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Sustainable campus improvement program design using energy efficiency and conservation

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A B S T R A C T

Reducing energy consumption is critical to improving campus sustainability. Both increased efficiency of built infrastructure and conservation by users can contribute. This work investigates feedback in the design of energy improvement programs that exploit both efficiency and conservation by developing a system dynamics model. The model formalizes the paid-from-savings approach and is validated using a sustainability program at a major university. Model simulations use five program designs, two forms of performance (energy savings and monetary savings), and capital requirements to test four hypotheses. This research indicated the existence of a trade-off space of program designs in which the preferred design will depend upon specific objectives. Other conclusions partially support improved performance with more investment and recommend the use of conservation to fund efficiency under capital constraints. A feedback analysis provides a richer explanation of the drivers of program success. The scientific contributions include an improved understanding of campus sustainability improvement program design, a formal dynamic model for program design, and an innovative staged design as an advanced solution to the dynamic challenges of designing campus sustainability improvement programs.

1. Introduction

Preserving nonrenewable energy resources for future generations is a primary goal of sustainability, as is avoiding the undesirable impacts of exploration, production, and use of fossil fuels (Fossil Fuels, 2013). Decreasing the energy needs of built infrastructure is a critical part of attaining this goal. Due to the relatively long lifespan of built infrastructure, energy-based sustainability opportunities are greatest in improving older, built infrastructures. As owners and operators of large collections of buildings, universities gain by improving sustainability for both the public good (providing benefits to whole communities and society) and from the private benefits derived from university ownership of the facilities. Therefore, the improvement of campus sustainability is important to both society and universities.

Improving campus sustainability can take many forms, including education (e.g. Lozano et al., 2014), the inclusion of green features in building designs such as green roofs (Saadatian et al., 2013), physical changes to existing built infrastructure, and changes in the behavior of facility users that will lead to reduced energy use. The latter two approaches can be particularly powerful, as suggested by Pimentel's (2004) claim that in the US $9.3 billion can be saved over 10 years in commercial and residential infrastructure energy use with energy efficient technologies and energy conservation by users. Exploiting efficient technologies through means such as replacing inefficient incandescent light fixtures with fluorescent fixtures improves sustainability by providing the same level of service (e.g. lumens) with less energy. In contrast, modifying the behavior of facility users to conserve improves sustainability by reducing the amount of energy required.

Limited funds challenge campus owners and operators to plan, design, construct, and operate sustainability improvement programs. One way to address this constraint is to use the sustainability program itself as a funding source for additional improvements. The concept is simple. Energy-saving projects decrease the amount of consumed energy and thereby the costs of

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providing energy. This generates savings in energy costs. These savings are accumulated over time and used to fund subsequent projects. This paid-from-savings approach creates revolving funds (Weisbord, 2011; Van Der Like, 2009), an economic instrument that is extensively used to promote clean technologies by governments (Peltier and Ashford, 1998) and has been adopted for many campus sustainability improvement programs (Indvik et al., 2013; Mero, 2012; Flynn, 2011). See Thomashow (2014) for a comprehensive review of revolving funds in sustainable campus investments. In many cases the funds needed to start these programs are borrowed, requiring that energy savings also cover loan repayment requirements (Peltier and Ashford, 1998). As will be described, these revolving funds are based on causal feedback and feedback structures. The primary feedback loops use energy savings to fund additional projects that create more savings, theoretically creating a perpetual, self-funded stream of money and energy improvements. However, as will be shown, the actual feedback structure is more complex. The dependence of paid-from-savings programs on feedback makes understanding those structures critical for the design of successful programs. The objective of the current work is to improve the understanding of how efficiency and conservation efforts, and their interactions through feedback, impact campus sustainability improvement program performance under capital constraints. That understanding can be used to guide the design of campus sustainability improvement programs.

Here, a feedback perspective of a single campus sustainability improvement program was adopted to build a model that was used to test hypotheses about campus sustainability improvement program designs. The feedback structure provided the basis for an explanation of the test results. Contributions included improved insights about the characteristics of effective and efficient designs, a validated simulation model that reflects many common features and challenges of these sustainability programs, and an innovative design based on manipulating feedback loop dominance. This paper is organized into six sections including this Introduction. Section 2 provides background information on sustainability improvement through efficiency and conservation and information on system dynamics, the modeling approach that was applied. Section 3 describes the specific problem investigated and four hypotheses concerning program design. Section 4 (Methods) describes the campus sustainability improvement case study and presents the model that was used for hypothesis testing, as well as the program designs used in hypothesis testing. Section 5 (Results) presents and interprets the simulation results, including a feedback analysis. The Conclusions section covers the contributions and impacts of the current work on practice and research, and opportunities for future work.

2. Background

The discussion of sustainability in higher education dates back to late 1970s with a primary focus on environmental education (Sauvé et al., 2007). However, the 1993 Kyoto Declaration increased campus sustainability interest and activity by obligating higher education institutions to promote sustainability by reviewing their operations to reflect sustainable development best practices (IAU, 1993). Thomashow (2014) indicated that this goal is attainable by implementing sustainable best practices in energy, food, materials, governance, investment, wellness, curriculum, interpretation, and aesthetics in campus infrastructure, community and learning. Several approaches have been investigated in the literature. Alshuwaikhat (2008) proposed integrating an environmental management system, public participation and social responsibility, and promoting sustainability in teaching and research. Disterheft et al. (2014) identified structural institutional conditions and an engaged campus populace, highlighting the importance of specific skills and competencies that contribute to the success of participatory approaches on university campuses. Waheed et al. (2011) evaluated sustainability at universities with a fuzzy multi-criteria decision-making model. Velazquez et al. (2006) demonstrated that sustainability initiatives contributing to reduced energy consumption are the most practiced activities in attaining sustainable campuses. The current work focuses on the use of efficiency and conservation to improve campus sustainability.

2.1. Improving sustainability through energy efficiency

Improvements in both the demand and supply sides of an infrastructure's use of energy can reduce energy consumption. Improving energy efficiency is a supply side approach that provides several benefits including cost savings through lower energy bills, cost-effective investment, mitigation of growing energy needs, decreases in environmental degradation, and the fostering of economic development (McLean-Conner, 2009). Specific actions to improve energy efficiency in buildings can take many forms, including (Energy Star, 2013):

- Upgrading and maintaining heating and cooling equipment
- Installing energy-efficient lighting systems and controls
- Purchasing energy-efficient products
- Installing window films and adding insulation or reflective roof coating
- Sub-metering buildings to more accurately measure and track energy

By making physical changes to facilities such as those above, energy supply side approaches increase the efficiency of providing the same level of services and reduce the use of energy that does not provide services (waste). These improvements are critical to creating sustainable campuses. Research at the Lawrence Berkeley National Laboratory (2013) indicates that improving energy efficiency is the most abundant and cheapest way to reduce greenhouse gas emissions. Thomashow (2014) considers physical improvement to be the ultimate energy improvement challenge for building sustainable campuses. The current work investigates improving the energy efficiency of built infrastructure as part of the design of campus sustainability improvement programs.

2.2. Improving sustainability through energy conservation

The energy demand side of sustainability approaches reduce energy consumption by modifying user behavior to conserve energy and thereby decrease the amount of energy the facility must provide. These demand side approaches are referred to here as energy conservation. Many changes in user behavior can reduce energy demand including turning off lights and appliances when not in use and using natural systems (e.g. windows and clothing) to remain comfortable. This approach is supported by the research of Wright and Wilton (2012) which indicates that 82% of university facility managers believe conservation and improved resources are the most important concepts in campus sustainability development.

Strategies for changing user behavior to conserve energy have been categorized as either antecedent or consequence oriented based on when behavioral interventions are made (Abrahamse et al., 2005). Increasing consumer commitment, goal setting, providing information, and modeling can be used as antecedent interventions. The effect of information intervention is dependent on several psychological factors that impact the processing of information by decision makers. Costanzo et al. (1986) presents these

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psychological factors as perceiving, favorably evaluating, understanding, and remembering the information. The current work explicitly models one of these factors (remembering). Consequence strategies include information feedback and incentives (Abrahamse et al., 2005). Feedback can be direct, indirect, inadvertent, utility-controlled, or in the form of energy audits (Darby, 2006). Incentives play a major role in the success or failure of intervention practices. Target groups can be divided into two categories: those with financial incentives and those without financial incentives. Handgraaf et al. (2013) investigates the efficiency of rewards in an office setting. That research suggests that social rewards are more effective than monetary rewards and that public rewards are more effective than private rewards.

Several factors can resist efforts to improve energy conservation. Personal values such as a lack of environmental concern and organizational cultures can make conservation a low priority (Sorrell et al., 2000). Incomplete and imperfect information can limit the range of decisions or investments in sustainability (Howarth and Andersson, 1993; Thollander et al., 2010). In addition, conservation benefits decay over time as facility users become used to efforts to change their behavior. A user's approach to behavior remediation is often based on what he or she considers to be acceptable limits of change. The influence of conservation information also decreases as user populations change when new facility users replace previously-informed users. Special efforts to maintain conservation practices can eliminate or reduce this conservation benefits decay, but conservation education can require frequent reinforcement because facility user turnover on campuses can be very high. For example, few students remain in university dormitories longer than four years and entire summer dormitory guest populations can change within days.

2.3. System dynamics

The system dynamics modeling approach (Forrester, 1961; Sterman, 2000) was adopted for the current work due to its ability to capture and reflect the causal feedback that drives program performance. System dynamics is one of several established and successful approaches to systems analysis and design (Flood and Jackson, 1991; Lane and Jackson, 1995, 2003). System dynamics has been applied to several aspects of sustainability including the impacts of transportation policies on carbon dioxide emissions (Fiorello et al., 2010), national energy policies (Naill, 1992), impacts of energy taxes on demand (Wirl, 1991), ecological incentives on sustainable supply chains (Georgiadis and Besiou, 2008), and regulatory measures to reduce greenhouse gas emissions (Walther et al., 2010). More recently system dynamics has been applied to sustainability in the palm oil industry (Choong and McKay, 2014), carbon emission management in forest growth (Machado et al., 2013), environmental impacts of polyol products (Zhao et al., 2014), sustainability of product-service systems (Lee et al., 2012), and sustainable energy policies based on residential usage (Blumberga et al., 2014). O'Regan and Moles' (2006) system dynamics model that investigates links between sustainability factors and mineral investment funds is closest to the current work in that both use feedback to relate sustainability and investment. However, the current context focuses on energy consumption on campuses. Using system dynamics to investigate sustainability implementation efforts on university campuses is a novel use of the modeling approach. The importance of feedback structures in the performance of campus sustainability programs makes system dynamics the most appropriate method for this research.

3. Problem description and hypotheses

Energy efficiency and conservation are two of the major elements of sustainable campus frameworks and models (Alshuwaikhat and Abubakar, 2008; Geng et al., 2013; Velazquez et al., 2006). However, most sustainability projects focus exclusively on either efficiency or conservation, even though they have several important things in common. Both efficiency and conservation require funding, and they interact to impact performance. They both depend on the same physical facilities. In addition, conservation reduces the savings possible through energy efficiency improvements (and vice versa). The current work considers both energy efficiency and conservation, their interactions and how they contribute to the effectiveness and efficiency of campus sustainability improvement programs.

Because conservation and energy efficiency improvements interact, designing effective (many benefits) and efficient (relatively low costs) sustainability improvement programs requires an understanding of those interactions. The design of programs to exploit feedback structures can potentially improve energy-based sustainability programs, and understanding how efficiency and conservation interact can help designers optimize sustainability improvement programs. Therefore, this work addresses the question *"How can energy-based campus sustainability improvement programs be designed to improve performance under capital constraints?"* Such an investigation requires a model that includes both forms of reducing energy consumption, how they impact the facility, and how they interact over time. The current work develops and uses such a model to better understand how physical and behavioral improvements impact sustainability program performance.

This investigation also requires performance measures that reflect the goals of the primary stakeholders. Bunse et al. (2011) provides an extensive discussion on energy efficiency performance measures used in the industrial sector. Similar to measures mentioned in that work, two performance measures were used to describe program success. The first performance measure is based on monetary savings measured with the size of the sustainability fund after benefits have stabilized. This performance measure is important to the owner of the facility, who may need to repay loans for improvements and seeks to capture savings to fund future sustainability improvements or for other uses. The second performance measure is the total energy saved, which is important to users of facilities and others who seek to reduce energy use, carbon footprints, and meet other sustainability goals.

Based on feedback theory (Sterman, 2000), it is generally hypothesized that shifts in feedback loop dominance and delays in capturing benefits can explain the relative performance of program designs (specified later). More specifically, we predict that:

- **H1:** No single campus sustainability improvement design dominates, i.e., provides the most benefits and requires the least investment. This creates a design trade-off space in which the preferred design will depend upon specific objectives.
- **H2:** Increasing initial investment increases the final size of the sustainability fund. This hypothesis is suggested by economic theory, which says that more investment should generate larger monetary returns. However, feedback theory suggests that the feedback structure and multiple dimensions of performance in sustainability improvement programs may cause this hypothesis to be false.
- **H3:** Increasing initial investment increases the amount of energy saved. This policy is also suggested by economic theory, which says that more investment should generate more of the "purchased" product or service. However, feedback theory

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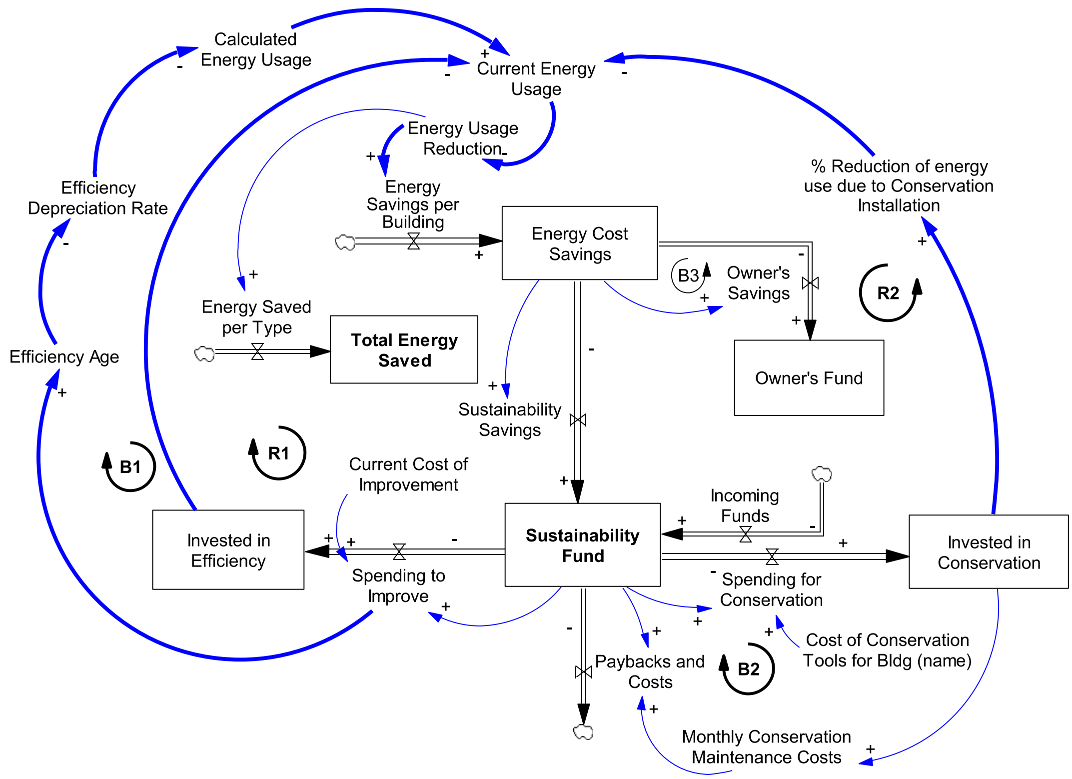

Fig. 1. The conceptual model of a campus sustainability improvement program. Legend of Loops: **R1** – **Energy efficiency improvement loop**: Improving built infrastructure reduces the energy supply required and generates savings, thereby providing funds for additional improvements or conservation efforts. **R2** – **Energy conservation loop**: Energy conservation efforts reduce energy demand and generate savings, which provide funds for more conservation efforts or efficiency improvements. **B1** – **Energy efficiency degradation loop**: Improving built infrastructure is followed by degradation of equipment over time, limiting energy savings and sustainability funds. **B2** – **Forgetting Loop**: Users are replaced by uninformed users or existing users forget to conserve over time, requiring additional conservation efforts to limit energy demand. **B3** – **Owner savings loop**: Energy savings are accompanied by payments to the owner, which limits the savings.

suggests that the feedback structure and multiple dimensions of performance in sustainability improvement programs may also cause this hypothesis to be incorrect.

- **H4:** Using a less expensive sustainability improvement effort to fund a more effective sustainability improvement effort can generate the best combined investment and performance. This policy is suggested by feedback theory, which includes the use of delays to purposefully shift feedback loop dominance to improve performance.

4. Methods

The research methods for this project included the development of a conceptual model of sustainable campus improvement, a data set based on the case study, formalization of the conceptual model into a simulation model and model testing, the specification of five program designs to be simulated to test the hypotheses, and the use of feedback to reveal the impacts of structure on program performance. Each of these are described in the following sections.

4.1. The conceptual model

The conceptual model captures the essential components and interactions of a campus sustainability improvement program. The core of the conceptual model is the paid-from-savings approach to fund sustainability improvements, as used for Harvard University's Green Campus Environmental Initiative Loan Fund (GCLF) (Van Der Like, 2009 and Appendix 1, Figure A1). The GCLF provides funding for energy efficiency improvement projects and alleviates the need to find initial capital for every project. In the GCLF seed money funds a sustainability project that generates savings. A portion of the savings is returned to the GCLF to fund additional projects. This creates a reinforcing loop of increasing funding for sustainability projects.

The conceptual model is illustrated using a system structure diagram[1] (Fig. 1). The three primary stocks in the energy efficiency improvement structure are the Sustainability Fund, Invested in Efficiency, and Energy Cost Savings. Initial improvements are funded from the Sustainability Fund. If those funds are inadequate future projects are delayed until adequate savings accumulate. Campus energy efficiency efforts were modeled with a reinforcing feedback loop based on the GCLF described above (Fig. 1, loop R1). Periodic savings are typically much smaller than project costs and accumulate slowly in the Sustainability Fund. When the fund reaches the required amount to improve a building, the building is improved. This decreases the remaining funds and increases the rate of savings, thereby accelerating the growth in the fund.

Reductions in energy use through conservation creates another reinforcing feedback loop (Fig. 1, loop R2) that generates savings. That loop was modeled based on an extensive literature review. Conservation efforts expend resources to modify facility users'

[1] In system structure diagrams boxes indicate stocks, pipes indicate flows, and arrows indicate the direction of causality. Signs indicate the polarity of causal relationships with "+"meaning both variables move the same direction and "–" meaning a move by the impacted variable that is opposite in direction from the impacting variable. Rienforcing feedback loops (R) amplify effects. Balancing (B) feedback loops generate goal-seeking behavior.

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behaviors to consume less energy. Specific conservation actions (e.g., mailings and electronic reporting of energy use) of three cases from the literature (Carrico and Riemer, 2011; Chen et al., 2012; Handgraaf, Jeude and Appelt, 2013) were selected based on their similarity and applicability to the case study, and whether the literature cases measured energy savings. The modelers estimated costs of implementing the actions described and conservation-maintenance efforts for use as model input (Kim et al., 2012).

The two reinforcing feedback loops in Fig. 1 are connected at the shared components represented by Energy Cost Savings and Sustainability Fund (center of Fig. 1). Theoretically these reinforcing loops create perpetual savings. However, actual systems are often constrained by the physical characteristics of infrastructures and users, creating several balancing loops. First, barring additional efforts, physical improvements for increased efficiency degrade over time, eroding the potential savings they provide (loop B1). Second, without additional support, users forget to conserve over time and uninformed users replace conserving users (loop B2). This requires additional effort to retain conservation benefits. Finally, facility owners often want a portion of energy savings returned to them for uses other than additional sustainability projects (loop B3). This can starve sustainability programs (Loops R1 and R2) of the funds needed for additional sustainability improvement. The model includes these balancing loops, but focuses on the reinforcing loops that drive the sustainability programs.

4.2. The sustainable campus improvement case study

Formulating the formal model required an understanding of the specifics of an energy-based sustainable campus program that adopted the approach described above. The research team focused on such a program at Texas A&M University (TAMU). Data about the case study was collected from TAMU utility records, the TAMU contract with the energy service company (ESCO) (The Texas A&M University System, 2010), the project's Utility Assessment Report, and meetings with representatives of the owner, ESCO, and improvement contractors.

TAMU owns one of the largest higher education campuses in the United States with about 750 buildings on 5200 acres. As part of its ongoing efforts to improve campus sustainability, in 2011 TAMU upgraded over 4 million square feet of 17 facilities; five parking garages (200 K–1000 K square feet each) and 12 teaching and research facilities (about 200 K square feet each). TAMU borrowed the $10 million required for the upgrades at a 2% interest rate from the Texas State Energy Conservation Office (SECO) under the federal American Recovery and Reinvestment Act (State Energy Conservation Office, 2010). Repayment is in ten annual payments. The University entered a guaranteed-performance contract with Siemens, a large ESCO, to perform the upgrades and provide maintenance for ten years (Siemens Industry US, 2011). An ESCO is a company that provides services of evaluation, design, and equipment installation to reduce energy costs over a specific period of time (Dobes, 2013). Similar to other campus sustainability improvement efforts (Koester et al., 2006), the TAMU Utilities Energy Management Department (UEM) led the case study program. That effort primarily improved heating, ventilation, and air conditioning (HVAC) systems, building automation systems, and increased lighting efficiencies. See Kim et al. (2012) for details on the TAMU program.

4.3. The formal simulation model

The conceptual model was first formalized to reflect the TAMU program, including repaying the loan. After the loan is repaid in full and all of the projects are completed, the improved buildings will continue to generate savings by requiring less energy than before the improvements. This "perpetual savings machine" continues as long as the improvements are maintained. Thereafter improvements are assumed to degrade and periodic benefits decline. The degradation of equipment installed as part of efficiency improvements was modeled by reducing the energy efficiency captured linearly over the 20 year average lifespan of equipment (Philibert and Pershing, 2002), starting after the ten years of maintenance required in the ESCO contract.

In the case study and the model, when there are enough funds in the Sustainability Fund to cover the initial cost of energy conservation activities these activities are implemented. The investment increases the variable "% Reduction of energy use due to Conservation Installation." The amount of the saved energy for each building was estimated by multiplying the percent reduction in energy use by the current energy usage. The monetary value of saved energy increases the Sustainability Fund. In the conservation portion of the model, forgetting and user turnover are addressed with a monthly conservation maintenance cost. That cost is withdrawn from the Sustainability Fund, which maintains the original reduction in demand.

In both practice and the model conservation reduces the effectiveness of efficiency efforts and vice versa. The model includes this interaction by applying these impacts sequentially. For example, the combined benefit of a 40% efficiency reduction and a 30% conservation reduction is not 70% (40% + 30%) but 58%, the compliment of the net energy needed (i.e. $1-(1-0.40)\times(1-0.30)$).

The basic model structure described above was replicated 17 times to separately simulate each of the improvement projects in the TAMU program and those performances were aggregated. Other features of the case study program and the contract were included in the formal model, including loan repayment, baseline energy use, predicted energy and cost savings, utility rates, and guaranteed savings. The formal model was calibrated to the TAMU energy efficiency improvement program at both the program (e.g. loan repayment) and building (e.g. energy savings) levels. For example, baseline consumption was measured with data from complete building energy use records for 2009. All forms of energy identified in the case study were converted to Million British Thermal Unit (MMBTU). The predicted annual savings were obtained from the Utility Assessment Report that was prepared by Siemens for TAMU. The formal model and supporting information are available from the authors.

4.4. Model testing

Standard tests for system dynamics models (Sterman, 2000) were used to validate the model. Structural testing included building the model based on descriptions of multiple instances of sustainable campus improvement programs. The model structure closely resembles the HGCI structure and the TAMU case study. However, the model structure extends and deviates from the structure of Harvard University's program to better represent the TAMU program, including the initial funding source. Unit consistency tests and model structure documentation also support the structural validity of the model.

Model behavior tests included extreme conditions testing and behavior pattern similarity tests. Extreme conditions testing reveals whether a model behaves reasonably over a wide range of conditions. A simple example of the results of extreme conditions is that, when the exogenous variable "Incoming Funds" was changed from its calibration value of $10 M to $0 the final size of the Sustainability Fund changed from $12.34 M to $0, indicating that no improvement could be applied to the projects without funding. TAMU's energy efficiency improvement program has not been in

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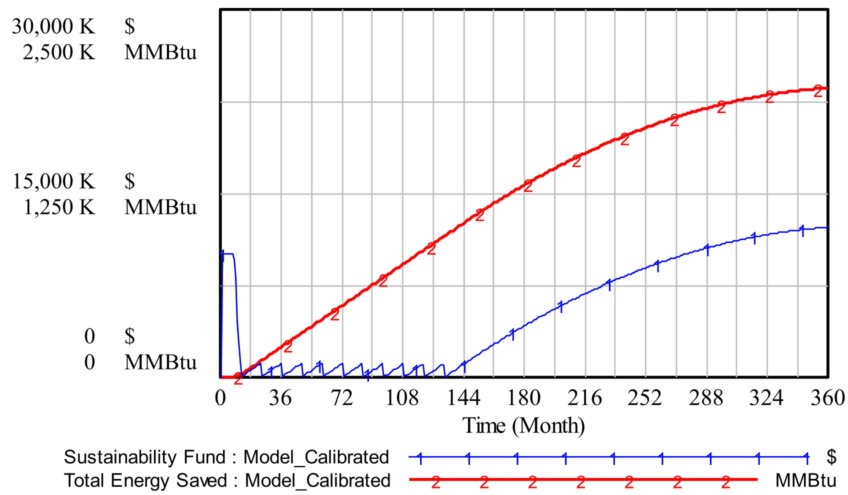

Fig. 2. The behavior of the Sustainability Fund and the Total Energy Saved in the calibrated model.

place long enough to generate useful time series behavior data. However, the program and contract documents provide an adequate basis for predicting typical model behavior modes for behavior validation. Fig. 2 illustrates the results of two behavior pattern similarity tests. Based on the case study description, the Sustainability Fund is expected to increase initially to $10 M when the SECO funds arrive and decrease quickly to near zero as the 17 projects are started within the next five months and completed by month eleven. Energy savings begin to fill the fund as projects are completed, but loan payments and maintenance costs decrease the fund annually over the ten year loan period, creating a saw-tooth behavior mode. Thereafter, savings are expected to increase, but at a decreasing rate as equipment degrades. The shape of the Sustainability Fund behavior for the calibrated model reflects this pattern (Fig. 2, Line 1).

The simulated behavior of the total energy saved (Fig. 2, Line 2) in the calibrated model also represents realistic behavior, reflecting the slow acceleration of energy savings as projects are completed (months 0–12), a linear increase in saved energy while improvements are maintained (months 12–133), and slowing of improvements as improvements decay (months 133–360). Based on these and other structure and behavior tests the model was assessed to be useful for investigating the design of energy-based sustainability improvement programs.

4.5. Sustainability improvement program designs

Five campus sustainability improvement program designs were defined to reveal the relative roles of efficiency, conservation efforts, and feedback in driving behavior and performance. Four of the five designs were selected based on their similarity to designs used in practice (including the TAMU case) and suggested by the literature. One design (D5) was developed by the modelers as a potential solution to the combined low capital requirement and high performance objectives of many campus sustainability improvement programs.

D1. **Efficiency-only Sustainability Program Design:** The first program design is the one used by TAMU. This design includes energy efficiency improvements but no conservation and obtains the total cost of those improvements at the beginning of the program from a loan. Improvements are maintained throughout the 10-year contract with the ESCO.

D2. **Conservation-only Program Design with Maintenance:** The second program design seeks to limit capital requirements but capture significant benefits. It uses only conservation and therefore requires substantially less initial investment than the efficiency-only design (D1), but can potentially generate significant benefits. The design assumes conservation maintenance efforts, and associated costs are used to sustain energy reductions indefinitely.

D3. **Conservation-only Program Design without Maintenance:** The third program design also seeks to limit capital requirements by only using conservation but does not spend funds to maintain benefits. It assumes conservation maintenance and the associated costs stop at the end of the second year; then users are assumed to forget to conserve energy over the next four years, after which there are no conservation benefits.

D4. **Combined Efficiency and Conservation Program Design:** The fourth program design seeks maximum benefits as quickly as possible by combining energy efficiency and conservation in the same program. Similar to the efficiency-only design (D1), this design is initially funded with a loan. It assumes both efficiency and conservation start at the same time and that conservation efforts are maintained.

D5. **Leveraging Conservation to Fund Efficiency Program Design:** The fifth program design is a more innovative approach that seeks to address both the capital constraint problem and capture both efficiency and conservation benefits. This design initially uses only conservation, which generates savings that

Table 1
The capital requirements and performance of the campus sustainability improvement program designs.

Design	Campus sustainability improvement program design	Initial capital required (×1000)	Performance after 360 months	
			Sustainability fund (×1000)	Energy saved (MMBtu) (×1000)
D1	Efficiency-only	$6743	$14,255	1141
D2	Conservation-only with maintenance	**$27**	$13,271	668
D3	Conservation-only without maintenance	**$27**	$1161	87
D4	Efficiency and Conservation (simultaneously)	$6770	$25,988	**1729**
D5	Conservation Used to Fund Efficiency	**$27**	**$27,989**	1613

are accumulated and used to incrementally fund efficiency improvements. As in the first design, efficiency improvements are assumed to be maintained during the program and then allowed to deteriorate. Like the second design, conservation efforts are maintained.

5. Results

The performance of each design as simulated with the formal model are presented in this section, followed by the results of testing the hypotheses using those results and a feedback analysis based on the model structure. Table 1 summarizes the initial capital requirements and final performance of the designs as the basis for hypothesis testing and evaluation. The lowest initial capital requirement and best performances are shown in bold.

The design that used conservation to fund efficiency (D5) generated the largest sustainability fund ($27,989 K). The combined efficiency and conservation (simultaneous) design (D4) saved the most energy (1729 K MMBtu). The designs that started with only conservation (D2, D3, and D5) had the lowest capital requirements ($27 K). Therefore none of the five designs was dominant, creating a tradeoff space for program designers. This result supports hypothesis 1, that no single campus sustainability improvement program design dominates.[2]

Comparing the low investment designs D2 and D3 to the high-investment designs D1 and D4 revealed that the final size of the Sustainability Fund was *higher* in the high-investment designs in all four pair-wise comparisons by an average of $12,905 K. In contrast, comparing the low investment design D5 to the same two high-investment designs (D1 and D4) revealed that the final sizes of the sustainability funds of the two high-investment designs were *lower* by an average of $7,867 K. These results partially support hypothesis 2, that increasing the initial investment increases the final size of the sustainability fund. This result is explained in the next section.

When the energy saved using the three low-investment designs (D2, D3, and D5) was compared to the energy saved using the two high-investment designs (D1 and D4) the amount of energy saved was larger in the high-investment designs in all six pair-wise comparisons by an average of 646 K MMBtu. This result supports hypothesis 3, that increasing the initial investment increases the amount of energy saved.

The design that used conservation to fund efficiency (D5) came close to dominating the other four designs. It generated the largest sustainability fund and saved only 7% less than the most energy-saving design (D4). Design D5 did this by delaying efficiency improvements until conservation efforts generated the required funds. This delay temporarily keeps the efficiency-based reinforcing feedback loop relatively weak, thereby limiting the amount of investment required. This purposeful use of a delay in activating the strong efficiency loop eventually captures benefits from both efforts with little capital. The shift in feedback loop dominance from conservation (Fig. 1, R2) to efficiency (Fig. 1, R1) creates a worse-before-better behavior mode in which owners can capture large savings in the distant future with little capital, but only if they are willing to accept no monetary savings in the near future. This design is particularly effective (large benefits) and efficient (low investment requirements) because it uses the (low investment) conservation-based reinforcing loop to activate the (high benefits) efficiency-based reinforcing loop. This design supports hypothesis 4, that a less expensive effort (conservation) that funds a more effective effort (efficiency) can generate the best combined investment and performance. Such an exploitation of the best characteristics of each reinforcing loop, i.e., the low capital requirements of the conservation loop and the large benefits of the efficiency loop, can only happen if designers understand the roles of feedback and delays in controlling the dominance of the system's feedback loops. This demonstrates how understanding the system's feedback structure and shifts in feedback loop dominance can improve sustainability improvement program design.

In summary, hypothesis 1 (no dominant design) is supported, hypothesis 2 (increased sustainability fund with investment) is partially supported, hypothesis 3 (increased energy saving with investment) is supported, and hypothesis 4 (leveraging conservation to fund efficiency) is supported. Feedback analysis is used next to explain these results.

5.1. Insights through feedback analysis

In addition to the results in Table 1, the behaviors of program designs over time reveal important advantages and disadvantages of individual designs that can best be explained with the feedback structure of the system. For example, in the efficiency-only design (D1) energy use reductions are immediate and significant (Fig. 3, line 1) because the efficiency reinforcing loop (Fig. 1, R1) quickly becomes and stays dominant. However, the sustained growth in monetary benefits is delayed due to the use of savings to repay the loan (Fig. 4, line 1). This is because the loan portion of the model structure impacts the monetary part of the same reinforcing loop. Owners must have access to capital to activate feedback loop R1 and use this design, but they must also be able to get energy improvement results quickly.

The conservation-only designs (D2 and D3) generate both types of benefits immediately due to the dominance of the conservation reinforcing loop (Fig. 1, R2). However, benefit increases fade if users forget and revert to their pre-program energy-intensive ways (Figs. 3 and 4, Lines 3). Including conservation maintenance efforts (Figs. 3 and 4, Lines 2) increases both energy savings and the sustainability fund over time. This result suggests that energy conservation program design should include incentives to continue conservation practices. The efficiency-only design increases monetary benefits faster than the conservation-based designs, but only after a significant delay (10 years). This illustrates that their relative performance depends on the delay in efficiency design's monetary benefits due to the need to pay for the relatively expensive physical upgrades.

In the combined simultaneous design (D4), the monetary benefits of both efficiency and conservation are captured faster (Figs. 3 and 4, Lines 4) but require the most initial capital. This demonstrates that having both reinforcing loops drive performance is better for reducing energy use than either loop working alone, but this design is also more expensive.

The behavior modes and feedback analysis show that the design preferred by specific program planners will depend on their measures of success. For example, program planners that require accumulated monetary savings early in the program will prefer conservation-only with maintenance (D2). However, program planners that value energy savings most will prefer the use of efficiency and conservation simultaneously (D4) even though it requires access to significant capital. The attractiveness of specific designs may also be determined by the need for early completion of improvements to the built infrastructure (Fig. 4, Lines 1 and 4) versus the willingness to wait for benefits (e.g., Fig. 4, line 5) or limitations on access to capital, and other objectives.

[2] Design D5 is close to being dominant, but may still be unattractive to designers for reasons described later.

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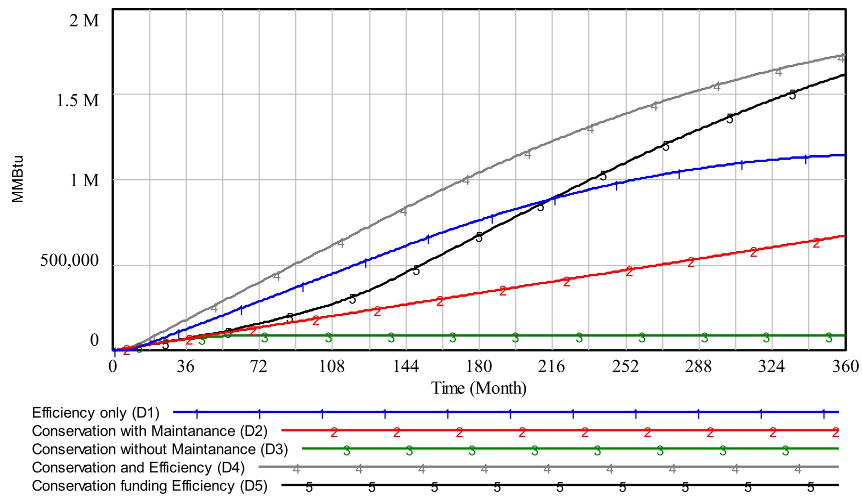

Fig. 3. The behavior of the Total Energy Saved using five campus sustainability improvement program designs.

6. Conclusions

The current work developed a system dynamics model of energy-based sustainability improvement programs that save energy and thereby generate monetary savings. Energy efficiency improvements to built infrastructure and energy conservation by facility users were also included. Model validation based on a sustainability program at a major US university and the literature indicate that the model is useful for investigating sustainability program designs to reduce energy requirements and generate monetary savings. Five program designs were simulated: efficiency improvement only, conservation only (with and without maintenance), both efficiency and conservation simultaneously, and using conservation efforts to fund efficiency improvements. Simulations tested hypotheses about the impacts of the relative sizes of benefits and initial investment and the effect of exploiting delayed loop dominance.

The current work finds that both efficiency and conservation save significant amounts of energy and money, but conservation requires maintenance to perpetuate energy saving practices. Energy and monetary savings from efficiency improvements grow faster than conservation efforts in most circumstances but require more capital. The amount of money saved is driven by whether the efficiency-based or conservation-based reinforcing feedback loop dominates system behavior and on when that dominance occurs. In some circumstances monetary savings are also strongly influenced by the need to use savings to repay loans for improvements. Using monetary savings from conservation to fund efficiency improvements can help overcome capital constraints, but this design delays capturing efficiency savings. After the repayment delay has passed the combined savings grow quickly and exceed those that would have been captured with an efficiency-only or conservation-only design.

Program design selection depends on the objectives and constraints of the owner and operator. For example, a need to quickly demonstrate energy saving improvement recommends efficiency improvements or both efficiency and conservation improvements simultaneously. In contrast, strict capital constraints recommend conservation efforts. Program performance is also dependent on the users and facilities. For example, conservation efforts will be more effective in some populations (e.g., students majoring in environmental domains) and facilities (e.g., high traffic laboratories) than others. High turnover of users (e.g., dormitories) will require more frequent education and maintenance efforts, generating increased costs. Newer facilities may already use more efficient equipment, limiting the potential benefits of efficiency

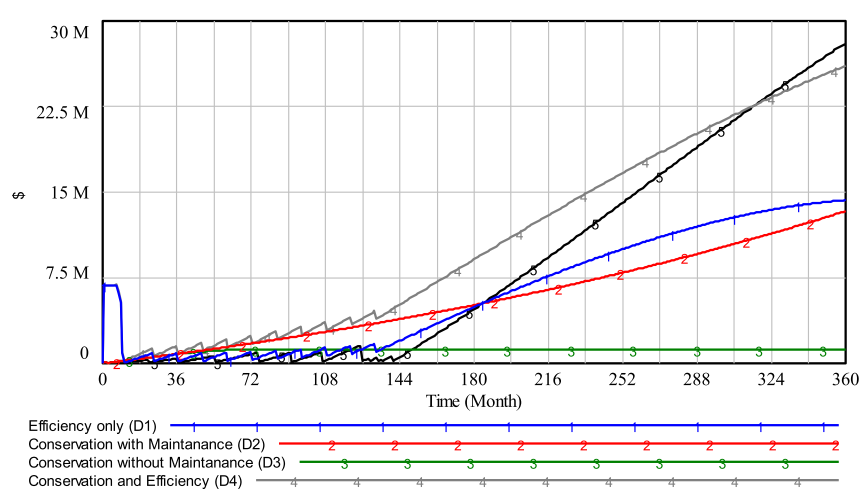

Fig. 4. The behavior of the Sustainability Fund using five campus sustainability improvement program designs.

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improvement efforts. These factors are among those that should be incorporated into specific program designs.

The current work contributes to the science of designing sustainability improvement programs by expanding the understanding of what makes campus sustainability improvement programs more or less successful. In addition, the work provides a model of interacting efficiency and conservation efforts in a sustainability improvement program. This model provides a validated tool that can be used for developing additional insights about sustainability programs and for program design. This model includes structures that reflect the habits and behaviors of facility users and how they may change in response to efforts to modify their behaviors. The improved understanding of sustainability programs and their feedback structures potentially improves their design and increases the energy and monetary benefits they generate.

In addition to the application of the program designs investigated here, additional case studies can further validate the model structure and expand the structure to include other sustainability program features and characteristics. These expansions can address other efficiency improvements (e.g., glazing films, architectural redesign), conservation (e.g., behaviors of specific populations), the interaction of sustainability improvement efforts, or the impacts of external factors (e.g., dynamic energy prices). This can lead to a more detailed understanding of the impacts of specific characteristics and to recommendations on the design of programs for specific sets of facilities and types of users and owners. Such efforts will further expand the understanding of energy-based campus sustainability improvement programs and thereby their performance.

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Appendix 1. The Harvard Green Campus Initiative

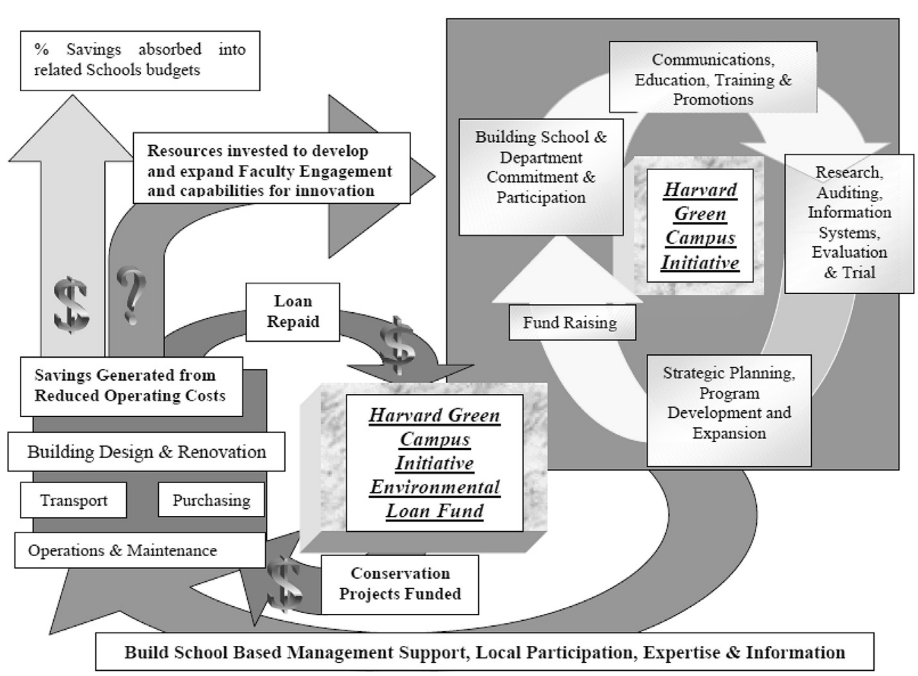

Figure A1. The Harvard Green Campus Initiative (Sharp, 2002)

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