

GREENKIT: A MODULAR VARIABLE APPLICATION COOLING SYSTEM

Erin Allison Ezell
Lesley Ellen Felton
Architecture Students, Cal Poly Pomona
3801 West Temple Ave.
Pomona, CA 91768
tetiadae@gmail.com
lesleyfelton@gmail.com

Pablo LaRoche & Michael Fox
Associate Professors, Cal Poly Pomona
3801 West Temple Ave.
Pomona, CA 91768
pmlaroche@csupomona.edu
mafox@foxlin.com

ABSTRACT

A team of Cal Poly Pomona Faculty and students received a P3 Grant from the Environmental Protection Agency (EPA) for a student driven research project titled the “GREENKIT: A Modular, Variable Application System for Sustainable Cooling”. The GreenKit project is being developed in a joint effort of architecture and engineering students working with local organizations in several locations in the USA, Uganda, Mexico, Venezuela and China.

Climate change is the biggest environmental threat facing our planet. To address the problems of energy consumption, thermal comfort and CO2 emissions, that affect climate change, while increasing student awareness of our environmental problems, we have designed the “GreenKit”. The GreenKit combines a vegetated component with a smart window and a distributed sensing and control system. The system, enables dynamic real-time management of environmental variables..

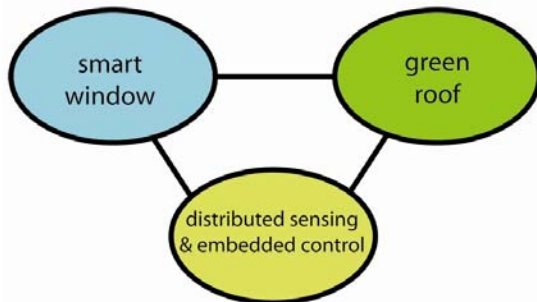


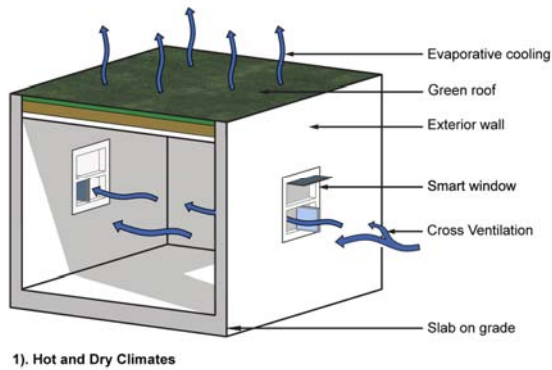
Fig. 1: GreenKit components

During the 2006/2007 school year, students gained an understanding of passive cooling methods used in building design and the functions of a green roof while developing the smart window prototypes. Research focused on seven sites around the world, representative of diverse climate types and a range of economies. The most successful cooling strategies, as determined by climate modeling software and experimental tests, were incorporated into the development of a smart window component that could be distributed as a universal product used to moderate solar radiation, daylight, and air movement, thereby maintaining occupant comfort within a building.

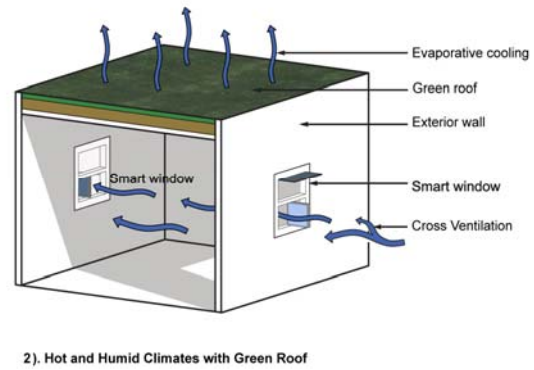
1. INTRODUCTION

The challenge proposed by this P3 team was to improve the comfort of building occupants by combining a green-roof with a smart window system and distributed sensing. In this inclusive GreenKit, the greenroof serves as an insulating barrier, reduces heat island effect in the environment, evaporatively cools the air and absorbs greenhouse gasses. The automated window system, is enhanced with sensors and controllers which respond to real-time climate changes to moderate the penetration of sun and wind into the building.

The purpose of the GreenKit is to improve indoor comfort (People) while simultaneously reducing energy expenses (Prosperity), dependence on fossil fuels and resulting generation of CO2 (Planet).



1). Hot and Dry Climates



2). Hot and Humid Climates with Green Roof

Fig. 2: GreenKit alternatives for different climate conditions

In the context of global implementation, the GreenKit offers an opportunity for substantial conservation of natural resources and monetary savings when used as a replacement for mechanical cooling systems. The GreenKit can be valuable in both developing and developed countries. Its different components: (window, green roof and sensors) also have the potential for use as a window replacement in new construction, or as a retrofit addition.

2. THE GREENKIT

While green roofs are a tried-and-true strategy for low-energy cooling, it is the additional integration of a smart window and mechanized regulating system that poses an innovative research and design challenge. This challenge became the primary focus of our research, our objective to develop the smart window as an automated, self-powered cooling system that utilizes both passive design strategies and low-tech actuators to respond effectively to real-time changes in temperature, sunlight, and wind conditions.

This GreenKit reduces the cost and environmental impact of cooling built spaces, with additional social and economical benefits. The capital costs for acquisition is lower than that of traditional mechanical cooling equipments. Long term operation costs would be low because of the little energy needed for operation and the possibility of incremental implementation and substitution of components. With the exception of the microcontroller and sensors, the GreenKit can be built at low cost using local labor and resources in either developed or developing nations.

The individual will benefit from the use of this system by achieving thermal comfort at lower cost than a traditional air conditioning system, and the entire planet will benefit through the reduction in the emission of green house gases, due to reduced energy consumption for cooling.

2.1 Smart Window

The smart window is designed to work effectively and efficiently either alone or in conjunction with known low-energy cooling methods. However, the optimized global zone for smart window performance is between the latitudes 34° N and -34° S. The smart window system can be a self-sustaining system or tie into the grid, and has the additional potential for use as either a window replacement in new construction or as a retrofit addition that keeps windows in current use out of the waste-stream.

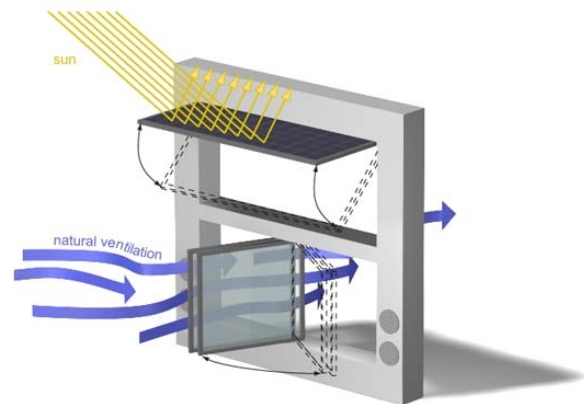


Fig. 3: Environmental response diagram

2.2 Green Roof

A green roof provides several benefits over conventional roofs: reducing storm water runoff, reducing CO_2 levels, and reducing solar loads. Furthermore, when the soil is un-insulated in mild and warm climates, it provides thermal mass for heat storage in the winter.

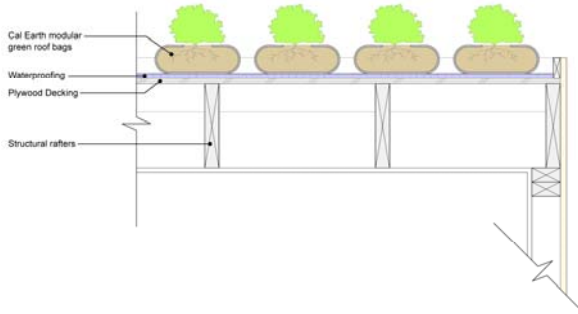


Fig. 4: Green roof prototype

At the current stage of development our green roof consists of an impermeable layer of plastic that acts as a moisture barrier on top of the regular roof and “Cal Earth” bags above these. These bags, (rice sack material), are filled with a growth medium, which could be a mixture of native soil with vermiculite (to reduce weight), and placed in rows perpendicular to the slope of the roof. These bags are designed to store earth and are very inexpensive, lightweight and easy to transport. They allow water to filter through them while containing the growth medium. The benefit of this system is that it allows the bags to be easily transported onto the roof and provides a structure around the soil while allowing the roots to establish themselves. When positioned on the roof, the top side of the bag is cut open to insert native plants with shallow root systems. This is very inexpensive and its thickness can be adjusted allowing for flexibility. Should one bag need to be replaced it is easily pulled out without having to replace the entire roof.

2.3 Controllers

The third component of the GreenKit is the distributed sensing and controlling system.

This component benefits the other elements in the GreenKit by optimizing their functions. The smart window uses sensors to detect indoor and outdoor temperature, sun angle, wind speed and occupant presence. The system will respond to the sensory input and control the sun shade, wind scoops, and fans accordingly. An actuator control system has been developed for the smart window using two actuating components, the photovoltaic (PV) panel and the wind scoops. While the PV panel provides power and shade from the sun, the wind scoops promote ventilation to the inside. The small computer fans can also be turned on for forced ventilation and night venting when the scoops must remain closed for security.

Sensors will be installed in the green roof that detect humidity levels in order to activate an irrigation system when needed, making it self-sustaining and optimizing growth conditions.

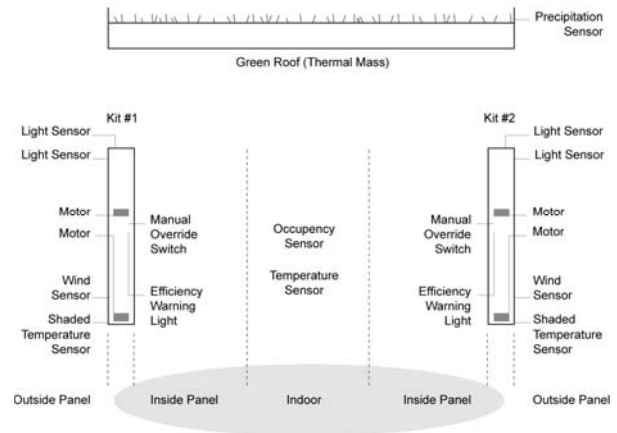


Fig. 5: Prototype Interaction Design: Phase I. Section Showing sensor and actuator location.

3. PROCESS

The implementation of this project for the P3 competition was realized through a series of interdisciplinary courses offered by the Architecture and Engineering departments. In Fall, 2006, students in the architecture design studio learned to apply passive ventilation and greenroof strategies to student-designed buildings. In conjunction with this studio, an architecture elective class worked closely with the design students and a group of engineering students to develop several prototype robotic window units to incorporate into the building designs. Design and engineering students further developed these mechanized units as full scale working models in winter 2007. During the same quarter, a second architecture elective course developed an objective evaluation method that was then used to select the most successful mechanized unit for further development as a full-scale prototype.

3.1 Architectural Projects

In the fall quarter of 2006, students developed architectural solutions that would incorporate the GreenKit and robotics systems. Several sites around the world were selected to develop socially responsible projects in developing and developed nations. Educational and medical facilities together with housing were the programs selected that would best satisfy these needs.



Fig. 6: Day Care Center for Peña Blanca, NM



Fig. 7: Classroom Design for Santa Monica, CA

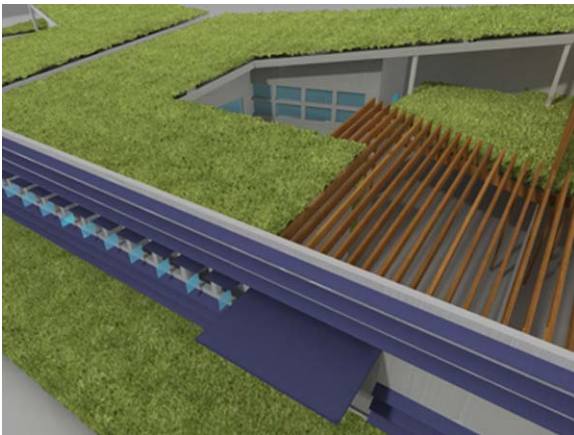


Fig. 8: Residential Design for Rancho Cucamonga, CA

Students had to understand local culture, demographics, and climate data to initiate their design work. The building fabric and materials, together with the robotic system, interact with the environment to regulate external conditions and achieve thermal, acoustic and luminic comfort. Students also developed the rules that would direct the robotic system to interact with environmental

variables, especially the sun and the wind. The students had to use digital and analogue tools to prove that their building designs worked. A simple wind tunnel was built and used to test airflow in buildings or parts of buildings. Shading and solar penetration was tested with different 3-D modeling software, and energy performance was determined with Home Energy Efficient Design, (HEED), developed at UCLA.

As a group, students set CO₂ reduction as a top priority of the GreenKit challenge. An architectural elective class undertook the challenge of proving and quantifying this reduction in the winter quarter of 2007.

In order to analyze the amount of CO₂ produced from the production of the unit itself, a Life Cycle Analysis (LCA) was done on the proposed materials. This analysis is a whole systems approach to determining the total sustainability of a given project, looking at the impact a product beyond just its initial cost or operation. The LCA focused on the primary components of the smart window, including the frame, photovoltaic panels (PV's) and the batteries. At times it was difficult to choose between high environmental costs of a raw material vs. the longevity of that material, but the students felt that some of the initial tradeoffs would help to reduce overall CO₂ production over the lifespan of the smart window.

To determine the environmental cost of operating the smart window, students analyzed the EPA power source data and average household mechanical cooling usage. Although variables such as average mechanical cooling usage and power sources varied by region, students determined that the implementation of the GreenKit resulted in a substantial net reduction of CO₂ production. Some of the research involved generating quantifiable benefits of the smart window components, such as the amount of CO₂ and energy use that is avoided by using the smart window in place of a mechanical cooling system. This research was accomplished by determining mechanical air-conditioning energy loads for each of the sites, using the computer program HEED to model buildings with typical window configurations and air conditioning systems. The difference was the energy savings achieved by substituting the smart window system for a typical air-conditioning system. This number was then multiplied by the amount of CO₂ in pounds per kWh generated by the specific power sources for each region. This gave us the total CO₂ in pounds per year avoided by the substitution of the smart window for a standard air-conditioner.

Table 1. Performance of Green Kit in a 1200ft² building in various climates

Hot and Dry Climates:	CO ₂ Offset	Energy Reduction	Radiation Blocked during Overheated Periods
Pena Blanca, NM, USA	890.19 lb/year	633.14 kWh/year	7389 Wh
Rancho Cucamonga, CA	709.14 lb/year	880.92 kWh/year	6332 Wh

Hot and Humid Climates	CO ₂ Offset	Energy Reduction	Radiation Blocked
Miami, FL, USA	3452.44 lb/year	2,483.77 kWh/year	4431 Wh
Maracaibo, Venezuela	925.08 lb/year	2,341.98 kWh/year	4266 Wh
Jinja, Uganda	24.55 lb/year	1,115.78 kWh/year	3794 Wh

Temperate Climates	CO ₂ Offset	Energy Reduction	Radiation Blocked
Santa Monica, CA	39.35 lb/year	48.88 kWh/year	6087 Wh
Tijuana, Mexico	245.80 lb/year	148.25 kWh/year	5741 Wh

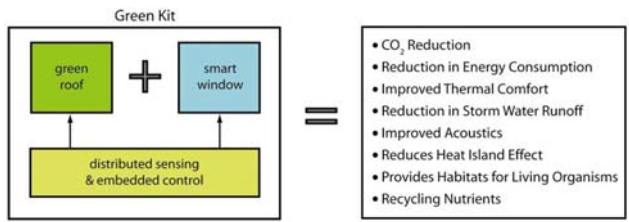


Fig. 7: GreenKit environmental impacts

This research validated the work done by the students and it will also be extremely useful in developing phase II of this project.

3.2 Smart Window

Within the winter design studio, student teams developed and built five smart window component prototypes for integration into the GreenKit. These variations offered different strategies to improve upon a standard window.

Concept 1 is a dual-layer, bi-folding panel system. The interior and exterior panels operate independently of one another, which serves to maximize versatility.



Fig. 9: Smart window concept 2

Concept 2 consists of a pivoting, three-panel system designed to track the sun and wind for optimum control. The frame contains low-voltage fans for increased ventilation and a radiant heating system to reduce cold-air infiltration.

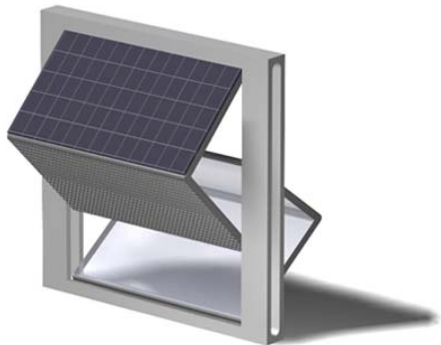


Fig. 8: Smart window concept 1

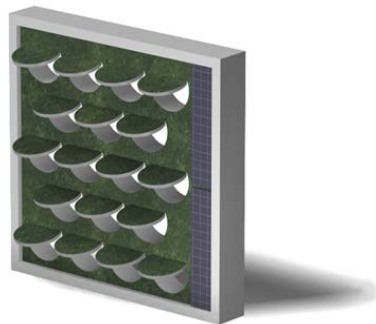


Fig. 10: Smart window concept 3

Concept 3 has circular vents that shade as well as let in air that is evaporatively cooled by the vegetated surface. In the closed position, insulating vegetation makes this design unobtrusive.

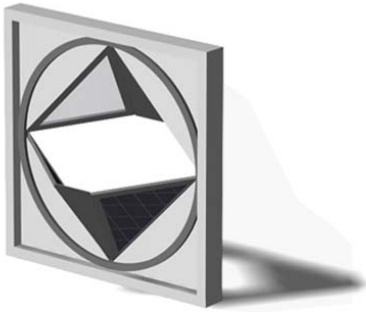


Fig. 11: Smart window concept 4

Concept 4 consists of a rotating track that allows for maximum versatility according to real-time conditions. The panels follow the sun for optimized winter heat gain, summer shading, utilization of the PV overhang, as well as wind-tracking for optimization of wind scoops.



Fig. #: Smart window concept

Concept 5 has an accordion folding system with simplified, accessible mechanics. The system is designed to work with one motor and is constructed from easily available materials, such as computer fans and a bicycle chain.

3.3 PRIME Evaluation System

After the development of the five robotic window systems, a method was devised to objectively rate each one. The P.R.I.M.E. (People, Responsive Interior, Materials and Environment) evaluation system, loosely based on the layout of the system proposed by Malcolm Wells, was developed as a methodological process by which the level of sustainability of each unit could be determined based on a scale of (-) 2400 to (+) 2400. The sustainability of the unit was determined by its positive or negative effect on People, Prosperity and the Planet. The PRIME checklist has three categories relating the unit performance to the three P's. In each of these categories there are eight areas that receive scores from (-)100 to (+)100.

People

- Interacts with user
- Maintains user comfort

Prosperity

- Promotes local economy through material selection
- Offers potential for local maintenance and fabrication

Planet

- Reduces CO₂ production through the reduction of mechanical cooling loads
- Responds to on-site climate changes
- Generates own energy

The systems were presented to in-house faculty and students, as well as to faculty and students of the University of Texas via a digital feed. Based on the P.R.I.M.E. scores received, the window system with the highest score was redeveloped and refined to serve as our final GreenKit window component. The final model went through several iterations as a result of discussion and collaboration by faculty and students. The resulting product is the smart window.

TABLE 2: P.R.I.M.E. EVALUATION SYSTEM

PRIME Checklist for Green Kit Evaluation							
		-100 always	-50 sometimes	0 balances	50 sometimes	100 always	
PEOPLE	People	specialized design- too expensive				flexible design for range of economies	cost analysis
		specialized labor				local labor	
	Resp. Int.	system reactions unclear to user				green kit system reactions educate user	
		ugly				aesthetically pleasing	survey
		less comfort than window				more or better control of comfort than window	test cell
		does not have manual override				has manual override	test cell
Materials	disruptive motion				seamless and smooth motion	test cell	
	blocks or interferes with view				allows or enhances view	test cell	
People Subtotal							
PROSPERITY	People	leaks in horizontal or vertical use				water-tight in horizontal and vertical use	test cell
		specialized maintenance/ access				user maintenance/ access	
	Materials	excessive or insufficient sensors				appropriate use of sensors	
		degrades or has specialized parts				durable or easy to replace	
		imported parts				locally manufactured parts	
		specialized assembly				user assembly	
Environment	bulky or awkward for shipping				compact or easy disassembly for shipping	Prosperity Subtotal	
	excessive or complicated mechanics				minimal and simple mechanics		
Prosperity Subtotal							
PLANET	Environment	benefits users in a specialized climate				benefits users in a variety of climates	test cell
		less management of sun/ wind than window				better management of sun/ wind than window	test cell
	People	imported materials and plants				local materials and plants	
		high embodied energy/ short life span				low embodied energy/ long life span	life cycle analysis
		needs mechanical heating or cooling				maintains comfort level passively	test cell
		does not respond to on-site climate change				responds to on-site climate change	test cell/ computer model
Materials	generates CO2				reduces/ filters CO2	test cell/ computer model	
	consumes energy				generates energy (PV panel)	test cell/ computer model	
Planet Subtotal							

-2400 min.	2400 max.	Final score:
---------------	--------------	--------------

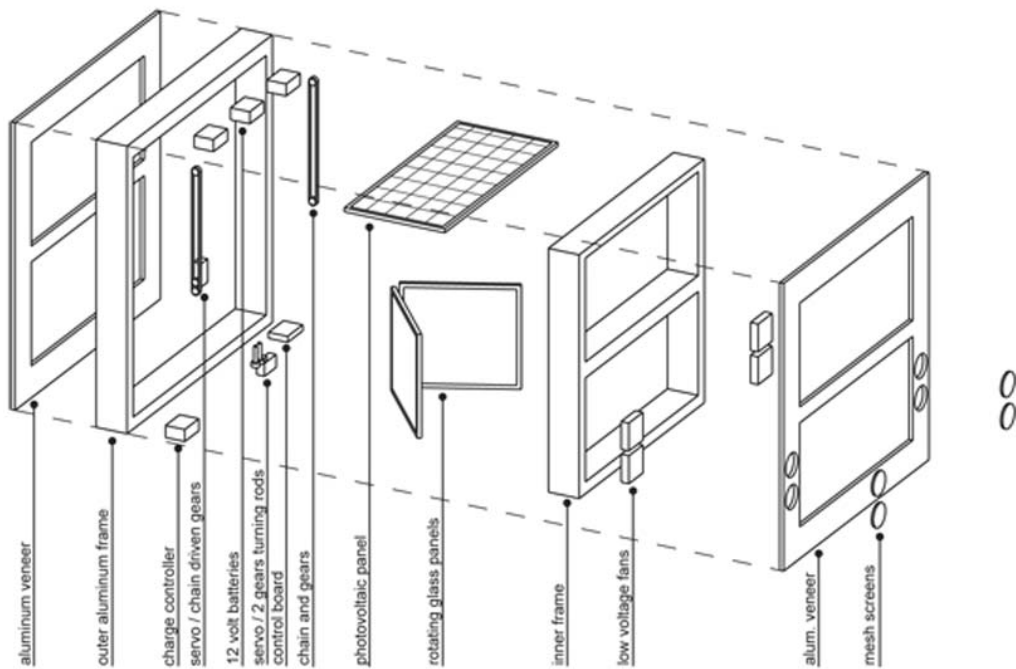


Fig. 7: Exploded axonometric diagram of the final smart window prototype

After evaluating the five initial smart window designs using the P.R.I.M.E Evaluation Checklist, it was determined that Concept 5 had the most potential for meeting the design challenge set forth in the original P3 GreenKit proposal. This design featured an accordion folding system with simplified, accessible mechanics designed to work with only one motor and was constructed using easily available materials.

The strongest features of this design were its mechanical system and material selection. The simplified design of the mechanical system allowed for ease for maintenance and user override. The system used only one motor to drive a chain, lifting the accordion shading panels in a single motion. By swinging open the maintenance panel (with attached motor), the occupant or mechanic had direct access to the operating system. Construction materials were selected for global availability. For example, the chain can be substituted with a common bicycle chain.

There were, however, four areas identified in the evaluation process as needing further development. The PV panels located on the accordion shading system were not fully maximized, due to overlapping and non-parallel movement. There was also a concern that the depth of the overhang did not provide adequate shade from summer sun. Additionally, the vertical design of the accordion panels did not provide a way of capturing or controlling wind. Finally, the design relied on the inclusion of a secondary interior window for waterproofing. This meant that the component relied either on an additional mechanism or on user participation to open that window for ventilation.

These problems were solved using variations of successful elements from other smart window concept designs. These 'borrowed' solutions include the half-panel photovoltaic from Concept 1 and the double windscoop from Concept 2. By integrating the half-panel PV shade into the winning concept design, it solved the two problems concerning PV optimization and shade depth while maintaining the simplicity of the mechanical system. The wind-scoops, redesigned according to wind tunnel testing, added increased control of indirect wind. After implementing these design changes, it was determined that the component no longer needed a secondary window for waterproofing, solving the final concern.

4. CONCLUSIONS

Phase I of GreenKit development proved successful in meeting the goals of the challenge set forth in the P3 competition. Not only did the project foster a rare interdisciplinary experience and teach students firsthand about sustainability and the competition process, it also gave us the opportunity to develop a prototype that has great potential to improve people, prosperity and the planet.

One of the greatest strengths in the GreenKit development process is the quantifiable research that represents real world knowledge in student education. This research includes life-cycle analysis, energy consumption and reduction, CO₂ emissions and reductions, solar design concepts, wind flow analysis and determining interior comfort, all of this is documented in our website: <http://www.csupomona.edu/~p3team/>

The GreenKit will positively impact the environment by reducing energy consumption and CO₂ emissions to the atmosphere by replacing conventional, energy intensive air conditioners with a very low-energy cooling system that will also help to clean the environment. Student research into the operation of the completed GreenKit demonstrates its improvements over a conventional air-conditioner and standard window. The reduced energy use and CO₂ resulting from the operation of the GreenKit prove that it has a lower environmental impact (Planet) and operating cost (Prosperity) than a conventional air-conditioner. The smart window's success at controlling sun and wind to maintain comfort (People), while operating as a self-contained unit, make it an improvement over a standard window.

The P3 project has increased student awareness of the impacts of buildings in the environment and has provided an interdisciplinary experience. The end result is a useful product that could be incorporated in other projects.

Acknowledgements:

EPA P3 Program for their funding.

Team Members: German Aparicio, Daniel Baker, Spencer Brennan, Salvador Ceja, Houston Drum, Erin Ezell, Lesley Felton, Ryan Hansanuwat, Brandon Henry, Sean Lee, Mark Lyles, Ben Millet, Santiago Montoya Jazmin Mora, Stephen Nieto, Naoko Oba, Yamin Oo, Lucas Reames and John Resurrecion.

Faculty Members: Michael Fox, Pablo LaRoche and Phyllis Nelson.