CIB W78 2008 International Conference on Information Technology in Construction
Santiago, Chile

GPOP: REPRESENTATION OF SUSTAINABILITY CONSIDERATIONS ON BUILDING PROJECTS

Mauricio Toledo
PhD Student, Civil and Environmental Engineering Department, Stanford University.
LEED AP.
Jerry Yang and Akiko Yamazaki Environment and Energy Building, RM 274
Stanford, California,
mjtoledo@stanford.edu

Martin Fischer
Professor of Civil and Environmental Engineering (Construction Engineering and Management Program) and (by courtesy) Computer Science.
Director, Center for Integrated Facility Engineering.
Jerry Yang and Akiko Yamazaki Environment and Energy Building, RM 297
fischer@stanford.edu

ABSTRACT

Sustainable development has attracted much attention in recent years and has created an increasing awareness of environmental issues affecting construction projects. Stakeholders of sustainable building projects seek inspiration and benchmarks on existing sustainable buildings. However, the documentation of the sustainability considerations (SC) on building projects is inconsistent and usually focused on the design solution with little or no attention to the project requirements or process and organizational aspects of the design. The comparison of sustainable projects is therefore difficult due to the varied nature and extent of the documented sustainability considerations. We propose a systematic representation of the SC, which we call gPOP model, that facilitates the comparison of sustainable projects. We created gPOP models of twelve recognized green buildings which led to a list of the 36 most common sustainability considerations (MCSC). We show that our representation of the SC allows the comparison of sustainable projects and helps uncover insights that otherwise remained hidden in the free-form text-based narratives used for documenting the SC.

KEYWORDS

S*ustainability, product model, process model, green building.*

1. INTRODUCTION

Sustainable development has attracted much attention in recent years. Consequently, owners, designers and public officials facing the challenges of delivering sustainable facilities have sought inspirational examples of sustainability practices and performance benchmarks on already built green or high performance buildings. However, in most cases the documentation of sustainability considerations have focused on descriptions of technologies incorporated in a particular design, and little attention has been put on elaborating the process followed or the organizational considerations that made that project happen. Therefore, without this context, practitioners are left with the description of the design solution (the facility itself), but without an understanding of the problem that this design addresses (requirements), the process followed to achieve it, nor the stakeholders' characteristics and dynamics, which might be critical for the project outcome (defining success or failure).

Private and public sectors acknowledge the growing "green" or "sustainable" trend among homebuilders and commercial buildings within the U.S. (Plunkett, 2004; USGBC, 2003). The National Association of Home Builders (NAHB) estimates that between 5% and 10% of new homes in the U.S. will be eco-friendly by 2010, up from 2% in 2005 (Plunkett, 2007). NAHB's eco-friendly specifications require resource-efficient design, construction and operation, focusing on environmentally friendly materials. Furthermore, state regulations and local building codes in many cities are requiring that greater energy efficiency be incorporated in plans before a building permit can be issued (Schwarzenegger, 2004). In more general terms, sustainable consideration (SC) such us energy consumption, water consumption, indoor air quality, site selection and material use are commonplace in the sustainability literature (Pearce and Vanegas, 2002) and in the influential sustainability guidelines (e.g., Minnesota Sustainable Building Guidelines or MSBG); sustainability assessment methods, such as the Leadership in Energy and Environmental Design (LEED™ by the US Green Building Council); or the Sustainable Project Appraisal Routine (SPeAR™ by Arup) developed to assist practitioners in designing and constructing sustainable buildings (USGBC, 2005; McGregor and Roberts, 2006).

Stakeholders of sustainable building projects –the design team in particular– look for comparable facilities for benchmarking purposes and as a source of inspiration for design ideas. The pragmatic approach of guidelines and assessment methods, such as MSBG, LEED™ or SPeAR™, has helped design teams to implement sustainability in the built environment. However, inconsistent documentation and explanation of SC and the process used to include them in the design has resulted in descriptions of a project's SC that are usually a mix of qualitative and quantitative statements without a particular order. Comparison of sustainable projects is therefore difficult due to the varied nature (e.g., water, energy, air quality, materials, etc.) and extent (e.g., reduction, elimination, minimization, etc.) of the SC. Often the description of such SC focus on listing what kind of technologies have been integrated into the design, while the rationale (or lack of it) that justify their inclusion in the design as well as other key factors for success or failure of the project remain hidden. When asked, stakeholders of green building projects have identified process elements and individual stakeholders' role and dynamics as key success factors for the sustainable outcome of the projects they were involved in[1]. García et al (2003) refer to such aspects as the product (building), organization and process (POP) aspects of the project. They argue that, throughout the project design, designers have to understand the distinctive and interrelated requirements that the project is trying to satisfy (functions), the chosen design solution (forms), and how well the requirements are met (behaviors). They propose a 3x3 matrix called the POP model to describe the functions, forms and behaviors (FFB) of a project's product, organization and process (Figure 1a shows a POP model with the product-organization-process columns and the function-form-behavior rows).

We propose a systematic and descriptive representation of the SC for projects that we call a gPOP model (green or sustainability-loaded POP model). gPOP models describe SC for the product, organization and process in terms of their functions, forms and behaviors. Our representation of the SC makes the comparison of sustainable projects easier using simple diagrams and metrics. In addition, we developed a list of key SC – including success/failure factors of the building projects– that provide the basis for standardizing the gPOP models.

Following, we discuss the points of departure for this work, including guidelines and assessment methods followed by practitioners faced with the task of delivering sustainable building projects. We explain our methodology and we describe how to create gPOP models. We show how they can be used to compare sustainable projects. Finally, we discuss future applications and research opportunities for the gPOP models.

2. POINTS OF DEPARTURE AND METHODOLOGY

The literature on built environment sustainability has grown dramatically in the last decade as a consequence of the increasing interest in sustainable development (Pearce and Vanegas, 2002). Practitioners have relied on sustainability guidelines and assessment tools –the most pragmatic types of sustainability literature– to address the challenges of designing and building sustainable facilities. The State of Minnesota Sustainable

[1] We interviewed Dr. Philippe Cohen, the Administrative Director of the Jasper Ridge Biological Preserve and Brad Jacobson, a Project Architect from EHDD who worked on the award-wining Global Ecology project from conception to the end of construction. Dr. Cohen gave credit to the Stanford Project Managers for the role they played in achieving a sustainable facility. He also acknowledged that a well defined building program was decisive for the positive project outcome. Mr. Jacobson attributes the successful outcome of the project in part to a clear set of goals from the beginning of the project and the positive attitude of the General Contractor toward sustainability learning and exploration of innovative alternatives. In both cases, we observe that organizational aspects (roles and characteristics of the organizational actors) and process aspects (well defined set of goals and building program) are considered essential to achieve project success, although these aspects are rarely reported as SC.

Building Guidelines (MSBG) is an example of this type of resource that helps a design team to define the functional requirements for a project and suggest sustainability strategies (aligned with the local needs) and performance goals in categories such as: site and water; energy and atmosphere; indoor environmental quality; and material and waste. These categories are representative of the most common considerations, though the extent to which they should be pursued varies for different guidelines and the organization/entity that originated them. Another common type of guideline comes from assessment tools such as LEED™ or SPeAR™. In nature, these assessment methods are prescriptive and they suggest strategies to comply with predefined "credits" that represent the interpretation of sustainability of a large and experienced consulting firm like Arup in the case of SPeAR™ or the sustainability view of the US Green Building Council in the case of LEED™. McGregor and Roberts (2006) point out that SPeAR™ provides flexibility to customize the four main categories of assessment: environment, social, natural resources and economic, according to the stakeholders' needs. The LEED™ rating system is more rigid and focuses mostly on the product (building) and distinguishes five categories for the credits: sustainable sites; water efficiency; energy and atmosphere; material and resources; and indoor environmental quality. There is an additional category for innovation and design process that provides some flexibility in the recognition of sustainability considerations (up to 4 credits for innovation out of a possible total of 69 credits). A project can achieve certification (26-32 points), or three levels of accomplishment: Silver (33-38 points), Gold (39-51 points) or Platinum (52-69). LEED™ has become a synonym of sustainability for many project stakeholders and a certain level of accomplishment (e.g., LEED™ Silver) is frequently considered a functional requirement for a facility (Schwarzenegger, 2004).

Practitioners have traditionally used all sorts of models to address their discipline-specific design needs (e.g., architects create scaled physical models of buildings to understand forms, spaces and materials; mechanical engineers create thermal/mathematical models of buildings to understand the energy dynamics associated with buildings, and so on). Designers can now quickly create and modify these models in a computer, therefore, the models become virtual. The Center for Integrated Facility Engineering (CIFE) has coined the term: Virtual Design and Construction (VDC) to refer to the use of multi-disciplinary performance models of design-construction projects. These models include the Product (i.e., building/facilities), Work Processes to deliver those facilities, and the Organization of the design-construction-operation to support the project business objectives. García et al (2003) explain that "the VDC approach defines project models as the composition of related models of Product, Organization and Process (POP)". Developing and modeling the Product, Organization and Process consistently and concurrently contributes to the success of the project development (García et al, 2003; Levitt and Kunz, 2002). The VDC methodology relies on incremental creation and integration of POP project models at increasing levels of detail: after creating an initial model at a coarse level of detail, designers analyze the model for cost, schedule and functional risks; and then elaborate on selected segments of the model to elucidate and eventually mitigate potential risks to project success (as defined by the project functional requirements). A project owner is concerned about the SC of the product, but obtaining these SC requires management, which means that the appropriate organization and process need to be specified.

A sustainable project involves economic, environmental and social aspects, therefore a holistic approach to address these aspects is needed. POP models offer a balanced way to plan and document SC. We propose to use the POP model methodology to represent the SC of projects according to the most common categories identified by assessment methods and guidelines. We selected twelve recognized "green" buildings from the High Performance Buildings Database (HPBD) maintained by the Department of Energy (DOE) and that have been recognized as AIA/COTE Top Ten Green Projects for 2004 and 2005[2]. We picked six buildings that pursued LEED certification and six that did not. We then built a gPOP model with about 10 elements to represent the product, organization and process for each of the twelve high performance buildings. We compared the twelve gPOP models and documented the insights drawn from these representations of the SC. The following section describes how to create a gPOP model for the sustainable projects and shows how those models can be used by the design team.

[2] A sustainability case study for each of the chosen buildings can be found at the following URLs: http://www.aiatopten.org/hpb/results.cfm?search=rating&RatingID=60&RatingYear=2004 and http://www.aiatopten.org/hpb/results.cfm?search=rating&RatingID=281&RatingYear=2005.

3. HOW GPOP WORKS

In this section we explain how to build a gPOP model and how to calculate two simple, but useful metrics associated with a gPOP model. We then summarize our analysis and comparison of the SC of the projects using the gPOP models and the their metrics. Finally, we explain why we created a gPOP model template that yielded a list of 36 of the most common sustainability considerations, and we discuss how to use this template to compare projects.

We built a gPOP model for each of the twelve green building project selected from the HPBD to compare SC across projects. We then created a gPOP model template that normalized the varied wording used by design teams to refer to a similar concept, thus facilitating the project understanding for non-technical stakeholders. We analyzed the SC documented for each project, and particularly the SC described in the overview section of the project's case study. More details are usually provided in the remaining sections of the case studies (e.g., energy, materials, indoor environment, etc.). We focused our attention on the documented considerations that distinguish the building as sustainable and we classified such considerations as either: product, organization or process elements of the gPOP matrix. We then further refined the classification of the considerations as either: function (functional requirement), form (design team choice of solution to address the functional requirement needs) or behavior (predicted or observed performance of the product, organization or process). Therefore, a SC (or gPOP element) occupies a single cell of the gPOP matrix.

Since LEED^{TM} is an important method to guide and assess SC in the U.S., we applied the gPOP method to the SC in the LEED^{TM} rating system. We classified the LEED^{TM} pre-requisites and credits into one of the nine POP-FFB categories based on the USGBC declared intent for them (mostly functional requirements in the gPOP context). There are 7 pre-requisites and a maximum of 69 credits, but only 65 credits can be classified into the POP-FFB categories, given that up to 4 credits can be earned for innovative/non-prescribed practices incorporated into the design. We found that 62 out of the 72 SC of the LEED^{TM} rating system (65 credits plus 7 pre-requisites) focus on features of the building facility (product). There are 9 SC for the process and 1 for the organization. Therefore we conclude that a particular LEED^{TM} achievement requirement is a product-function element in gPOP.

The following list shows examples of SC for each category of the gPOP matrix for the Lake View Terrace Library (LVTL) in Los Angeles, CA (Figure 1a) and explains the classification.

- *Product-Function*. The gPOP matrix shows that the stakeholders designed the LVTL to achieve a LEED^{TM} Platinum level. Most of the SC of the LEED^{TM} rating system refer to the building facility and its expected performance, this constitutes a functional requirement of the product.
- *Organization-Function.* The "Incorporate public review" SC in the Organization-Function category of the gPOP matrix describes a functional requirement of the organization responsible for delivering the project. This SC refers to the need of engaging the "public" in the sustainability discussion about the building.
- *Process-Function.* The "Minimize soil erosion from construction activities" SC in the Process-Function category of the gPOP matrix refers to the commitment of the design team to conduct the construction process in an environmentally friendly manner. It describes a functional requirement for the construction process.
- *Product-Form.* It constitutes the designers' choice of technology to address the project requirements. A typical example for this category is "Roof mounted PVs". This gPOP element represents the most common way of describing a sustainable facility by enumerating the technologies included in the design.
- *Organization-Form.* The "Third party commissioning agency" SC refers to an organizational actor chosen to participate in the project delivery process.
- *Process-Form.* It is the stakeholders' chosen approach to create a sustainable facility. The "Daily design meetings from the outset of the project" SC points to a work process that took place during the project to make the facility and its delivery process more sustainable.
- *Product-Behavior.* The "25% reduced stormwater runoff" SC refers to the predicted performance improvement of the building compared to a baseline, due to the chosen design alternatives (e.g., bioswales and restoration of soil using native plants in this case).
- *Organization-Behavior.* There is no SC in this category, but predictions or actual observations of organization related performance would populate this cell (e.g., predictions or observations of latency to respond to design inquiries requested by other designers).

- *Process-Behavior.* The “75% construction waste reduction (diverted to local recycling facilities)” SC is an observed behavior of the construction process. It constitutes a performance benchmark for the chosen construction process.

We classified each SC of the 12 projects into one of the gPOP categories to build each project’s gPOP model. We then grouped the twelve projects into two major categories: projects that pursued LEED^{TM} certification and projects that did not, and we explored quantitative and qualitative uses for these gPOP models. The quantitative comparison of the gPOP models points to the number of SC in each POP-FFB category. We could then determine the minimum and maximum number of SC per category. However, we could also calculate the distribution of SC among the POP-FFB categories. We attempted to standardize the SC, so we created a list of the most common sustainability considerations (MCSC). The qualitative comparison is based on this list of the MCSC. We computed the frequency of appearance of the MCSC in the twelve projects and we identified commonalities and differences across the projects. Following we discuss the quantitative and qualitative analysis and comparison of the twelve gPOP models.

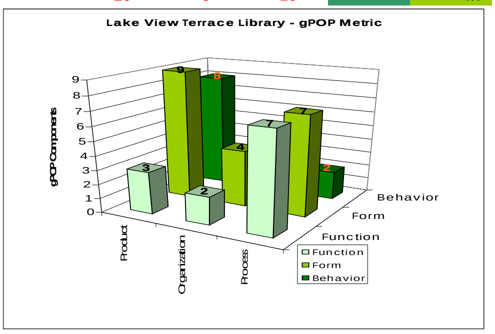
On the quantitative side, we counted and recorded the number of SC in each category of the gPOP matrix. We then calculated the total number of these gPOP elements per row and column of the gPOP matrix and finally we computed the total number of SC for the project. We defined a simple metric called the gPOP index as the ratio between the total number of gPOP elements divided by nine. The gPOP index represents the average number of SC per gPOP category. We realize that a single average number can not fully represent the complexity of the SC and that knowing where in the gPOP matrix the SC are contributes to the understanding of the sustainable nature of the project. We created a simple graphic that depicts the number of occurrences of SC for each cell of the gPOP matrix which we call the gPOP profile. This gPOP profile is a three-dimensional representation of the information contained in the gPOP matrix. Figures 1b and 1c show the gPOP index and the gPOP profile for the LVTL.

		PRODUCT		ORGANIZATION		PROCESS
FUNCTION	1	Located within walking distance of public transportation	1	Incorporate public review	1	Integrated design process guided by energy modeling and frequent public review
	2	Designed to achieve LEED Platinum	2	Public and Staff: early included stakeholders	2	Workshop for public and staff to educate and collect information and ideas
	3	Demonstration project for future library projects in LA (expected higher unit cost)	3		3	During predesign and design high degree of interaction of architects and engineers
	4		4		4	LEED used as framework for sustainability achievment
	5		5		5	Community funds and third parties mandated to promote environmental stewardship
	6		6		6	Minimized soil erosion from construction activities.
	7		7		7	Look for synergies between environmental and client golas.
FORM	1	Daylight dimming and occupancy sensors	1	Design team leader was a LEED AP	1	Daily design meeting from outset of project
	2	Use of bioswales to control water runoff. Native plants restore habitat for wildlife (drought tolerant).	2	Separate LEED AP for managing info about environmental goals	2	Solar2 and Solar5 used for schematic energy models.
	3	Local breezes are harvested by a passive cooling tower that conditions portions of the building.	3	Many consultants assited design	3	Comissioning extended to occupancy phase
	4	Water management system for optimization of irrigation system.	4	Thrid party commissioning agency	4	LCCA used for ROI of several energy-efficiency measures
	5	Skylights and photocells for daylit control.	5		5	2-weeks building flushout (for VOC)
	6	Roof mounted PVs	6		6	Early commitment to energy-simulation models (incremental refinement).
	7	Night flush for cooling	7		7	Commissioning started "before construction" to understand goals and expected deliverables.
	8	Materials: Glu-laminated beams are FSC certified; concrete masonry (less finishes);	8		8	
	9	Emphasis in local resources: 60% within 500 mi, 30% within 100 mi	9		9	
BEHAVIOR	1	25% Reduced stormwater runoff	1		1	75% construction waste reduction (diverted to local recylcing facilities)
	2	34% less water than EPA 1992	2		2	650k out of 4400k (15%) of funds brought to project from environmental interests (stewardhip)
	3	40% more energy efficient than CA standards and 50% compared to ASHRAE 1999	3		3	
	4	80% of building is naturally ventilated	4		4	
	5	PV's will provide 15% of electricity	5		5	
	6	93% of public areas in typical day are daylighted	6		6	
	7	Achieved LEED Platinum (52/69) - SS11/14 - WE3/5 - EA15/17 - MR6/13 - IEQ12/15 - IDP5/5	7		7	
	8	Fly ash replace 20% cement content.	8		8	

(a)

Instances of gPOP components
(default=10 elements)

(b)	Product	Organization	Process		
Function	3	2	7	12	
Form	9	4	7	20	
Behavior	8	0	2	10	gPOP index
	20	6	16	42	4.7



(c)

Figure 1. gPOP Model (a – top), gPOP index (b – bottom left) and gPOP profile (c – bottom right) for the Lake View Terrace Library project.

We compared the projects using the gPOP model, the gPOP index and the gPOP profile (see Table 1 and Figures 2a and 2b) and following we present the insights from this comparison:

1. From Table 1 we observe that the projects have the highest number of SC in the product-form category (average of 9), which corresponds mostly to a description of the sustainable technologies used to achieve

the buildings' high performance in areas such as energy, water conservation, harvesting of solar power, etc.

2. The buildings we modeled do not have many organization-behavior SC (an average of fewer than 1). Almost none of the documented case studies record predicted or observed behaviors of the organizations that carried out the design and construction of the buildings.
3. 64% of all the SC from our sample are related to the product (Table 1).
4. 53% of the SC from our sample describe the form of either the Product, Organization or Process (e.g., technologies and building component used [product-form]; participants of the team [organization-form], tasks that made the project happen [process-form]).
5. The organization SC were the least frequent (average of three instances) followed by the SC describing predicted or observed behaviors (average of six instances).
6. The SC distribution among the POP categories was independent of the value of the gPOP index (see percentages columns in Table 1 and Figure 2b). The decreasing curves in Figure 2a –associated with the descending gPOP index value from left to right– became flatter in Figure 2b.

Table 1. Number of occurrences of SC per gPOP category and summary grouped per POP and FFB. The projects were arranged in descending order according to their gPOP index. The gPOP index column is calculated as the sum of the Product, Organization and Process columns divided by 9. Green shaded projects represent LEED^{TM} projects.

#	Project	LEED	Pr-Fn	Or-Fn	Ps-Fn	Pr-Fm	Or-Fm	Ps-Fm	Pr-Bh	Or-Bh	Ps-Bh	Product	%	Org	%	Process	%	Function	%	Form	%	Behavior	%	gPOP Index
1	Lake View Terrace Library (City of Los Angeles)	y	3	2	7	9	4	7	8	-	2	20	48%	6	14%	16	38%	12	29%	20	48%	10	24%	4.67
2	20 River Terrace	y	6	1	3	10	4	8	5	-	2	21	54%	5	13%	13	33%	10	26%	22	56%	7	18%	4.33
3	The Plaza at PPL Center (Liberty Property Trust)	y	4	1	2	10	3	5	10	-	-	24	69%	4	11%	7	20%	7	20%	18	51%	10	29%	3.89
4	Pittsburgh Glass Center - AIA 2005		1	1	2	10	2	10	5	2	2	16	46%	5	14%	14	40%	4	11%	22	63%	9	26%	3.89
5	Woods Hole Research Center (Woods Hole Research Center)		7	-	4	10	2	1	4	-	1	21	72%	2	7%	6	21%	11	38%	13	45%	5	17%	3.22
6	City of White Rock Operations Building	y	4	-	2	10	2	4	4	-	2	18	64%	2	7%	8	29%	6	21%	16	57%	6	21%	3.11
7	Genzyme Center	y	5	2	2	10	1	2	5	-	-	20	74%	3	11%	4	15%	9	33%	13	48%	5	19%	3.00
8	Eastern Sierra House - AIA 2005		7	-	2	10	1	4	2	1	-	19	70%	2	7%	6	22%	9	33%	15	56%	3	11%	3.00
9	Herman Miller MarketPlace (The Granger Group)	y	5	1	5	6	1	2	3	-	-	14	61%	2	9%	7	30%	11	48%	9	39%	3	13%	2.56
10	Factor 10 House (F10)		4	1	1	10	-	2	2	-	-	16	80%	1	5%	3	15%	6	30%	12	60%	2	10%	2.22
11	Greyston Bakery (Greyston Foundation)		6	1	2	8	-	-	2	-	1	16	80%	1	5%	3	15%	9	45%	8	40%	3	15%	2.22
12	Pierce County Environmental Services Building (Pierce County Public Works and Utilities)		-	1	2	9	1	4	2	-	1	11	55%	2	10%	7	35%	3	15%	14	70%	3	15%	2.22
	AVERAGE		4	1	3	9	2	4	4	0	1	18	64%	3	10%	8	26%	8	29%	15	53%	6	18%	3.19
	LEED Projects		5	1	4	9	3	5	6	-	1	20	62%	4	11%	9	28%	9	29%	16	50%	7	21%	3.59
	NON-LEED Projects		4	1	2	10	1	4	3	1	1	17	67%	2	8%	7	25%	7	29%	14	56%	4	16%	2.94

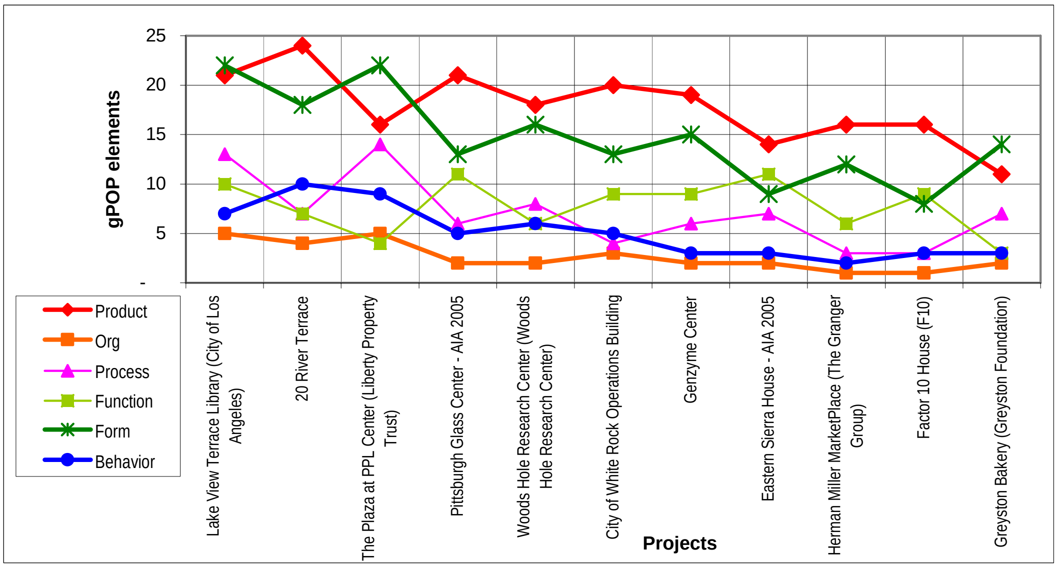


Figure 2a. SC per category for each project. The figure shows a set of decreasing curves, given that the projects were ordered by decreasing gPOP index, which is a proxy for the number of SC in the project.

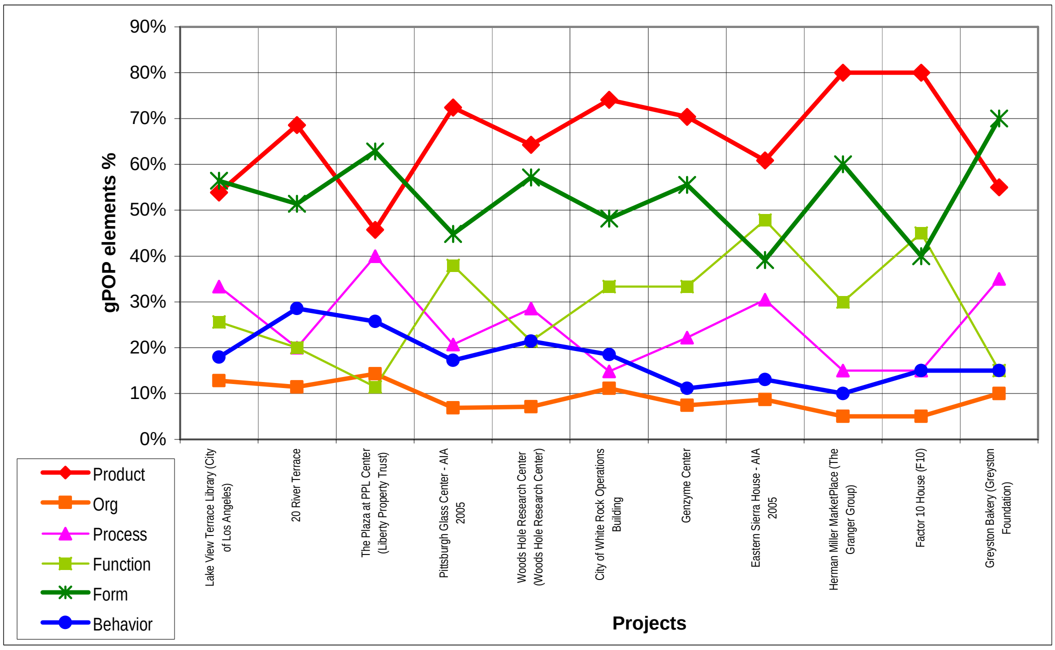


Figure 2b. Sustainability considerations per category for each project - Percentages. Each column shows the percentage of gPOP elements or SC for each POP-FFB category compared with the total number gPOP elements. The figure in this case shows that the curves are flat when we consider percentages, indicating that regardless of the value of the gPOP index, the distribution of SC among the POP-FFB categories remains constant (relatively flat curves) for the twelve projects studied.

Observations three to five are also evident when studying Figures 2a and 2b, where the thicker top lines (product and form) and thicker bottom lines (organization and behavior) depict the number of instances of gPOP elements for each of the twelve projects of our study.

On the qualitative side, we identified the SC that appear most frequently for each category of the gPOP matrix. We tried to describe each of the most common sustainability considerations (MCSC) as broadly as possible to avoid characterizations applicable only to a particular project. For example, in Figure 3, the first SC from the product-function category ("Achieve a given (or max/min) environmental performance target") can include goal setting for either energy consumption, water consumption or both. If both of these performance targets are mentioned in the documented case study for a particular project, they both will appear in the respective gPOP model, but they are counted just once. The shades of purple in Figure 3 correspond to product SC (function, form and behavior in descending order); the shades of red correspond to organization SC (note that we did not find explicit mention of organization behaviors as pointed out earlier); and the shades of blue correspond to process SC.

It is interesting to note that despite the disparity in terms of frequency for product, organization and process SC, there is one SC for each form category among the considerations with the highest frequency of appearance:

- *Product-Form (10 instances)* – In general, most of the documented cases address the topic of construction materials as an important element to achieve a sustainable building (10 out of 12), by either incorporating high recycled content materials, reusing materials (e.g., lumber, wood siding, etc.) or using innovative sustainable materials (e.g., sustainable harvested lumber materials, low VOC emitting interior finishes, etc.).
- *Organization-Form and Process-Form (9 instances each)* – There is a recognition of the importance of commissioning [process-form] to ensure that the building will perform as designed and that the organization best suited to perform this job is an independent commissioning entity [organization-form] hired directly by the owner. We should point out that a significant percentage of our sample (6 projects or 50%) pursued LEED^{TM} certification and several others used the LEED^{TM} system as a guideline for sustainable design, which could explain the high frequency of commissioning (both organization and process form) as it constitutes a prerequisite for LEED^{TM} certification (i.e., it is an unavoidable requirement for buildings pursuing certification).

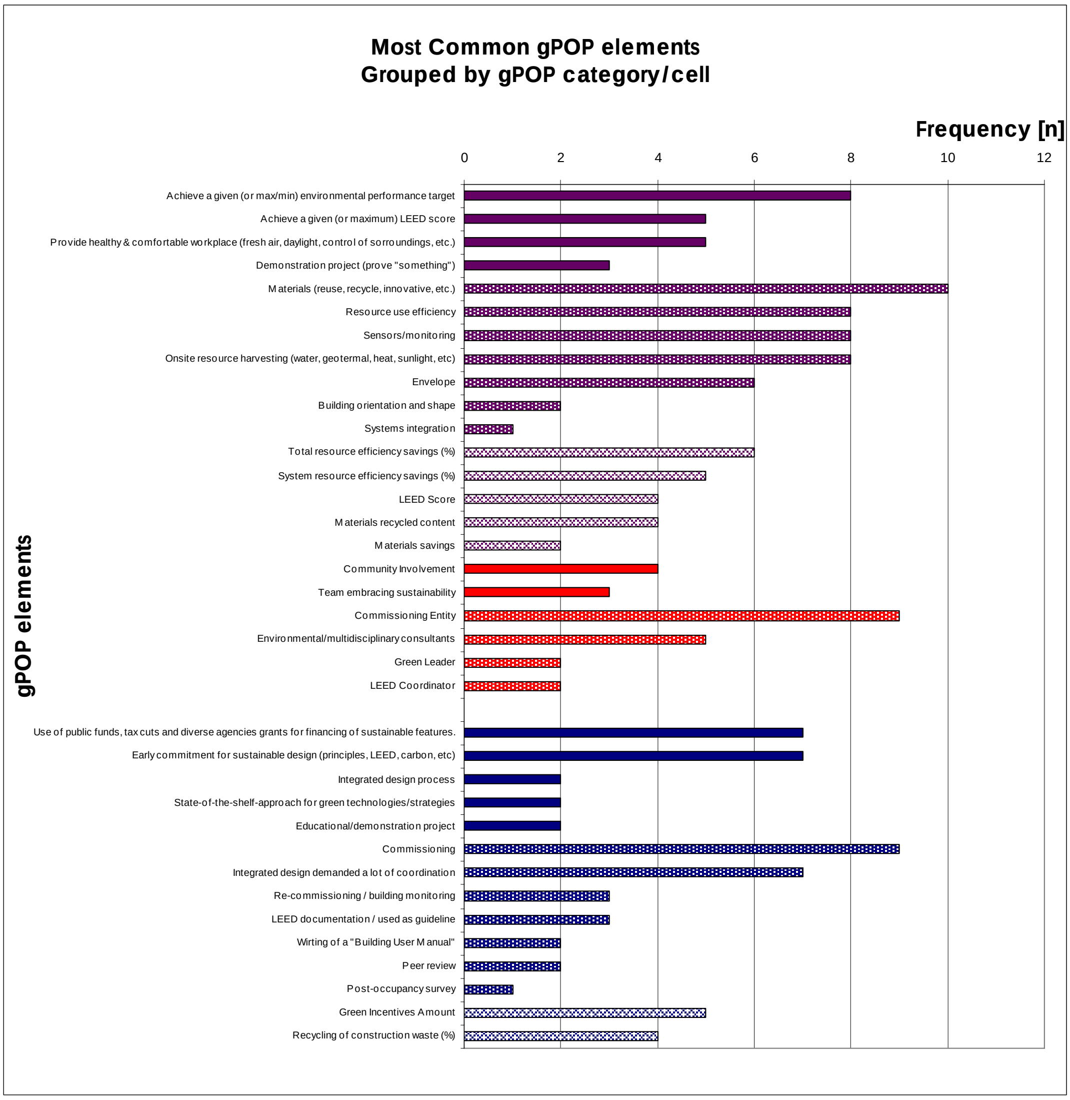


Figure 3. MCSC grouped by gPOP category. Shades of purple distinguish the product considerations, while shades of red indicate organizational considerations, and shades of blue indicate process considerations of the gPOP model. Within each set of shades of a color (purple, red, or blue) the function, form and behavior elements are arranged from top to bottom (solid, dotted and hatched, respectively). The gap after the red shades indicates that there are no organization-behavior elements.

Another observation from Figure 3 is that 8 out of the 12 building projects (67%) documented a functional requirement that explicitly requests pursuing a performance based sustainable design [product-function], i.e., they either sought a maximization of resource savings, a minimization of consumption of resources or they set a given target goal (e.g., reduce energy consumption by 50% compared to ASHRAE standards). It is interesting to note that there is consistency between the product-function just mentioned and the fact that 8 out of the 12 buildings documented resource use efficiency measures or strategies [product-form] to address the performance requirements just mentioned. The resource use balance includes both the demand and supply of resources. Many of the strategies (forms) have focused on lowering the demand side of the equation by using more efficient systems and/or equipment, but there is also a significant number of buildings (8 out of the 12) that explore the supply side of the resource use balance, with technologies devoted to "onsite harvesting" of resources, such as wind or solar (for electricity production and/or heat); storm water management that can provide water for irrigation and other non-potable uses (e.g., flushing toilets); greywater recovery (for non-potable uses); heat recovery from water, waste or from other processes, etc. In general, efficiency comes first (is the cheapest way to lower net consumption of resources), but the use of financial incentives and special programs has made it economically attractive to explore the onsite harvesting of resources and, for example, photovoltaic arrays have become a common sustainable feature (although the percentage of total electricity supplied by these arrays varies widely from about 5% to 33%).

A final qualitative observation points to the use of public funds, tax cuts, grants from diverse agencies and other programs that stimulate the advancement of high performance buildings for partially funding the first cost premiums usually associated with delivering a sustainable facility. This is a remarkable common SC that sometimes constitutes a significant portion of the cost of the building. It is not uncommon that 10% or more of the total construction cost is covered by these sources of funding (e.g., 75% of construction cost was provided by this type of funds for the City of White Rock Operations Building; the Greyston Bakery was entirely funded by site remediation and passive energy design grants; 15% of the cost of the Lake View Terrace Library was covered by stewardship funds; and 12% of the construction cost for the Woods Hole Research Center came from grants promoting sustainable construction). This kind of funds was also used on other projects (e.g., 20 River Terrace and Genzyme Center), but with a lower relative contribution to the total construction cost.

4. DISCUSSION

The list with the MCSC is an attempt of standardizing the creation of gPOP models that allowed us to compare sustainable projects beyond the enumeration of green features included in the design. The representation of the SC using the gPOP models template helped us to uncover some hidden insights about the sustainability project delivery process that are described next. We conclude this article suggesting future research directions for gPOP models.

gPOP Models Comparison Insights. There are no big differences among the gPOP models of projects pursuing LEED™ certification and the NON-LEED™ projects, with the exception of a larger number of process-function, organization-form and especially product-behavior considerations for projects seeking LEED™ certification (Table 1). Therefore, our sample of buildings shows that following the LEED™ certification process means: better defined process-related functional objectives; more sustainability-related organizational forms; and a larger number of product-related behaviors when compared to projects not pursuing LEED™. The only relevant difference in Table 1 between LEED™ and NON-LEED™ projects is in the last column: the gPOP index. On average, LEED™ projects have a larger number of SC than NON-LEED™ projects (a gPOP index of 3.6 versus 2.9 respectively). We could interpret this gPOP index variance as a sign that the rigor imposed by the compliance with the many LEED™ pre-requisites and credits forced the design team to explicitly address more sustainable considerations.

MCSC insights. From the list shown in Figure 3 we were surprised to discover that there is an explicit acknowledgement (documented on the HPBD) of the use of LEED™ documentation as a guideline to achieve a sustainable outcome for only three instances, although 6 of the 12 projects in our sample pursued LEED™ certification. This could mean that either the design and construction of the facility was guided and organized by self-developed standards or documents other than those provided by the USGBC for certification purposes (which would rule out a "LEED™ point collection" approach to sustainability), or this could also mean that the parties involved did not report explicitly the use of the LEED™ guidelines – a more likely scenario, we think. Likewise, although all the projects in the sample are recognized sustainable buildings, only in three instances is there documented evidence (in the HPBD) that the design/construction team had committed itself to embrace sustainability as a central part of the project delivery process.

At the *function* level, the most common SC we observed are related to the pursuit of environmental performance targets [product-function] and the early commitment to a sustainable design process [process-function]. The use of funds designed to promote sustainable buildings to cover a significant portion of the construction cost (7 out of the 12 projects) speaks to the importance of such incentives to either cover the additional design expenses associated with the high performance buildings (to cover for instance early engagement of stakeholders or additional consultants, etc.) and/or pay for the first cost premiums of some of the technologies such us control and monitoring systems.

At the *form* level, the most common SC that we observed relate to the sustainable strategies selected to achieve the high performance goals (product) either by addressing resource efficiency (demand) and/or by providing onsite harvesting of resources (supply). The most common organization and process form SC are related with commissioning the building to ensure that it performs as designed (hiring of a commissioning entity and design and implementation of the commissioning tasks). There is also a significant recognition that sustainable design is a very integrated process [process-form] with a resulting highly integrated product-form (i.e., the building itself).

At the *behavior* level, the most common SC that we observed are those that provide a prediction or actual figures for the functional requirements established by the design team. Examples of these behaviors are LEED^{TM} scores or expected energy savings [product-behavior] and percentage of recycled construction waste or amount of funding coming from green incentive programs [process-behavior].

Future Steps

A natural extension of our work can include the creation of a comprehensive database of the MCSC. Every additional gPOP model we build can potentially add new SC that are added to the MCSC database. This process should be repeated until saturation is achieved (new projects and their gPOP models do not add new MCSC). A comprehensive database of MCSC might help to standardize and ease the creation of gPOP models and to facilitate cross-project comparisons.

The gPOP profile enabled us to see the “imbalance” of gPOP models in terms of number of SC per gPOP category (POP/FFB). Severe gPOP imbalance might constitute a red flag that jeopardizes the sustainable outcome of a project and deserves the design team’s attention. Therefore, we suggest further exploration of the concept of “(im)balance” in the gPOP models and its impact in the sustainable outcome of a project.

In this research, we used gPOP models to study already built sustainable buildings (retrospective analysis). However, according to Paulson (1976), the earliest the design changes occur during the project lifecycle, the largest the potential for design improvements at a relative low cost. For this reason, we think it is interesting to explore the use of gPOP models to compare different alternatives of SC being studied during the early phases of a project. Additionally, the incorporation of SC from a standardized database of the MCSC; and the analysis of (im)balance in the early-project-phase gPOP models could help designers/builders to improve the design and deliver a better [sustainable] facility. Haymaker et al (2006) and Toledo et al (2006) document an exploratory research that includes the use of POP models prospectively in early phases of design, which is a step in the suggested direction.

5. ACKNOWLEDGEMENTS

We want to thank Dr. Cohen and Mr. Jacobson for sharing their project insights with us. We want to thank Dr. John Kunz for his support and enthusiasm for testing our framework in his class Virtual Design and Construction at Stanford. We also want to thank CIFE and its members for providing the financial support for this research [CIFE Seed Research: PPM0404 – Sustainability in Early Stages of Virtual Design and Construction (VDC)].

REFERENCES

García, A. C. B.; Kunz, John; Ekstrom, Martin & Kiviniemi, Arto. (2003). *Building a Project Ontology with Extreme Collaboration and Virtual Design & Construction*. CIFE Technical Report #152.
Haymaker, John; Ayaz, Engin; Fischer, Martin; Kam, Calvin; Kunz, John; Ramsey, Marc; Suter Ben; and Toledo, Mauricio. (2006). *Managing and communicating information on the Stanford Living Laboratory*

feasibility study. ITcon Vol. 11, Special Issue: Process Modelling, Process Management and Collaboration, p607-626, http://www.itcon.org/2006/42

Levitt, Raymond and Kunz, John (2002). *Design Your Project Organization as Engineers Design Bridges.* CIFE WP073. http://cife.stanford.edu/online.publications/WP073.pdf

Regents of the University of Minnesota, Twin Cities Campus, College of Architecture and Landscape Architecture (2001). *Minnesota Sustainable Design Guide*. Retrieved from the following URL: http://www.sustainabledesignguide.umn.edu/default.htm on 02/25/2004

Regents of the University of Minnesota, Twin Cities Campus, College of Architecture and Landscape Architecture (2006). *The State of Minnesota Sustainable Building Guidelines (MSBG) Version 2.0.* Retrieved from the following URL: http://www.msbg.umn.edu/index.html on 03/15/2007

Paulson, B. (1976). *Designing to Reduce Construction Costs.* Journal of the Construction Division, ASCE, Vol. 102, No. CO4, Proc. Paper 12600, pp. 587-592.

Pearce & Vanegas (2002). *A Parametric Review of the Built Environment Sustainability Literature.* International Journal of Environmental Technology and Management. Vol. 2, no. 1-3, pp. 54-93.

Plunkett Research, Ltd. (2004). *PLUNKETT'S REAL ESTATE AND CONSTRUCTION INDUSTRY TRENDS.* Retrieved from the following URL: http://www.plunkettresearchonline.com/Trends/Default.aspx?Industry=19 on 02/25/2004.

Plunkett Research, Ltd. (2007). *PLUNKETT'S REAL ESTATE AND CONSTRUCTION INDUSTRY TRENDS.* Retrieved from the following URL: http://www.plunkettresearchonline.com/Trends/Default.aspx?Industry=19 on 05/21/2007.

McGregor, Alisdair and Roberts, Cole (2006). *Using the SPeAR Assessment Tool in Sustainable Master Planning.* Retrieved from the following URL: http://www.arup.com/_assets/_download/download129.pdf on 04/08/2007.

Schwarzenegger, Arnold (2004). *EXECUTIVE ORDER S-20-04 by the Governor of the State of California*. Retrieved from the following URL: http://www.governor.ca.gov/state/govsite/gov_htmlprint.jsp?BV_SessionID=@@@@1630662020.1176249254@@@@&BV_EngineID=cccfaddkifjgmmhcfngcfkmdffidfnf.0&sFilePath=%2fgovsite%2fexecutive_orders%2f20041214_S-20-04.html&sTitle=Executive+Order+S-20-04&sCatTitle=Exec+Order&sSubCat=null&iOID=60045 on 03/15/2007.

Toledo, Mauricio; Fischer, Martin; Haymaker, John; Kunz, John; Ramsey, Marc; and Suter, Ben. (2006). *A Case Study In Integrated Product, Process, And Organization Modeling In Early Stages Of Sustainable Design.* Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering. Montreal, Canada, June 14-16, 2006. p2544-2553.

U.S. Green Building Council (2005). *LEED-NC Version 2.2 Reference Guide*. First Edition. October, 2005.

U.S. Green Building Council (2003). *Building Momentum - National Trends and Prospects for High-Performance Green Buildings.* Prepared for the U.S. Senate Committee on Environment and Public Works. Retrieved from the following URL (09/21/2006): http://www.usgbc.org/Docs/Resources/043003_hpgb_whitepaper.pdf