SIMPLE BoS: Towards a Multidisciplinary Integration of Photovoltaic Energy in Buildings

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ABSTRACT: The Department of Energy has outlined the SunShot initiative, a plan to increase the adoption of solar energy by making it more cost competitive without requiring subsidies. A key component of this plan is to reduce costs associated with the balance of systems (BoS), which accounts for more than 40 percent of the total installed cost of solar energy systems. Balance of Systems encompasses the reduction of costs derived from all aspects related with the use of solar other than the photovoltaic panels and inverter. A careful understanding of architectural factors that may influence building energy performance is a critical and under-addressed aspect of the problem. The Solar, Installation, Mounting, Production, Labor, and Equipment Balance of System (SIMPLE BoS) project addresses the problem through a multidisciplinary team with emphasis on the integration of solar photovoltaic panels into buildings. Our goal is to produce new photovoltaic module racking and mounting designs, integration strategies, materials and wire management methods aiming to reduce the hardware and associated labor costs by fifty percent. Industry PV installers, university research engineers and students measured the field installation time of current commercial systems on project sites, providing a labor cost benchmark for BoS. Concept designs have been systematically improved through aerodynamic analyses, advanced structural optimization and building systems design integration. According to our estimates, material use reduction, part count reduction, use of commoditized materials, and low cost manufacturing processes have enabled greater than 50% BoS material cost reductions in residential, commercial, and utility designs. Cost-critical aerodynamic and structural aspects have been validated through complete and underway wind tunnel test, computational fluid dynamics (CFD), and finite element analysis (FEA). Current design concepts are introduced as case studies of multidisciplinary collaboration. The implications of multidisciplinary building systems integration is discussed, with reflection on education and practice of architectural design.

KEYWORDS: Solar photovoltaic systems, renewable energy, balance of systems, building systems integration, multidisciplinary collaboration

INTRODUCTION

In the United States alone, the market for solar photovoltaics (PV) has grown by 800% from 2005 to 2012, with installed capacity rising from 4.5 GW to 65 GW. At this rate, it is expected that the cost of alternative generation of electricity could become equal or cheaper than conventional generation. To reach this goal, known as grid parity, it is necessary to push the cost of PV systems down by 50-75% (Energy.gov 2011). Historically, the cost structure of solar PV systems was dominated by the cost of silicon. In 2012, given the significant decrease in cost of raw silica, the market has seen PV module prices dropping from $4.00 per Wp to $1.00 per Wp (Aansen 2012).

However, focusing efforts solely on efficient utilization of silicon is no longer a viable long-term strategy for maintaining the market growth rates. Module prices might be expected to decrease another 30%, but this alone will not drive the system cost to reach grid parity. Experts in the field agree that the most significant contribution needs to come from a drastic reduction of the “balance of system cost" (Bony et al. 2010). Balance of Systems (BoS) costs are all costs associated with a PV system, except the cost of the PV modules and the inverters. It encompasses all auxiliary components that allow the system to work, as well as labor and soft costs required to implement a solar panel system project. From the hardware side, balance of system includes mounting and racking hardware, electrical hardware and monitoring equipment; labor costs include mounting, racking, and electrical labor; soft cost include permitting, inspection, interconnection agreement, overhead, and profit. Currently, BoS costs account for more than 40 percent of the total installed

cost of solar energy systems, while inverters and panels are each 20%-40% percent respectively, with variation occurring across applications, module types and other factors (Green Tech Media 2012).
In recognition of the potential of solar PV to contribute to US energy independence and security goals, the United States Department of Energy launched the SunShot initiative in 2010. The SunShot initiative aims to decrease the cost of solar energy by 75% by the end of the decade. The goal is to be achieved by reducing technology costs, grid integration costs, and other soft costs and through economies of scale (U.S. Department of Energy 2012).Given the diffuse cost structure of solar PV systems, there is the need to recognize that no single component can accomplish alone the SunShot cost reduction objective. Multiple cost drivers must be concurrently addressed, including material cost, manufacturing cost, business process, on site labor and equipment usage. This condition implies the need to identify new opportunities for systems integration that could eventually lead to more significant innovation in the field.

One strategy to deal with the complexity of BoS is a “divide and conquer” approach. This strategy entails the optimization of individual components and activities, launching isolated cost reduction efforts. A benefit of this approach is that it allows a high number of stakeholders to engage in relatively low complexity tasks. The downside is the high cost of maintaining compatibility standards between sub-systems, while missing the opportunity to achieve more innovative solutions through development of multifunctional components. Alternatively, a systems design approach revisits the requirements from the top down and focuses on fulfillment of system level objectives. A characteristic of this approach is that it questions legacy solutions, shifting the focus towards opportunities to produce more revolutionary results (Department of Defense 5000). The existing DoE SunShot Initiative takes a pragmatic hybrid approach. Components and activities with low degrees of interdependence have been portioned out while highly interdependent subsystems have been kept intact and funded via systems design projects. The Georgia Tech led SIMPLE BoS project, is one such project that aims to reduce balance of system cost, a highly interdependent subsystem that has only recently been brought into research domain. A key component of this interdependency is the need for better integration of PV systems with buildings, in a way that allows different aspects of building performance to remain uncompromised, and are eventually improved through PV system integration. The complexity inherent to the problem necessitates a multi-disciplinary approach and fuels the opportunity for transformational solutions.

1.0 RESEARCH PROBLEM

The SIMPLE BoS project is committed to developing solutions with at least 50% cost reduction for racking and mounting hardware as well as associated labor cost for the installation of PV systems in residential and, commercial buildings (for existing and new construction), as well as utility (ground mount) markets. Currently, the project is in its second year of development, which includes extensive testing of selected prototypes. By the end of the three-year project, these solutions should be commercial ready, with safety certification, pilot projects and viable business models.

To achieve such drastic reduction goals in labor and hardware costs, while maintaining acceptable levels of safety and performance, is a difficult problem. The main obstacle is the identification and management of negative interactions that emerge among different and often conflicting requirements. For example, a change of materials used for framing PV panels, from aluminum to carbon fiber, would increase the productivity of installers, given the resulting lightweight panels. However, it would also increase material and fabrication costs significantly. On the other hand, it is also important to understand potential chemical interactions between new materials and environmental factors that could potentially cause structural degradation further in the lifetime of the system.

Therefore, there is a need to approach the design of BoSsystems from a holistic perspective, with a careful consideration of requirements that become relevant at different stages of the system lifecycle and the relationships that emerge among them. The analysis of the most critical lifecycle requirements and the design methodology intended to fulfill them is presented in the next section. An overview of the main criteria for performance evaluation is also introduced.

2.0 OVERALL APPROACH AND METHODS

Our analysis of life cycle requirements led to the classification of eight main phases related to BoS: 1) fabrication, 2) transportation, 3) installation (assembly), 4) operation (including systems level integration for building performance), 5) maintenance, 6) disassembly, 7) reuse and 8) recycling (Goodman 2011). Each phase contains a group of requirements that are loosely classified under different first-principle domains. Thus, the installation phase contains requirements that belong to ergonomics and usability domains (e.g. ease of learning to reduce installer training costs, safety factors, etc.), requirements belonging to the mechanic domain (kinematics of moving parts for quick deployment, easy assembly, etc.), requirements from the structural domain (e.g. loading conditions applicable to the PV system as well as the building structure during installation), and electrical domain (e.g. wiring and electrical testing among others). The operation stage includes several technical requirements as well as aesthetic requirements related to the way the building form is affected and perceived.

To address the variety of requirements in a holistic manner, the SIMPLE BoS team is composed of members from diverse disciplines, including architectural design, structural engineering, aerodynamic analysis, biologically inspired design, electric systems, mechanical engineering, physics, business, and systems engineering. The general philosophy adopted to capitalize on this diversity of backgrounds is through the reformulation of the specific problems from the solar panel systems domain into more general descriptions. This is done through different methods, based on functional decomposition and generalization through abstraction (Pahls 1996, Bhatta 1996). The intent is that team members may recognize familiar patterns in the general problem formulation that could eventually evoke precedent solutions from their own domain. Once a precedent or relevant example is found, the effort is shifted towards the identification of its general working principle and its transferability to the specific problem in the form of a design concept (Goel 1997). Preference was given to concepts that embraced multi-functionality at different levels and across several lifecycle stages, and had the potential to fulfill the levels of performance required by the industry.

2.1 Functional decomposition analysis

Along with identification of the main lifecycle requirements, the research team studied how the satisfaction of these requirements is being addressed by current commercial products and industry best practices. In partnership with industry members Suniva and Radiance Solar, a solar PV panel manufacturer and installer respectively; and experts from the Rocky Mountain Institute (RMI), a think-and-do tank, the SIMPLE BoS team developed analyses of different projects, gathering data to determine a current benchmark of the PV systems market. This data included labor costs based on installation activities and a detailed breakdown of hardware and material costs for current commercial, residential, and utility scale racking and mounting systems.

Combined with data provided by the Department of Energy, the research team identified a subset of functional requirements that have the most significant impact in cost across system types, and therefore became the main targets to achieve the 50% cost reduction goals. The subset includes ground equipment, accommodate handling, fix position, maintain electrical connection, align PV arrays, and keep operational temperature (Figure 1, in solid red boxes).

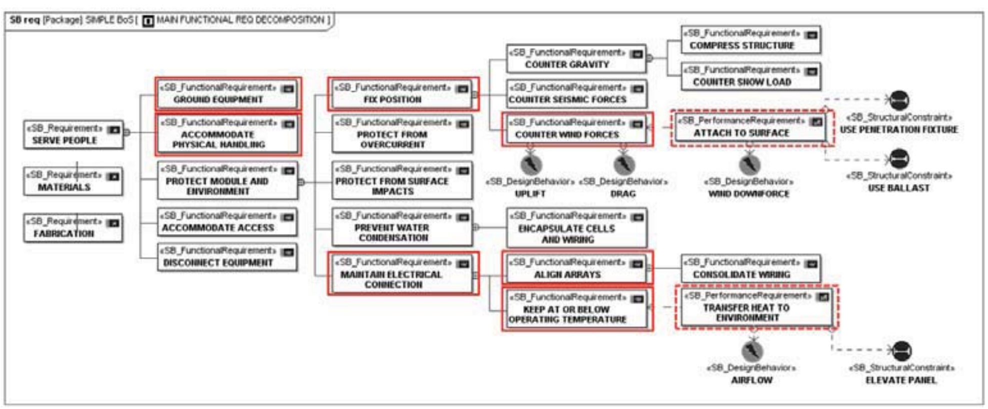

Figure 6: Function decomposition analysisfrom left to right, in SysML language. Red boxes depict functions identified as priority for cost reduction. Bottom functions, in dashed lines depict performance requirements that can be optimized.

For example, in commercial building rooftops, the requirement “fix position” has different challenges than residential roofs. In many cases, commercial roofs are covered by thin film membranes that cannot be penetrated to allow mechanical attachments to the roof structure, otherwise the warranty of the membrane would be voided. The conventional solution to avoid penetration is a combination of ballast and wind-deflection devices to keep the system attached to the roof. However, this implies additional complexity to the system, requiring the use of many heavy ballasting elements that increase the loading condition on the roof. The use of ballasts also has consequences on the cost of installation. Given that the load needs to be distributed, ballasted system usually rely on high number of small ballast units (e.g. CMU blocks), that need to be carried individually, with the associated risks of damaging the solar panels, the thin film membrane, or of injuring the installers. Given these conditions, it is estimated that the requirement of countering wind forces account for approximately 75% of the structural cost of commercial rooftop systems (Bony 2010).

2.2 Design based on functional integration

After the main limitations of conventional rooftop systems were identified and the relations between conflictive requirements were understood, the research shifted towards the identification of solutions in external domains that could be applied to the problem in hand. In the case of commercial building rooftop systems, an useful analogy came from the world of concrete masonry construction, from which some members of the team have extensive experience. Given that ballasted systems are already making use of CMU block as source of weight, the research team decided to take advantage of the natural compression capabilities of CMU blocks and use them as racking structures. In this manner, the function of ballast was merged with the function of PV panel support at a given tilt angle.

The new design, called the Concrete Curb, brings important advantages regarding installation costs. Since the same CMU block can be used as ballast and racking element, the number of installation activities is reduced significantly. The same rationale can be applied to reduction of material and manufacturing costs.The main motivation for this design came from the ubiquity of existing concrete masonry unit manufacturing facilities and their standard equipment. The block specifications are based on typical CMU manufacturing tolerances and the logic of lifting masonry blocks by voided cells for efficient deployment by a small installation team. The blocks can be produced rapidly within the constraints of standard specialized CMU machines.

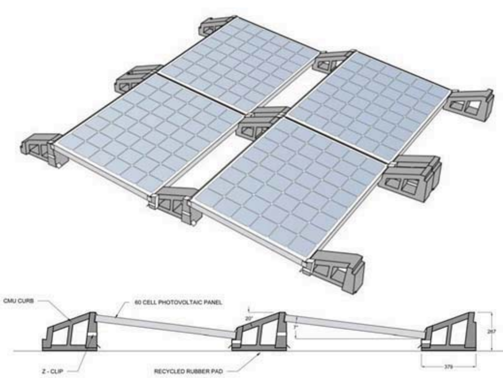

Figure 7 Concrete curb design concept: ballasting and racking functions merged in one element.

Other design concepts for commercial rooftops developed so far include racking structures made of injection molded plastic and sheet metal. Each concept takes advantage of different material characteristics and manufacturing techniques that could contribute to cost reduction, while improving many performance aspects related to installation, operation and maintenance requirements.

2.3 Evaluation of design performance: general approach

As introduced earlier, the project adopts a systems level approach to design, following many principles from systems engineering related to specification and management of requirements (Gilb 2005). In particular, the project focuses on the specification of metrics for validation of requirements and for verification of performance for proposed design solutions. Recently, this approach has been introduced by Augenbroe in the context of performance-based building design (2011). In this model, functional decomposition is not necessarily a deterministic method, but rather intended to be negotiated and agreed upon by various design stakeholders. At the bottom of the decomposition, there must be a set of functional requirements that can be formulated as measurable expressions of performance, described in terms of a Performance Indicator (PI). A functional requirement expressed in terms of a PI becomes a specialization called Performance Requirement. Since a functional requirement can be satisfied in various ways, it may be specialized in more than one performance requirement, each characterized by one particular PI.

Many of the performance requirements and measurement metrics (PI), related to PV systems are already prescribed in available standard codes, such as NEC 690 for electric requirements applied to PV systems, UL 1703 and 2703 for PV module structural and electrical integrity respectively, ASTM E-1830 and ASCE 7 for static and wind loads (NEC 690, 2011; UL 1703 and 2703, 1993; ASTM E-1830, 2012; ASCE 7-05, 2006). Other requirements are not prescribed and therefore need to be elaborated by the research. Some of these requirements are related with installation of PV systems, and current efforts are underway to define them according to the level of feasibility of verification experiments. Table 1 presents some of the performance requirements in SIMPLE BoS.

Table 5: Performance requirements. Green cells represent target values.

Requirements	Criterion	Measurement (PI)	Residential	Commercial	Utility
Submit and review permits	system size	kW	5	100	1000
	install time	man hours	24	120	640
Install system	tool count	number of tools	less than best	less than best	less than best
	part count	number of parts	less than best	less than best	less than best
	Skill level required	description	$22.5/hr	$40/hr	$45/hr
	wire management system	Y/N	Y	Y	Y
	squaring/leveling capability	Y/N	Y	Y	Y
Inspect System	dynamic and static loads	ASCE 7	See Detailed	See Detailed	See Detailed
	electrical requirements	See NEC 690 tab	See Detailed	See Detailed	See Detailed
Physical Characteristics (operation requirements)	power density	watts/square foot	15	15	15
	multifunction: roof shading	roof life increase (years)	Y	Y	N/A
	multifunction: insulation	R value increase	Y	Y	N/A
	racking impact (penetrations)	# of penetrations	Low	0	N/A
	charge acumulation	leakege current	N	N	N
	grounding required	Y/N	N	N	N/A

The purpose of performance characterization in terms of PI's is two-fold. First, it allows the specification of the type of quantification method (e.g. a feasible experiment given the constraints of the project) required to verify that a requirement is satisfied. Second, it promotes the identification of all relevant design elements, as well as parts, features, and actors from the operating environment that have a role in the satisfaction of the given performance requirement. The identification of the collection of elements that have a role in the satisfaction of a requirement, either positively or negatively, is critical for the purpose of the project. More specifically, whenever two or more elements have a positive role in the satisfaction of requirements, there is a potential for integration of functions, such as the one described in section 2.2.

2.4 Teaching, learning and research: The SIMPLE BoS pedagogical structure

An early motivation of the Simple BoS proposal was to directly engage both undergraduate and graduate students across various disciplines in order to simultaneously impact teaching, learning, and research at Georgia Tech. The DoE recognized the enduring benefits of strong student participation in the research, not only as it directly impacts the Simple BoS outcomes, but also in terms of fundamental cultural shifts in the future of the design and construction industry. As such, thirty-five students and nine faculty members from Architecture, Mechanical Engineering, Civil Engineering and Biology contributed through design studios, capstone courses, and a PV systems seminar to develop 24 concepts over a four month period in the spring of 2012, with weekly industry collaboration and review sessions. The structure of the cross-disciplinary design problem was organized around a three credit hour PV seminar open to architecture, engineering, and biology students. The seminar served as a solar industry fundamentals course and disciplinary 'mixing chamber,' where knowledge, ideas, and methodologies could be exchanged between students, faculty, and industry partners. The course provided in-depth lectures on PV system principles, manufacturing, business practices, utility integration, and installation procedures. This content fed laterally into a third year architectural design studio and a fourth year capstone design problem in mechanical engineering. The greatest source of design tension among the group was highly standardized and flat form of current PV modules. Because structural depth enables so many positive attributes in structural systems and in nature, it is an obvious consideration for designers, but not one fully exploited by the solar industry

The different classes challenged students to develop different aspects for integration of next generation PV systems in both retrofit applications and for new construction. Projects and exercises focused on different market segments, from small (residential) installations of five kilowatts on sloped roofs, medium (commercial) installations of one hundred kilowatts on flat roofs, and large (urban/utility) ground-mount and canopy installations of one megawatt or larger. Design solutions were developed at the detailed design level, supported by typology analysis, solar orientation/optimization, architectural integration, aesthetic, mechanical and thermal stresses, wind loading, manufacturing strategies, material specifications, deployability, installation procedures, attachment hardware, and overall system costs.

The PV seminar, architectural design studios and engineering capstone courses contributed to the overall goals of the Simple BoS project by providing a platform for students and faculty alike to first gain in-depth understanding of the problem through research and analysis, and then to generate a wealth of novel solutions from which the most promising could be further developed. This experience was critical in providing practical insight for the functional requirements of a PV system described earlier, and informed many decisions in later designs. Members of the design team and advisory board selected nine of the concepts for proof of concept design and five systems are currently being fabricated as prototypes.To date, the project team has filed 14 invention disclosures based on many principles and concepts developed during these courses.

3.0 PROTOTYPE DEVELOPMENT, TESTING AND EVALUATION

Based on the methods described above, and in many of the contributions developed by students in the classes integrated to the project, the research selected five main design concepts for further development and potential commercialization. Our results on labor cost and material cost savings on these concepts are still preliminary, but promising given the feedback provided by our industry partners. The reduction on labor costs are based on the reduction of part and tool count first, then in more detailed, fine grained time and motion studies which are still in development. The basic criteria to achieve these results are the reduction on the number assembly steps, simplification of tasks and the increase of speed, particularly on commercial rooftop solutions (Sheet-metal Curb and Concrete Curb). Reduction of material costs are also preliminary, but consistent with three main design principles: 1) avoidance of expensive materials and associated manufacturing methods, such as aluminum or stainless steel (e.g. Sheet metal Curb); 2) reduction of volume for the most expensive parts wherever possible; and 3) reduction on number of parts by using aggregation strategies (e.g. pre-assemblability of Mega-Module and Quad Pod) and functional integration (e.g. Concrete Curb, Sheet Metal Connection Clip and Quad Pod). A summary of these concepts is presented in Table 2.

Table 6: Design concepts selected for final development, with preliminary estimates on cost reductions.

	Mega-Module		Solar Ridge		Sheet Metal Curb		Concrete Curb		QuadPod	
	Cost Savings ($/W)	% Reduction	Cost Savings ($/W)	% Reduction	Cost Savings ($/W)	% Reduction	Cost Savings ($/W)	% Reduction	Cost Savings ($/W)	% Reduction
BoS Labor	n/a	n/a	0.24	72.1%	0.30	>70%	0.30	>70%	0.05	71.4%
BoS Materials	0.07	5.8%	0.17	55.0%	0.16	53.3%	0.29	>70%	0.13	65.6%

Meanwhile, other fundamental requirements are also being tested, to ensure that full functionality is achieved. Some experiments completed so far include wind-tunnel tests for tilt angle optimization, computational structural analysis and physical testing to verify the satisfaction of load conditions. One example where extensive testing is currently underway is for the Quad Pod concept for utility (ground mount) markets with several potential architectural applications.

3.1 The Quad Pod

The Quad Pod is a lightweight three-dimensional truss system that uses ¾” EMT struts and aluminum-framed PV modules to create an inexpensive and quick-to-assemble module aggregation technique for ground-mount applications. Following the design principle of functional integration, this design makes use of the aluminum frames of conventional 60-cell PV modules as top chords of the truss, thus taking advantage of structural capabilities already existing in this product, while saving material.

The first Quad Pod structural tests will follow the requirements of UL 1703 and UL 2703 for the so-called “above roof mounting” configuration. According to ICC AC 428, this system would be described as a “freestanding system.” These two tests will assess the efficacy of the system under extreme wind down-force and uplift. Per the requirements of UL 1703, the basic design load wind pressure is 30 psf, with a down-force multiplier of 1.5 (load case 1) and an uplift multiplier of 1.95 (load case 2). The loads will therefore be 45 psf [2.15kN/m2] in down-force and 60 psf [1.72kN/m2] in uplift (as, from a practical standpoint, the uplift multiplier can be conservatively taken as 2). Passing these load tests will allow the system to be used in most of the United States, with the exception of regions with unusually high wind or snow loads.

The test article consists of a 2 module by 4 array of Suniva 60-cell modules, each module having an area of 1.62 square meters or 17.44 square feet. With an allowance for a ¼” gap between modules the total area of the test article is calculated to be 140 square feet. The reduction in uplift force is borne out by UL 2703, requiring an uplift force loading should be 36 psf. Therefore, the required down-force load for load case 1 will be 6,300 pounds and the required uplift force for load case 2 will be 5,040 pounds. The load will be applied using dead load ballast of small bags of pea gravel. In this first series of tests, the quad-pod will be oriented in the horizontal configuration (0 degrees), and thus all of the loads will be vertical on the modules. In practice, the installation will likely be tilted, and thus wind loads will apply a combination of vertical loads (down-force or uplift) and horizontal loads (drag).

The series of tests on Quad Pod is expected to demonstrate one or more of the anticipated failure modes. Some failure modes are: 1) Bolt shear in the strut bolts, 2) Block shear of the end of the strut, 3) Buckling of the end of the strut, 4) Buckling of the strut, 5) Local buckling at the crimp, 6) Combined shear / tension of apex bolt, 7) Block shear in the clamp connectors, 8) Eccentric bending of clamp connectors, 9) Combined axial / flexural failure of aluminum frames used as top chords, 10) Tear out of module angles and 11) Overstress in module glass laminates. Figure 5 (on the left) illustrates the first completed down-force test. For this first test article, the connections at locations 1 and 2 (right), identified as critical locations in preliminary analysis, began to yield given eccentric bending of clamps (failure mode 8) at a load of approximately 70% of the test load. The test was discontinued, and these critical connections are being currently redesigned to increase their capacity.

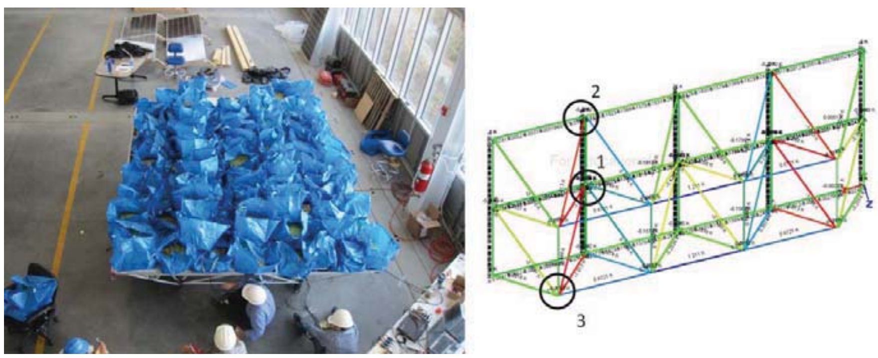

Figure 8: On the left, down-force structural test using gravel bags. Sensors and instruments were installed to measure real-time stresses. On the right, free body diagram (FBD) anticipating possible failure points.

CONCLUSION

The paper described a multidisciplinary research project aiming to produce new PV racking designs, new integration strategies, and new materials and installation methods aiming to reduce racking/mounting hardware costs along with associated labor costs by fifty percent of current industry best practice. Through an unprecedented partnership between industry and university, 35 students and nine faculty members from Architecture, Mechanical Engineering, Civil Engineering and Biology contributed through studios, capstone courses and a PV systems seminar to develop 24 concepts over a four month period, with weekly industry collaboration and review sessions. To date, 14 invention disclosures have been filed by the project team, nine of them have been developed as proof of concept design and five systems are being fabricated as prototypes for testing. Industry PV installers, university research engineers and students measured the field installation time of current systems on actual project sites. These data provides a benchmark for the cost of labor for each design concept through a series of ongoing time and motion studies. BoS concept designs have been systematically improved through several aerodynamic analyses, advanced structural optimization and revision of performance requirements for building systems integration.

One of the main challenges being addressed by research team is to provide a common language to enable communication and collaboration among members with diverse domain background. While the method of functional decomposition proposed originally by Pahl and Beitz (Pahl 1996) has been used for several years in many engineering design domains, its use in architecture has been restricted. One recurrent critique to this method has been its reductionist view of design, and the delusion of deterministic ‘one-to-one’ mappings from problems to solutions, that almost never apply in real design situations. While these critiques have valid points, they do not preclude the usefulness of the method as an analytic and communication tool. In the systems design variation adopted in this research, the emphasis has been put in the use of functional decomposition as a representation medium to express views and needs from diverse stakeholders. It also supports negotiation on the selection of critical functional requirements, and their description as measurable expressions of performance. The final intent is to facilitate the validation of designs, and to verify that important high level design requirements are being met. The methods of generalization and analogy transfer allow retrieving potential solutions from other domains, while the emphasis on functional integration supports discovery of ‘one-to-many’ mappings from problems to alternative solutions, in ways that are more akin to creative design processes.

From an industry perspective, while the current research is focused on optimizing the installation of existing conventional PV panel modules through innovations in the BoS space, future work will focus on fundamental design shifts in the design and manufacture of silicon based PV generators. New module designs will require overhauling the current manufacturing infrastructure and will take significant time to implement. These changes will open new markets for ubiquitous low cost PV integration in the built environment.

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DISCLAIMER

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