Publication date	2004
Publication information	Laefer, Debra F., William J. O'Brien, and Ruth Lorraine Steiner. "Integrated Modeling Agenda for Sustainable Communities via Reconfigurability." American Society of Civil Engineering (ASCE), 2004.
Conference details	Recycled Materials in Geotechnics : ASCE Civil Engineering Conference and Exposition, October 19-21, 2004, Baltimore, Maryland
Series	Critical Infrastructure Group
Publisher	American Society of Civil Engineering (ASCE)
Item record/more information	http://hdl.handle.net/10197/2137
Publisher's version (DOI)	10.1061/40756(149)15

Downloaded 2023-10-05T14:16:07Z

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

Integrated Modeling Agenda for Sustainable Communities via Reconfigurability

Debra F. Laefer¹, Member, ASCE, William J. O'Brien², Member, ASCE,
Ruth L. Steiner³

ABSTRACT

Sustainability in the construction industry can only be achieved through a radical rethinking of building construction and reuse. This paper outlines the problems and offers innovative solutions that embrace technological innovations, advances in manufacturing and distribution, and integration of building and land use concepts through: 1) application of a dismantlable and reconfigurable structural system, 2) promotion of the concept of kitting, and 3) reconceptualization of the relationships between construction management, engineering, supply chain configurations, environmental modeling, design, and urban planning. Basic components are described with the modeling and research agenda needed to make these solutions both viable and adoptable.

KEY WORDS: Sustainability, Reuse, Reconfigurable Structures, Solid Waste

INTRODUCTION

Current construction practices are unsustainable both in terms of use of raw materials and with respect to generating solid waste. For the construction industry to stop being a lead polluter in the generation of waste and the contamination of land and water, a fundamental shift must occur, one that incorporates the reusability of all building components. Material reuse is largely contingent upon basic changes in how structures service the end user. To achieve this will require three things: a change in building construction to maximize reusability, a paradigm to shape this new course of action, and a subsequent consensus from a myriad of groups that influence the planning, design, construction, and usage of structures. This paper outlines such a construction system, a relevant paradigm, and some of the current obstacles to such a consensus based upon integrated modeling for reconfigurable and reusable structures.

New product and process technologies make possible reconfigurable and reusable structures. Yet, to speed development and ensure environmentally sound design choices, fundamental research is needed. In particular, urban planning models must be integrated with cost and engineering models to provide useful and rationale policy assessments for investments in reconfigurable structures. At the same time, as recon-

¹ Assistant Professor, North Carolina State Univ., Dept. of Civil, Construction, and Envir. Eng., Campus Box 7908, Raleigh, NC 27695, dflaefer@unity.ncsu.edu.

² Assistant Professor, Dept. of Civil Engineering, University of Texas at Austin, 1 University Station C1752, Austin, TX 78712-0276, wjob@mail.utexas.edu

³ Associate Professor, Dept. of Urban and Regional Planning, University of Florida, PO Box 115607, Gainesville, FL, 32611-5706, rsteiner@ufl.edu

figuration and reuse remain novel concepts (Liapi 2001), there is a need for development of new knowledge and models within technical and social science disciplines.

Although a major impetus for such a system is a need to minimize landfill expansion, immediate as well as long-term financial incentives must be an inherent part of the adoption of sustainable technologies. Without such economic inducements, pioneering advancements in how buildings are manufactured and connected will languish under established systems and inertia. Fundamental to all of this is the need for integrated models that account for both technical aspects and social science requirements.

This paper outlines the extent of the problem of the construction industry's contribution to unnecessary landfill expansion and solid waste generation, the patterns in suburban sprawl related land use that promote this, the additional challenges posed by rapid growth communities, current efforts in sustainable construction, new alternatives, and some of the changes needed for adoption of these options.

SUSTAINABILITY ISSUES WITH CURRENT CONSTRUCTION AND THE NEED FOR RECONFIGURABLE STRUCTURES

The construction industry has long been a major consumer of environmentally intensive materials (e.g. concrete, asphalt, steel, and wood). Commercial and residential construction use 40% (3 billion tons annually) of all raw materials (US DOE 2003). The raw materials used, methods required for their processing in terms of energy, pollutants and clean water, affiliated transportation needs, and customization required in their installation pose large challenges for implementing sustainable design. A particular difficulty in reducing this is the effective reuse of construction materials. An EPA study estimated that building construction activity (excluding roads and bridges) generates 136 million tons of construction and demolition waste per year in the United States (U.S.) alone (US EPA 1998). Of this, 125 million tons per year is from demolition and renovation. The construction portion continues to grow. Florida's Department of Environmental Protection reports a growth in construction and demolition debris from 1990 to 2000 from 19% of all municipal solid waste in Florida to 23% of it (FDEP 2001). Construction related debris is a significant part of the waste stream. To change this nearly all construction materials and components must be reused.

Material removal from during demolition and renovation and the subsequent material use during new construction, with attendant problems of transport and energy use, pose perhaps the greatest problems for sustainable construction (see below). Yet new construction, or alternatively, the reuse of existing structures is needed. The community impact and environmental cost of this resource intensive cycle of new construction, renovation, and demolition retards environmentally sustainability. Innovations must fundamentally address the problems of existing land usage patterns.

Redevelopment: Renewal on 13th Street in Gainesville, Florida

Old suburban shopping malls are being abandoned and replaced by larger retail facilities – big-box retail, outlet malls, power centers, and lifestyle centers – that are be-

ing built at greater distances from city centers and nearer interstate highways. The Gainesville Mall on NW 13th Street and 23rd Avenue in Gainesville, FL, built in 1967 as the region's first suburban shopping mall, is such an example. Sears and a regional department store were the original anchor tenants. When it was built, the mall attracted customers from throughout the community. Today, the mall is almost empty, and the WalMart across the street plans to close and replace its store with a Super-WalMart at a new, greenfield location further from the city center. Arguably, the existing mall is in a prime location. Located 2 miles north of the major employer in the region, the University of Florida, the mall is situated along a major interurban highway that carries 33,000 vehicles per day. In spite of these geographic advantages, the redevelopment of this area will be a challenge, because the mall looks old and worn and is not well integrated with the surrounding neighborhood. Furthermore, most of the recent residential growth in the community has been westward, near the interstate. Yet the health of the larger Gainesville community depends upon some type of intervention, and the community leadership remains divided as to the most feasible solution. For both the developers and the community leaders finding new uses for the site represents a major expenditure. Current construction trends become barriers to accommodating further uses as there are only so many clients who require a big box, which effectively further discourages subsequent reconfiguration on the part of a developer and community leaders should the second scheme be unsuccessful.

New Construction: Las Vegas and Constant Urban Reconfiguration

Many cities experience boom periods, where the existing commercial, residential and governmental infrastructure is wholly inadequate for rapid population gains. A current example of this is Las Vegas, Nevada and its bedroom community Henderson. At 6,000 newly registered drivers per month, not only does the phone book have to be issued twice a year, but governmental services cannot begin to accommodate the population boom, even by extending service periods, such as keeping all Department of Motor Vehicles' facilities open on Saturdays. There are insufficient schools to teach the children, inadequate low security jails to accommodate the prisoners, a lack of apartments to house the residents, and a shortage of available space for retailers wishing to enter the area. The result is "boom time" construction, where the cheapest, fastest construction methods are selected and within a period of 5-7 years torn down; often replaced by a structure of an entirely different functionality, geometry, and loading distribution. The original structures are carted to the landfills and more resources are consumed to generate their replacements.

Buildings, their uses, and their neighborhood context are not static. Gainesville and Las Vegas are seen in various forms around the globe. Traditional building systems dedicated to single applications represent impediments to sustainable materials use and sustainable communities. The constant stream of waste materials from demolition (and associated pollutants from new construction) poses great environmental challenges, and the cost and time associated with "renovation-demolition—new construction" cycle retards a community's ability to address the problems of renewal, as in Gainesville. Similarly, the limited ability to invest in flexible structures restricts ef-

fective planning in rapidly expanding areas such as Las Vegas. A solution must address the construction waste stream through reuse of materials and the need for facility change. A reconfigurable structure that promotes both and can greatly alleviate both the environmental and community issues associated with urban redevelopment.

CURRENT EFFORTS IN SUSTAINABLE CONSTRUCTION

Several efforts exist with the goal of creating more sustainable constructed structures: green buildings, deconstruction and reuse, and Open Building. These efforts represent significant improvements over traditional construction practices and provide pathways to realize a new paradigm for reconfigurable structures.

According to the U.S. Green Building Council, green design requires the reduction or elimination of the negative impact of buildings on its occupants and the environment in 5 broad areas from which a rated point distribution is based: sustainable site planning (22%), safeguarding water and water efficiency (8%), energy efficiency and renewable energy (27%) conservation of materials and resources (20%), and indoor environmental quality (23%) (USGBC 2002). These are realized in the Leadership in Energy and Environmental Design (LEED) guidelines for new construction and major renovations. Under LEED guidelines, facility designs score points for environmentally friendly materials, energy efficiency, and improvements to air quality. Although the LEED program is being adopted throughout the federal government and to a more limited extent in the private sector, it fails to address the fundamental precepts of building usage, which may be the critical component for decreasing solid waste.

While USGBC goals focus on life-cycle environmental improvements for specific facilities, some research efforts exist in the areas of deconstruction and materials reuse. Chini and Bruening (2003) define deconstruction as “the systematic disassembly of buildings in order to maximize recovered materials reuse and recycling.” A problem with the current waste stream in construction is that waste products are commingled. A major goal of deconstruction is to separate recyclable and reusable building materials at the point of initial dismantling. As such, deconstruction is a time-consuming process, and certain buildings better lend themselves to deconstruction. Favorable candidates possess heavy timbers, specialty architectural details, high quality brick placed in soft mortar, and those buildings that have maintained weather tightness through their life (NAHBRC 2000). Their goal is to generalize findings from case studies to create guidelines for new structures to promote deconstruction and reuse.

Complementing the goals of deconstruction is the Open Building movement, which seeks to promote the reuse and reconfiguration of structures by taking a layered approach to design and implementation of building systems (Kendall 1999; 2003; Habraken 2004). Existing design for single-use structures promotes a dense interweaving of building utility systems that complicates selectively reconfiguring elements for new uses (Kendall 1999). This makes renovation expensive and encourages demolition and new construction, rather than adaptive reuse. Furthermore, building systems can have different life spans, from an indefinite period for major structural

systems to only a few years for interior finishes. Open Building design promotes separation of building systems to increase the ability to reconfigure for new uses.

RECONFIGURABLE STRUCTURES

The LEED standards and deconstruction techniques address single-purpose structures. Open Building principles seek reuse and owner directed transformation of structures, but operate in the context of a fixed structural system that ultimately determines building size and constrains future programmatic usages. What is needed is a class of structures that promotes near complete material reuse, while enabling reconfiguration of the structural system and hence building usage. This not possible with existing facilities, because current structures are not designed with reuse in mind, both in terms of disassembly techniques and materials choice.

Rapid disassembly construction methods are needed. An examination of modular construction demonstrates that flexible assembly/disassembly requires precision tolerances (Ferguson 1989, Gibb 1999). Traditional construction methods have difficulty accommodating these requirements because of non-uniform foundation settlement, which results in differential movements in the slab on which these prefabricated assemblies need to be placed. In particular, modular assemblies using environmentally benign materials (in both their ability to be manufactured and ability to be reused and recycled) have been limited due to their brittleness and the precision required for their installation, often unachievable using current construction methods.

A new structural system and changes in the manufacturing/distribution chain offer economical, widespread deployment of reconfigurable and reusable facilities. Firstly, a hyper-rigid foundation, in conjunction with a rapid connector system for the structural and non-structural walls was recently developed specifically for reconfigurable structures via the concept of repeatable dismounting (Laefer and O'Brien 2004). The design decouples the superstructure from the substructure. This enables reuse of the foundation. In particular, a hyper-rigid foundation provides a stable platform, independent of loading. This allows, within large load limits, a wide variety of superstructures that can be built to precise tolerances subjected to minimal differential settlement. This allows use of new, environmentally sensitive materials (in terms of manufacturing and recycling) that have not been deployable in traditional construction, due to the stresses generated during differential foundation settlement exceeding the performance capabilities. In essence, a dismountable structural system promotes reuse and reconfiguration of the superstructure, facilitates new material incorporation, and requires only a one-time investment in foundation construction.

Secondly, development of flexible production methods in the manufacturing and logistics industries support deployment of materials in highly customized configurations or "kits". This concept of "kitted" parts enables low-cost, modular construction supporting reconfiguration and changes in function of facilities. Delivery of pallets with customized component lists is standard practice in many subsectors of the construction industry, such as mechanical and lighting systems. There are several efforts underway to extend delivery of highly customized kits of parts to enable last minute

configuration of structures to address specific, individual tenant needs (Kendall 2003). These construction supply chains can be extended to the delivery of new, environmentally sensitive materials and, eventually, to entire structures. This practice has precedent. The base concept has been realized since the early part of the twentieth century: over 100,000 Sears, Roebuck and Company catalogue homes were constructed from 370 different house designs, with each delivered with all necessary pre-cut lumber and component parts ready for assembly (Thornton, 2002).

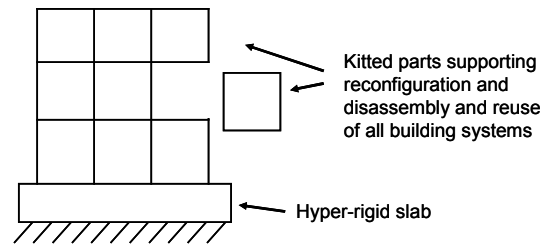


Figure 1. Reconfigurable structures concept

Figure 1 is a conceptual overview of the reconfigurable structures idea. Combining a hyper-rigid foundation and flexible supply chains supports reconfiguration of the superstructure. Reconfigurable structures as a paradigm enables complete reconfiguration of the superstructure, including structural systems (Fig.s 2-5). Such a reconfiguration and associated reuse is achieved through the deployment of a hyper-rigid foundation system allowing incorporation of novel building materials assembled in kitted or modular components (described below). Simultaneously, reconfigurable structures promote reuse of nearly all building materials and components following green building principles and enabling a radical reduction in construction material waste.

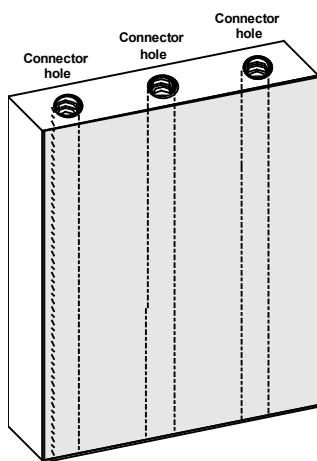


Fig. 2. Precast wall

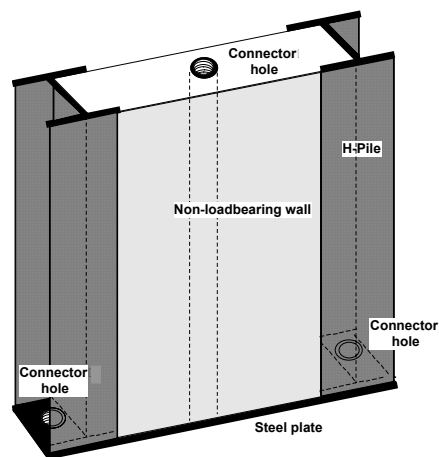


Fig. 3. Hybrid pre-assembled wall

An example of the core structural system for the reconfigurable structures paradigm can be seen in figures 2-5, which uses a precast or prefabricated wall system in conjunction with a hyper-rigid slab system. To attach the wall units, large, post-tensioned bars that screw into couplers or nuts are cast or variably located in the slab (Laefer

and O'Brien, 2004). The basics rely upon a foundation system that is from a structural loading capacity over-designed. This approach generates highly uniform settlement of the structure under both the weight of the building and normal service loads. The approach permits the indiscriminant placement of loads without concern as to the load path, as the entirety of the slab is assumed to be carrying a pre-specified portion of the maximum design load at any single point.

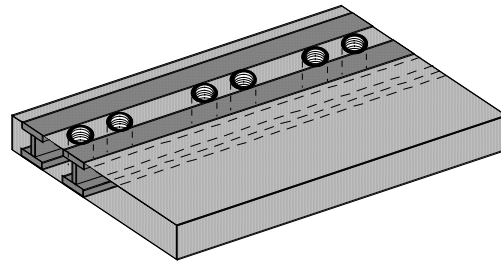
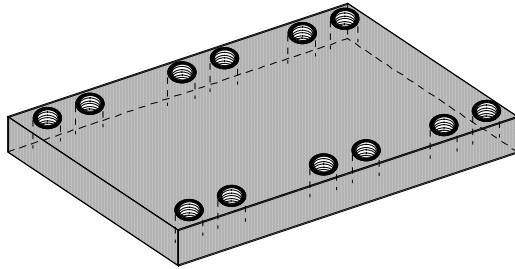


Fig. 4. Fixed slab with multiple attachment points

Fig. 5. Mutable slab

ANTICIPATED BENEFITS

Large-scale sustainability in the construction industry may be achievable through reuse of both above- and below-ground structural elements by decoupling the superstructure from the substructure. Such a system would further facilitate off-site manufacturing and assembly leading to decreased energy consumption and minimized material waste. Such an approach could result in a cost-effective incorporation of high-tech and energy efficient materials that would not otherwise easily lend themselves to field assembly. Importantly this could result in faster construction schedules and improved construction quality by having most of the traditional inspections occur in a factory setting, instead of having to schedule visits by local building officials. In general, reconfigurable structures achieve through remounting potential benefits in a wide range of areas from environmental to fiscal.

1. Natural resource consumption, including land consumption and development costs can be reduced.
2. Risks related to construction and development will be decreased as buildings being safer to deconstruct, the schedule and costs to deconstruct can be established, the time and expenses for initial construction and reconfiguration can be predicted, and further foundation installation is avoided, thus no subsurface surprises.
3. From a programmatic stance, there will be greater flexibility in changing the configuration of residential, commercial, and industrial for future uses.
4. Businesses will benefit fiscally from a more optimized life-cycle performance and improved tenant retention by offering fast, flexible, future growth; truncated vacancy time between tenants through shorter construction schedules; shorter periods of disruption for employees experiencing temporary relocation; and exploitation of mass-production based efficiency via off-site manufacturing to lower costs. The building may also qualify for local or state tax incentives for green building compliance.

RESEARCH AND QUANTITATIVE MODELING NEEDS – TOWARDS A UNIFIED MODELING FRAMEWORK

With respect to technical performance of the reconfigurable structures concept, as well as for assessment of benefits, there are several areas that must be addressed:

1. Load capabilities of a hyper-rigid slab, including the extent of differential settlement with respect to required tolerances.
2. Ability of the superstructure to be reconfigured with respect to the building envelope, interior use and loading. Durability and safety must also be considered as part of initial design for reconfiguration.
3. Cost and time savings that stem from increased use of modular components, as well as reuse of the superstructure elements for future configurations. An assessment of the tradeoffs between initial investment in the foundation for reuse versus cycles of demolition and reconstruction would be particularly useful.

While to a certain extent each of these areas can be addressed individually, assessment of specific design alternatives requires information from multiple domains. For example, engineering models may suggest load capacities for a hyper-rigid slab to support a certain maximum capacity. Such load capacities are, however, most appropriately informed by regional-level, urban planning models that calculate future usage needs for structures based on growth patterns for land usage. Correspondingly, such calculations may frame governmental decisions from zoning to tax breaks for investments in reusable foundations. There is a need for a quantitative modeling framework to address these complexities and support social and technical decisions about the deployment of reconfigurable structures.

Figure 6 depicts a base set of interactions among disciplines as they relate to design and investment choices for reconfigurable structures. A basic decision axis starts with urban planning models that concern economic activities and derive projections for space and land use. These projections, in turn, inform decisions about capacities that direct engineering design. Similarly, engineering design drives construction costs, which then informs decisions about the form and capacities of a specific instance of a reconfigurable structure. As each of these models operates on different levels of detail – for example, urban planning models may operate on the level of regions and neighborhoods, while engineering models operate on the level of individual buildings – there are considerable challenges in making explicit links between the models.

The need for explicit, integrated modeling stems from the existence of feedback loops among the elements of figure 6. For example, costs and configuration from engineering design and construction supply chain models inform environmental assessment of various potential facility configurations. In turn, environmental models may modify growth predictions (urban planning models) either directly or via public policy choices. Similarly, aesthetic design interacts with engineering design. Because the reconfigurable structures paradigm is novel, these feedback loops must be addressed through integrated modeling rather than empirically or through heuristics determined by practice. Similarly, to enhance sustainable materials use in construction, develop-

ment of formal, verifiable quantitative models may be instrumental in speeding and directing deployment of reconfigurable structures.

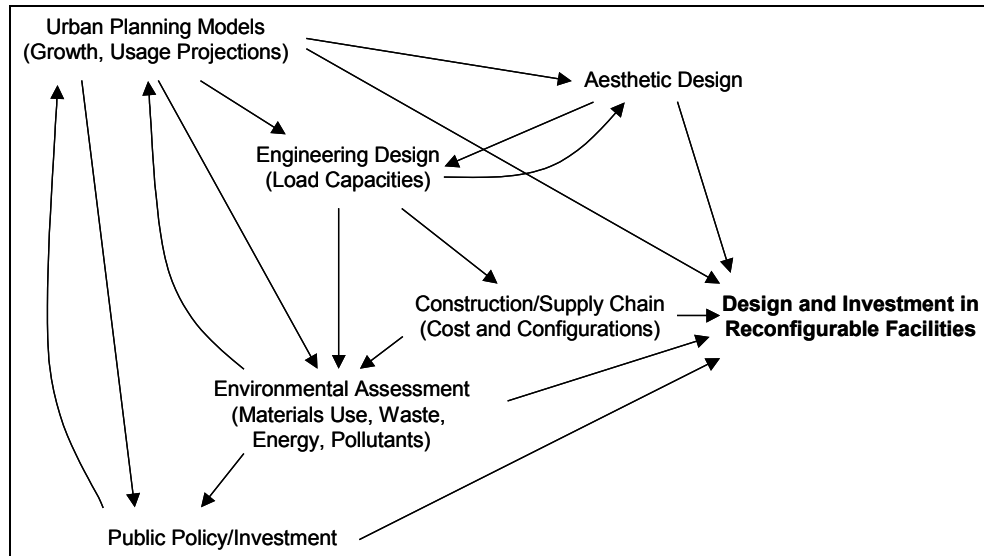


Fig. 6. Decision modeling framework for reconfigurable structures

Research activities to extend the framework depicted in figure 6 are considerable. For quantitative modeling, there is a need to integrate models with different purposes (e.g., economic, physical), different characteristics (e.g., spatial/GIS, analytic), and different levels of detail (e.g., regional economic patterns, local environmental impact). There are further issues as to how to treat uncertainty across such models. As a preliminary categorization, concerns are divided into the categories of engineering, construction management, environmental modeling, design, and urban planning.

RESEARCH ISSUES WITHIN DISCIPLINES

The reconfigurable structures paradigm represents a dramatically new approach that poses large implications for theory and practice within several disciplines. Before integrated modeling can take place, there is a need to address models and assumptions within each domain. Some of these challenges cross a variety of domains and thereby provide direction for the development of multi-disciplinary models.

Engineering: Precast and prefabricated components have flourished in the building industry since the 1960s. Yet, their adoption has been limited by the differential settlement of the foundations. Furthermore, despite their identifiable component nature, only limited work has been done to exploit the technology for dismountable, remountable, or reconfigurable structures. To take advantage of all of the benefits of this largely unexploited industry as a solution for sustainability, key parameters must be established.

To show how a better understanding of engineering needs and concerns is highly desirable, a specific solution of reconfigurable structures is explored (other solutions

may contain a wider range of materials and component types). Consider the slab and wall sections depicted in figures 2-5 (above). Aspects of such an arrangement that need to be modeled include the assumed stress distribution across the slab, whether adequate reinforcement can be included to support such randomized loading without violation of current codes through excess reinforcement, and without interfering in the slab's constructability. Of particular concern is whether sufficient reinforcing can be introduced into the slab, without the various elements conflicting with each other, in terms of assembly and access areas for utilities. The modeling process must then be extended to account for the introduction of the embedded couplers that receive the high-strength threaded rods that serve as a means of connection, of post-tensioning, and points of disassembly. Stress distribution models for a hyper-rigid slab as (1) a slab-on-grade, (2) with shallow foundations, and (3) with deep foundations considering untensioned, pre-tensioned, and post-tensioned slabs are also needed.

Since the disassembly and reassembly of the structure is critical, new models must be address such highly complicated issues as prediction of durability loss due to residual stresses. Each time the structure is dismantled and reconstructed, how the previous usage of the various pieces impacts the future structural performance and longevity must be clearly established. Currently there are no models or codes that provide guidance on this issue. Without such items, the proposed system will be largely unadoptable as it may be seen as out of compliance with building codes and may be considered too much of a liability by designers, contractors, owners, and insurers.

Critical to all of this is verification of a stress distribution model that accounts for the path and magnitude of the loading from the superstructure to the substructure. This is also a substantial engineering challenge as most foundation modeling programs use a simple set of inputs (either point loads or distributed loads) to define the loading parameters. A major concern with a hyper-rigid slab is its capacity for significant uplift during high asymmetric loading scenarios, where one side of the foundations could actually be pulled upward from the ground. Traditional gravity load foundations are utterly inadequate for such a scenario. Even those systems with substantial lateral capacity will probably be inadequate for the post-tensioning needs of the superstructure to maintain an adequate structural connection in such a scenario. What is needed is a model that can address this issue of pull-out and how those stresses then generate others within the slab as it tries to accommodate both the asymmetric loading and the foundation restraint.

Construction Management: As identified above, a basic need for evaluation of investment in a reconfigurable structure is estimation of construction cost and schedule changes. As reconfigurable structures anticipate use of kitted parts for nearly all building elements, assessment of off-site production costs and capabilities will be a primary driver of overall construction performance. Improvements to off-site or construction supply chain performance are viewed by many as key elements to radical reduction in construction time and cost for traditional as well as novel building methods (e.g., FIATECH 2003). Therefore, management and coordination of a construction supply network remain areas poorly addressed by current models (O'Brien et al. 2002). Any given project may have dozens of subcontractors, and each subcontractor

may have several suppliers and sub-suppliers. Hence, projects require the close coordination of hundreds of firms. Elements of this complexity are shown in figure 7, a conceptual model of a supply chain for a traditional construction project. To what extent the construction supply network will be modified in a paradigm for reconfigurable structures is unclear; it is likely, however, that complex coordination issues will remain. While kitted parts may reduce the number of subcontractors on-site, the complexity of materials management may simply be moved off-site to distribution hubs (O'Brien 1997). Similarly, deconstruction and reuse involves transport of parts off-site for use in other structures.

Principal modeling difficulties involve assessment of particular supply chain costs and capabilities, as well as comparative analysis of alternate supply chain configurations. Relevant models stem from the production and operations management literature. These models do not, however, fully address the low volume and heterogeneous production environment posed by projects (O'Brien et al. 2002; Yang et al. 2003). Promising hybrid approaches mix qualitative and quantitative assessment. For example, Christopher and Towill (2000) suggest a hybrid supply chain model, dependent on the decoupling points for material flow and information flow. The proper location of decoupling points is determined by how lean or agile a supply chain is and the requirements for the order fulfillment process (see also Naim et al. 1999; O'Brien 1997). A potential benefit of the reconfigurable structures paradigm, with expected increased use of manufactured components, is clearer delineation of decoupling points in the project supply chain (in turn enabling more accurate predictive models).

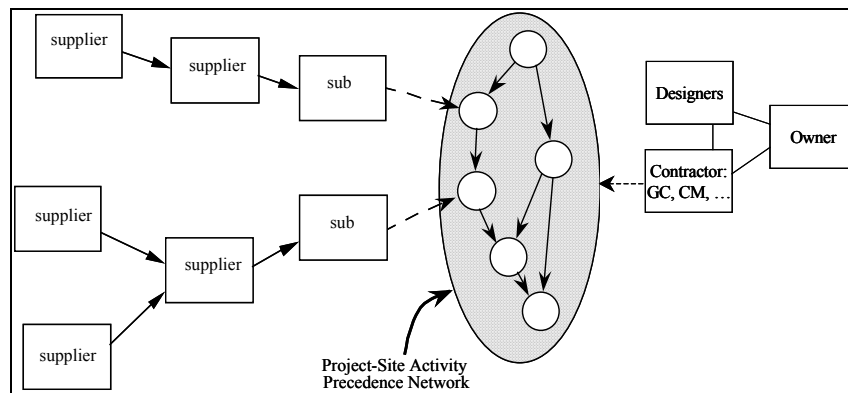


Fig. 7. A construction supply chain. Configuration of the supply network (left) is a major component of supply chain performance and evaluation

Environmental Modeling: The need for improved quantitative models to address issues of sustainability is well understood, thus the discussion here is limited to highlight a few areas related to the interactions among the various elements and disciplines shown in figure 7. Of particular importance is the extension of life-cycle assessment (LCA) models and concepts to whole building performance, when considering reconfigurable structures. Osman and Ries (2003) have recently begun such integrated assessment for various building systems, while Guggemos and Horvath (2003) have started to develop environmental assessment models and empirical data related

to specific construction processes. These frameworks and assessments are currently deployed on traditional commercial buildings, but appear to be extensible to reusable and reconfigurable structures. Within the framework of an LCA assessment, the largest challenge for new models is determination of energy use when structures are reconfigurable over their entire lifecycle and the establishment of lifecycle parameters. Some probabilistic assessment or profile of potential energy use (perhaps informed by planning models) is necessary to gauge energy needs and performance. Similarly, the impact of new materials on building energy performance is poorly understood as there is a paucity of empirical examples.

Other areas for model development relate to interactions between environmental assessment and construction supply chain models. Examination of the energy saving benefits of a material must be weighed against the total impact across its lifecycle, including the energy needed for creation, transport, and the impact of any recycling. Hence, there is a growing understanding of the need to consider the supply chain processes (including fabrication and transport, Figure 6), when making a lifecycle assessment of materials use. As reconfigurable structures and components promise increased use of prefabricated and manufactured products, the need for environmental assessment of supply chain performance is magnified. Integrated environmental and supply chain performance models may allow comparative assessment of alternative materials and supply chain configurations across several metrics including cost, production flexibility, and environmental impact. As the intent of reconfigurable structures is that they are able to have reusable components, models must also be extended to include deconstruction and reassembly (Languell 2001).

Design: How a structural component is configured may impact its ultimate aesthetic qualities. An example is modular construction in the brick industry. Beginning in the 1950s, U.S. masonry started to move to a modularity. Instead of 20.32 cm bricks and 0.32 cm to 1.27 cm mortar joints, the standard size of both the mortar joint and the brick together was to be considered as 20.32 cm together. As a direct outgrowth of this, brick size decreased to accommodate the change. The modification simplified both design and construction by building everything to a standard unit, although the modular system limited some of the flexibility in design details. Since that time, many other features in construction have been adapted to take advantage of this modularity. Doors and windows are common examples. Although other sizes are available, the greatest choices and best prices are usually affiliated with units that reflect masonry modularity. One question is whether remountable wall panels can exploit this current standard and how that can best be achieved, but the more compelling question becomes what is the default aesthetic that such a system generates. Pre-ordained dimensions will necessarily have a strong visual impact on the final product.

The U.S. now lives with the legacy of half a century of concrete masonry units. Their widespread usage has left an undistinguished and unexceptional architectural history. The use of dismountable structures is not necessarily fated to repeat these errors of the past. By fully embracing the role of the “designer” as an aesthetic and artistic contributor to the product development team, the concept will have a greater probability

of widespread usage. Issues of sustainability and artistic livability need not be competing needs. Aesthetics can help motivate adoption of sustainable structures.

Urban Planning: The impacts and cost of sprawl patterns in land use development are well understood (e.g., Burchell, et al. 1999; Parsons Brinckerhoff Quade & Douglas 1999; US EPA 2000). The sprawl development pattern is associated with the decline and abandonment of existing urban sites with all of the embedded materials and costs of construction, decline in the surrounding neighborhoods, increases in the distances traveled, with their attendant air pollution and energy usage, the destruction and fragmentation of habitat, and degradation of water resources and water quality, the alteration of regular stream flow and watershed hydrology, and increased runoff. Regional transportation models, which use a series of mathematical equations to represent how travel choices are made, have evolved since the 1950s. They do not, however, adequately represent the impacts of sprawl. The demand for travel is the result of the decisions of thousands of individual travelers making individual decisions about how, where, and when to travel. These decisions are made based upon the characteristics of the person traveling, and the choices (destinations, routes, and travel modes) available for the trip. These use the current and projected regional economic activity, the location of various land use, and the current and projected transportation network to represent the human behavior in making transportation choices. The models are used to estimate the number of trips made on the transportation network to establish priorities for transportation investments, prepare environmental impact statements, and conduct major investment studies. While these models are widely used, they do not adequately represent alternative land use and transportation configurations, fail to account for the cumulative impacts of development (Steiner et al 2003), and limit their analysis to air quality, energy consumption and impacts associated with travel and the land development pattern. Even the U.S. EPA's Smart Growth INDEX (SGI), which was developed to simulate "alternative land-use and transportation planning scenarios" and to evaluate "their outcomes using indicators of environmental performance (US EPA 2001)," only develops indicators of land use, housing, employment, travel and air quality (US EPA 2001). Costs associated with urban decline and abandonment with embedded materials, habitat loss, and water quality impacts of alternative development scenarios are not addressed.

At the local level, additional research is needed to understand how sustainability can be modeled and incorporated into planning practice. Many communities incorporate sustainability into practice with green building codes, community and neighborhood redevelopment and revitalization plans, and preservation and conservation plans. Yet, concepts of sustainability are only partially incorporated into local plans (Berke and Conroy 2000) and many components, such as waste reduction and energy consumption, are largely ignored (Jepson 2004). Many planning tools, such as zoning and setbacks, are inflexible in responding to new technologies and innovations. Connections need to be made between local sustainability practices and the associated environmental impacts. Thus, environmental impacts at the individual building level and local sustainability practices need to be incorporated into regional models that consider a wider range of environmental impacts than existing regional transportation models.

CONCLUSION

Construction in the U.S. today is unsustainable. A re-envisioning of construction material usage and a re-engineering of social conventions concerning the development and occupancy of constructed structures are needed. Reconfigurable structures are a proposed solution to provide unprecedented flexibility for building reuse, while radically reducing the construction waste stream. To successfully promote such an approach, research is essential in several areas: 1) comparative cost models to judge a reconfigurable system with traditional systems, in terms of initial installation and manufacturing expenses, life-cycle costs, embodied energy requirements, and scheduling needs; 2) stress distribution models for a hyper-rigid slab with various foundation configurations and different tensioning arrangements; 3) supply chain models for a new level of kitting of structural and architectural building; 4) an integrated urban planning model to predict changes in land usage and infrastructure related to the potential reusability of both a building's superstructure and substructure; and 5) life-cycle sustainability evaluations for reconfigurable building reuse. Each aspect needs a multi-disciplinary vision and engagement of a wide range of stakeholders.

REFERENCES

- Burchell, R. W., Lowenstein, G., Dolphin, W. R., Galley, C. C., Downs, A., Seskin, S., Still, K. G., and Moore, T. (1998). *The Costs of Sprawl – Revisited. Transit Cooperative Research Program Rep. 39*. Wash, DC: National Academy Press.
- Chini, A. R., and Bruening, S. F. (2003). "Deconstruction and materials reuse in the United States." *Intl. E-Journal of Construction*, 22 pages.
- Christopher, M., and Towill, D. (2000). "Supply chain migration from lean and functional to agile and customised." *Supply Chain Mgmt: Int'l J.* 5 (4), 206-213.
- FDEP. (2001). "Solid waste management in Florida 2001-2002." FDEP, 110 pages.
- Ferguson, I. (1989). *Buildability in Practice*, Mitchell Publishing Co. Ltd, London.
- Gibb, A. G. F. (1999). *Off-Site Fabrication: Prefabrication, Pre-assembly and Modularisation*, John Wiley & Sons, Inc., New York.
- Guggemos, A., and Horvath, A. (2003). "Framework for environmental analysis of commercial building structures." *Proc. Constr Cong.* 7, HI, Mar. 19-21.
- Habraken, J. (2004). "Open Building Resources." Web source: <http://www.habraken.com/john/open.htm>. Accessed Mar. 29, 2004.
- Jepson, E. J. Jr. (2004). "The Adoption of Sustainable Development Policies and Techniques in U.S. Cities: How Wide, How Deep, and What Role for Planners?" *J. Planning Education and Research* 23, 3: 229-41.
- Kendall, S. (1999). Open Building: an approach to sustainable architecture. *J. Urban Technology*, 6(3), 1-16.
- Kendall, S. (2003). "An open building strategy for converting obsolete office buildings to residential uses." *11th Conf, Intl. Group for Lean Construction*, Blacksburg, VA, 12 pp.
- Laefer, D. F. and O'Brien W. J. (2004). Prov. Patent "Dismountable Structures."
- Languell, J. (2001). "Development of a Prototype Assessment Tool to Evaluate the Potential to Successfully Implement Deconstruction as a Regional Waste Reduction Strategy." Univ. of FL, Gainesville, FL, 230 pp.

- Liapi, K. (2001). "Transformable structures: design features and preliminary investigation." *J. Architectural Engineering*, 7(1), 13-17.
- NAHBRC (2000). *Deconstruction: Building Disassembly and Material Salvage*. Report, US Dept. of Housing and Urban Development.
- Naim, M., Naylor, J., and Barlow, J. (1999). "Developing lean and agile supply chains in the UK housebuilding industry." *Proceedings of IGLC-7*, Berkeley, CA, July 26-28, 7/PDF/AlSudairi&Diekmann&Songer&Brown.pdf, 159-170.
- O'Brien, W. J. (1997). "Construction supply-chains: case study, integrated cost and performance analysis." *Lean Construction*, ed. L. Alarcón, A. A. Balkema, The Netherlands, 187-222.
- O'Brien, W. J., London, K., and Vrijhoef, R. (2002). "Construction supply chain modeling: a research review and interdisciplinary research agenda." *10th Annual Conf. Intl. Group for Lean Construction*, Gramado, Brazil, 19 pp.
- Osman, A., and Ries, R. (2003). "Environmental impacts of commercial building systems." *Proc. Construction Cong.* 7, HI, Mar. 19-21, 2003, 8 pp.
- Parsons Brinckerhoff Quade and Douglas (1999). *Land Use Impacts of Transportation: A Guidebook*. Washington, DC: National Academy Press.
- Steiner, R. L., Li, I., Shad, P. and Brown, M. B. (2003). "Multimodal Trade-Off Analysis in Traffic Impact Studies." Fl. Dept Transp. Systems Planning Office.
- Thornton, R. (2002). *The Houses that Sears Built: Everything You Ever Wanted to Know about Sears Catalogue Homes*. Gentle Beam Publications, Alton, IL.
- US DOE (2003). U.S. Dept. Energy, Energy Efficiency and Renewable Energy Network. Center of Excellence for Sustainable Development.
- US EPA. (2001) *Smart Growth Index® A Sketch Tool for Community Planning, Reference Guide*, Wash, DC: US EPA, http://www.epa.gov/dced/pdf/reference_guide.pdf. Accessed June 10, 2004.
- US EPA (2001/2000). *Our Built and Natural Environments: A Technical Review of the Interactions between Land Use, Transportation, and Environmental Quality*. Wash, DC: US EPA.
- US EPA (1998). "Characterization of building related construction and demolition debris in the US." EPA530-R-98-010, The U.S. Environmental Protection Agency Municipal and Industrial Solid Waste Div. of Solid Waste. <http://www.epa.gov/epaoswer/hazwaste/sqg/c&d-rpt.pdf>, 94 pp. Accessed Jun. 15, 2004
- USGBC (2002). *Building Momentum: National Trends and Prospects for High-Performance Green Buildings*. http://www.usgbc.org/Docs/Resources/043003_hpgb_whitepaper.pdf. Accessed June 15, 2004.
- Yang, B., Geunes, J., and O'Brien, W. J. (2003). "A heuristic approach for minimizing weighted tardiness and overtime costs in single resource scheduling." *Computers and Operations Research*, accepted for publication, 34 pp