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Exploiting design thinking to improve energy efficiency of buildings

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ABSTRACT

This paper studies an interdisciplinary approach for improving building energy efficiency. In particular, the proposed approach integrates design innovation (DI) techniques, existing energy audit methods (EAM), and data-driven & engineering modeling techniques (DET) in the process of sustainable smart energy system design. From this perspective, DI methods are extended and modified to suit the content of sustainable smart energy system design and a DI 4D (Discover, Define, Develop and Deliver) framework is introduced to guide the design process. The motivation behind and the implementation procedure of each of the DI phases is explained separately, and the process of integrating DI methods, EAM and DET in developing a sustainable smart energy system is demonstrated. The proposed approach is deployed within the campus of a tertiary education institution to show its effectiveness in designing a smart sustainable energy system.

1. Introduction

Buildings are responsible for the majority of electricity consumption of a country. In the United States of America, for example, 40% of the total electricity consumption is due to buildings [1]. As a consequence and due to increasing concerns about environmental sustainability and climate change, there has been a significant push towards developing means for increasing energy efficiency of buildings [2–4]. In fact, a large number of studies have been conducted recently to develop solutions focusing on electricity usage of buildings. These studies can generally be classified into three categories.

The first category of studies develop solutions that automatically schedule the operation of different appliances within a building in order to improve energy efficiency[1] and to reduce electricity cost. Examples of such studies include [5–9]. The second category of studies, such as [10–15], exclusively focus on the control of air-conditioning (AC) and lighting systems of a building. These studies explore both mathematical and experimental techniques to demonstrate the control of electricity consumption of ACs and lights without compromising the user comfort significantly. The final category of studies emphasizes the benefit of using renewable energy sources such as solar photovoltaic [16], solar thermal [17], and energy storage devices [18] for enabling efficient use of electricity within a building.

Nonetheless, it is also critical that the technology integrates with the user experience and positively affects the users' electricity consumption behavior according to the provided guideline by the solutions. Otherwise, smart energy solutions and trading mechanisms may potentially become obsolete in the long run [19]. To this end, this paper introduces a design innovation (DI) approach that integrates user empathy and desirability, and takes into consideration design thinking techniques to design a sustainable smart energy system for buildings by making following contributions:

- A 4D (Discover, Define, Develop and Deliver) DI framework is proposed in order to guide the design of the smart energy system.
- The motivation and the implementation procedure of each of the 4D phases are explained separately, and the process of integrating DI methods in developing sustainable smart energy system is demonstrated.

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[1] We have used both energy efficiency and conservation to refer to energy performance improvement in the manuscript.

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- The proposed approach is deployed within the campus of a tertiary education institute, and the results show that the designed process is effective for sustainable smart energy system design.

We stress that there a number of energy audit techniques available in the market such as in Refs. [20,21], and [22] to improve building energy efficiency. However, there are two drawbacks in the existing energy audit procedure:

- Existing energy audit approaches of commercial buildings mainly focus on the building owners' needs, i.e. reduction of the building energy consumption and cost benefits to the owners. However, there are various types of users/stakeholders in a building, e.g. building owner, facility manager and operators, and different types of occupants. Different users have different needs and usage patterns. In the existing energy audit process, only simple occupant surveys are conducted to discover user needs. Therefore, the needs of occupants are usually not well addressed. The lack of proper consideration of users' needs during energy audit may lead to energy wastage which is contrary to the aim of the energy audit.
- The procedure of the existing energy audit approach is relatively standardized, and energy audit professionals usually refer to Energy Conservation Measures (ECMs) checklists to determine opportunities and solutions for energy savings. Therefore, many potential energy saving opportunities may be overlooked, and innovative solutions are not generated in the process.

Given this context, this paper aims to propose an interdisciplinary approach to improve the general energy audit process by integrating, adapting, and extending Design Innovation techniques to identify more energy saving opportunities beyond the existing energy audit checklists. In particular, the 4D DI framework in designing the audit and solution development, as proposed in this paper, transforms the approach to be user-centered and focuses on people the technology/service is created for, which leads to better products, services, and internal processes.

2. Design innovation: theory and practice

DI is a human-centered and interdisciplinary approach to innovate and address complex systems challenges in our world. It integrates design thinking, business process design, design engineering, and systems engineering [23–25] To extend traditional comprehensive energy audit technique, the adopted DI approach in this study comprises four phases including Discover, Define, Develop, and Deliver (4D). An overview of different phases of the DI technique and their interpretations is shown in Fig. 1.

Each phase of DI, as shown in Fig. 2, consists of a number of tools to meet the minimal, standard or extended requirement of the design [25]. As such, what follows is a detail discussion of the proposed 4D framework and DI methods. To elaborate some of the methods, we provide examples from the perspective of an energy system. It is important to note that although all the methods and techniques described below are effective, it is not always necessary to include all of them in every application of the 4D process. The methods and techniques should be selected, tailored and customized based on the problem to solve and the progress of the studies. A summary of the functions of each method is shown in Table 1.

2.1. Discover

The Discover phase identifies and understands opportunities and needs collaboratively through co-creation with stakeholders.

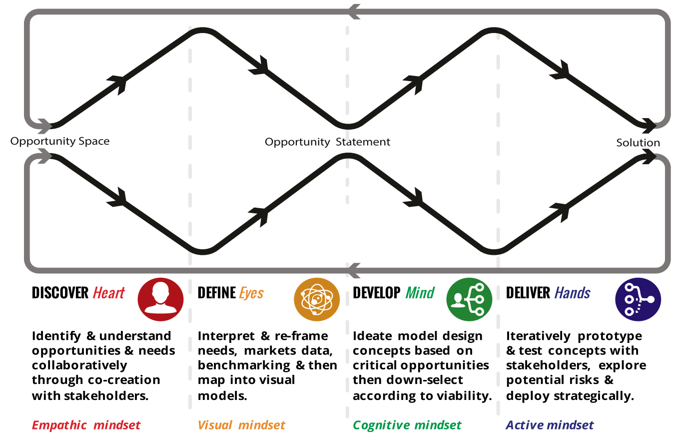

Fig. 1. Design Innovation Process/Sprint: this figure demonstrates the functionalities of different phases of the proposed DI process.

Discover	Define	Develop	Deliver	
Tools				
CN Analysis Contextual Needs Journey Mapping	Mission Statement Black Box Activity Diagram Affinity Analysis	C-Sketch Design by Analogy Word Tree Mindmapping	Prototyping User-Validation Scaled Prototypes Iterative Prototypes	Minimal
Likes/Dislikes Multisensory Analysis Articulated Use Surveys	Personas Functional Modeling Workflow Benchmarking	Bio-Inspired Brainstorming Co-Creation Morphological Matrix SCAMPER	Isolated Subsystem Mock-ups Parallel Testing Requirement Relaxation Design of Experiment Testing (Spiral Plan)	Standard
Site Analysis Lead User Scenarios Focus Group Empathic Lead User	Specifications Sheet Want/Needs Requirements Document Background Research	Pugh Chart TRIZ Storyboarding Deep-dives	Paper prototyping	Extended

Fig. 2. Demonstration of the tools used at different phases of DI process.

For this purpose, the key data collection methods include data collection before site visit, detailed end-use measurement, user studies and user need analysis.

2.1.1. Building and system data collection

One of the earliest steps of smart energy design is to collect building and system information including architectural, mechanical, and electrical drawings; utility bills; HVAC, lighting, and other equipment specifications; occupancy types; and building usage. This information is useful for zoning of the building, identifying areas of visit, calculating Energy Use Intensity (EUI) and benchmarking. Further, it contributes to many other methods in the 4D process, such as detailed end-use measurement and environment monitoring, C-sketch, and lead user test.

2.1.2. Detailed end-use measurement and environment monitoring

Some information is more dynamic and difficult to obtain, e.g., schedules of lights, plug loads, HVAC and occupancy. Wireless Sensor Networks (WSNs) provide a more cost effective solution to monitor building environment by collecting and transmitting data in real-time. Various kinds of information can be collected by WSN including temperature, relative humidity, illumination, occupancy, and power consumption. In this study, we use a multiple sensor node consisting of a relative humidity sensor, a temperature sensor, a lux sensor, a motion sensor and a noise sensor. It is also equipped with a communication module to send data to a local server in real-time.

2.1.3. User study and user need analysis

Understanding the needs to the users and stakeholders on the specific issue plays a significant role in discovering the challenge elaborately. For example, there could be different types of users and

Table 1
Function of each method.

Phase	Method	Category	Function
Discover	Building and system data collection	EAM	Collect basic building information; facilitate further discover, define, develop and deliver
	Detailed end-use measurement and environment monitoring	EAM	Discover existing building energy usage and ambient environment condition
	User studies and user need analysis (semantic enquiry, scenarios, interviews, user journey map, card rating exercise, etc.)	DI	Discover user needs, preferences, pain points and behaviours
Define	Building and utility data analysis	EAM	Define usage pattern of the building and systems
	Building energy modeling	EAM	Set baseline energy consumption
	Persona	DI	Map user behavior pattern into archetypal profiles, allowing focused study on the user
	User activity diagram	DI	Identify user behaviors which cause energy wastage
	Affinity analysis	DI	Organize or achieve 'sense-making' from a large set of needs or design concepts.
	Hierarchy of purpose	DI	Help to scope a design problem statement
	Behavior-based framework	DI	Elicit underlying causes of termed energy overuse failure modes
	Functional structure	DI	Define functions of smart energy systems
Develop	ECM checklist	EAM	Identify existing solutions
	Ideation (Mind mapping, C-Sketch, Desing by analogy)	DI	Ideate, synthesize, and combine novel model design concepts
	Real? Win? Worth it?	DI	Down-select design concepts
	Motivational psychology	DI	Serve as a potential concept to motivate users to participate in smart energy system
	Data-driven techniques	DET	Serve as a potential concept for smart energy system
	Building energy modeling	DET	Serve as a potential concept for smart energy system
Deliver	Building Energy simulations	EAM	Evaluate the energy performance of solutions
	Cost benefit analysis	EAM	Evaluate the cost effectiveness of solutions
	Mockup	DI	Emulate the function or form of a design for communication and to prototype interaction
	Lead user test	DI	Iteratively prototype and test concepts with users

DI - Design Innovation; EAM - Energy Audit Mechanism; DET - Data Driven and Engineering Modeling Techniques.

stakeholders need based on how clearly they can be expressed by the users and stakeholders and how fast they may change over time. Example of such needs include direct needs, latent needs, constant needs, variable need, general needs, and niche needs, which can be analyzed by following methods:

2.1.3.1. Semantic inquiry

Semantic inquiry [26] is geared towards discovering the desired emotion, experience, appearance, and usefulness of the building. To implement semantic inquiry, the energy innovation team (EINTM) first brainstorms and ideates descriptive words related to user needs in a building and forms pairs of adjectives that are of extreme ends. They let the users rank 1 to 5 on how they feel about the building with regards to the chosen adjectives. An example of semantic inquiry form is shown in Table 2 to discover occupants' experience of thermal comfort, visual comfort, acoustic comfort, air quality, and access to nature.

2.1.3.2. Scenarios

EINTM first ideate possible scenarios that may evoke critical latent needs and prepare and present scenario cards to users while they are engaged with the building and systems to learn their reactions. The findings from these scenarios may give insights on user needs and the severity of unsatisfactory building systems.

2.1.3.3. Interviews

There are three effective approaches for conducting interviews in DI process [26]:

- *Like/dislike method:* To discover latent needs, EINTM interviews users as they are in their usual locations in the building and ask what they like and dislike about the building and why. The interviewer also ask about how the user wants to improve the current building or system.
- *Articulated-use method:* The users are asked to walk the interviewer through their use of the building and systems.
- *Contextual needs analysis:* To obtain and understand the users' needs on every step of interacting with the building, the users are asked target questions to elicit important context.

2.1.3.4. User journey map

A user journey map is a visual or graphic interpretation of the overall story from an individual's perspective of their relationship

Table 2
Example of a semantic inquiry form.

	Extreme Left						Extreme Right
Thermal comfort	Cold	○	○	○	○	○	Hot
	Windless	○	○	○	○	○	Windy
	Low Radiant Heat	○	○	○	○	○	High Radiant Heat
Visual Comfort	Dark	○	○	○	○	○	Bright
	Even	○	○	○	○	○	Uneven
Acoustic Comfort	Quiet	○	○	○	○	○	Noisy
Air Quality	Fresh	○	○	○	○	○	Stale
	Dry	○	○	○	○	○	Humid
	Clean	○	○	○	○	○	Polluted
Access to Nature	Natural	○	○	○	○	○	Artificial

with the building and systems over time and across channels. To create a user journey, EINTM shadows a user through a specific activity and record their action and reaction [27] to identify touch points, channels and emotions.

2.1.3.5. Card rating exercise

Card rating exercise is a conjoint analysis tool [28] that elicits and explores preferences of users through their revealed (observed) behavior or through experimental procedures. The card rating exercise starts with identifying the set of product attributes presented to the users for decision making. This can be done by using previous studies, expert opinion, or conducting a primary research study. Examples of the cards are shown in Fig. 3.

2.2. Define

The objective of the Define phase is to interpret and re-frame user needs and building data, and then map them into visual models. The methods utilized for this purpose include persona, user activity diagram, hierarchy of purpose, behavior-based framework, and system functional modeling.

2.2.1. Personas

Personas map user behavior pattern into archetypal profiles, allowing focused study on the user. To create a persona, the EINTM gather information from interviews ans/or other forms of data collection. Based on collected data, behavior patterns that show commonalities of certain users are consolidated. Then, personas are presented with details including name, stock photograph (to protect identity), personifying vignette and characteristic needs.

2.2.2. User activity diagram

A user activity diagram is a block diagram of sequential and parallel activities that captures user interactions with a product, service or system [26]. In energy audit, the user interactions with the audited building and systems should be observed and recorded each step in an individual activity block using post-it or digital form. The activities are then connected in a single block diagram with directed arrows.

2.2.3. Hierarchy of Purpose

The hierarchy of purpose assists the team consider root causes and to re-write the problem statement in a quantitative way. The core problem statement is written in a given format. Then, higher and lower abstraction problems are identified [26]. For example, the original statement is “To reduce air-conditioner operating time by 30%“. A higher abstraction of this statement would be “To reduce the electricity consumption of air-conditioner by 50%“, and a lower abstraction would be “To switch off air-conditioner 1 h in advance”.

2.2.4. Behavior-based framework

A behavior-based framework [29] is used to elicit underlying causes of termed energy overuse failure modes (EOFMs): high energy consuming habits and lack of energy awareness. The procedure is to identify all the possible process paths for the given activity, and identify the minimum energy consuming path and other more energy consuming paths. Then define the energy overuse level using the minimum path as a benchmark and conduct a two phase behavior study with an intervention and formulate user behavior categorization matrices as shown in Fig. 4. The EOFMs and proposed interventions can then be prioritized based on the likelihood of occurrence, severity, magnitude or a combinatorial strategy to suit the sustainability objectives.

2.2.5. System functional modeling

Based on the data collected in the Discover phase, usage patterns of the building and systems can be identified. An example is shown in Fig. 5.

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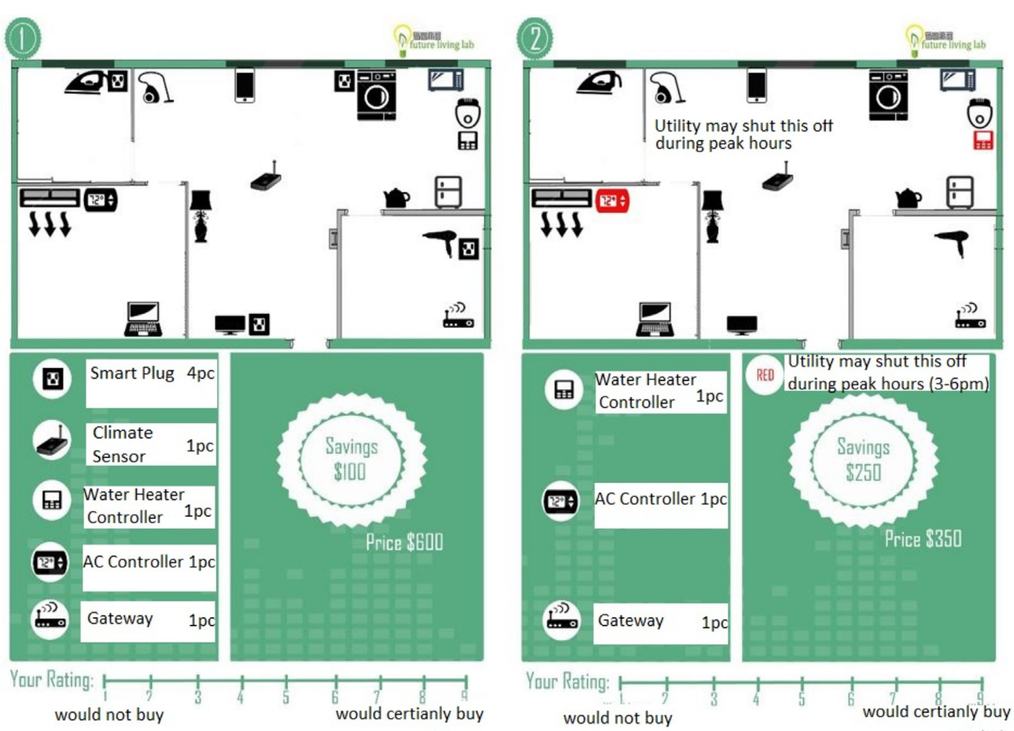


Fig. 3. Demonstration of sample cards.

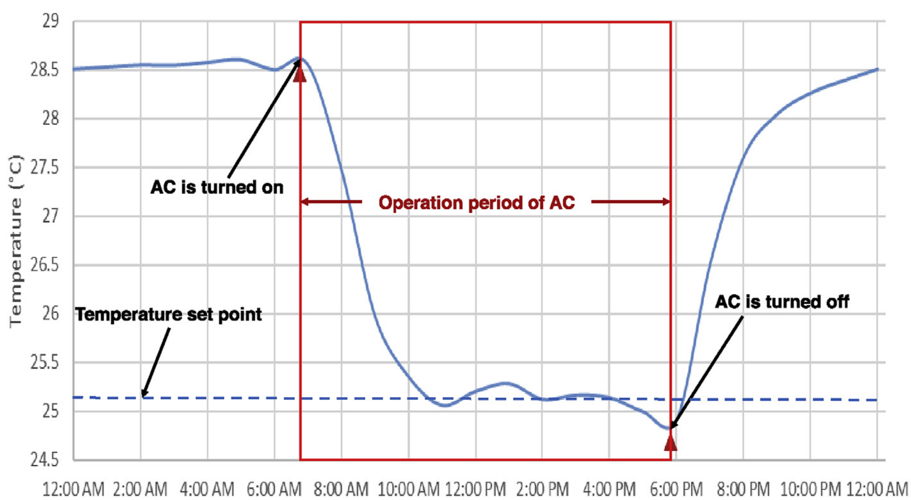
	Correct behaviour	Wrong behaviour
Changed	**Knows but does not do** *Spur and Steer* *Control: Product and User*	**Misconceptions or guesses** *Behavioural strategies* *Control: User*
Unchanged	**Good, knows and does it**	**Missed opportunities** *Increase knowledge and create attention* *Control: User and product*

Fig. 4. User behavior categorization matrix.

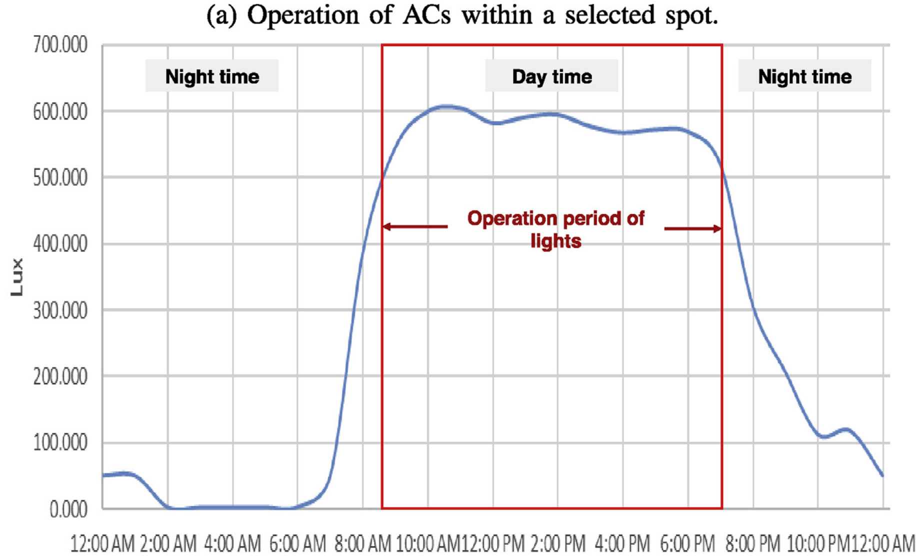
in 5.

- Fig. 5 (a): The average temperature of the selected office space (the data is averaged over 5 working days) is around 28.5°C during night and drops to around 25.2°C during day (office period). Further, the AC is switched on at around 7 a.m. each day and terminates its operation at 6 p.m.
- Fig. 5 (b): The illumination is about 580 lux during the day and it drops to 0 – 120 lux at night. The lux level gradually increases in the morning and decreases at night because the lighting time varies each day.

Based on the available information of operational pattern of equipment within the space and the people occupancy pattern in those space, the reason behind the energy wastage can be determined. This can further be used to develop energy conservation measures. For example, in Fig. 6, we show the usage of lights in a selected office room. The office is occupied by two people. A motion sensor and a noise sensor were deployed in the office to detect human presence. The room was considered to be occupied if either of the two sensors indicates human presence. Now, as shown in Fig. 6, during a working day, the light was switched on from 7:15 to 18:51. However, it was occupied only for 61% of this time period. That is, the occupants did not switch off the lights when they left the office during office hours, which resulted in energy wastage in the lighting system.



(a) Operation of ACs within a selected spot.



(b) Operation of lights within a selected spot.

Fig. 5. Demonstrating the operational schedule of ACs and lights in some selected spot for building and utility data analysis.

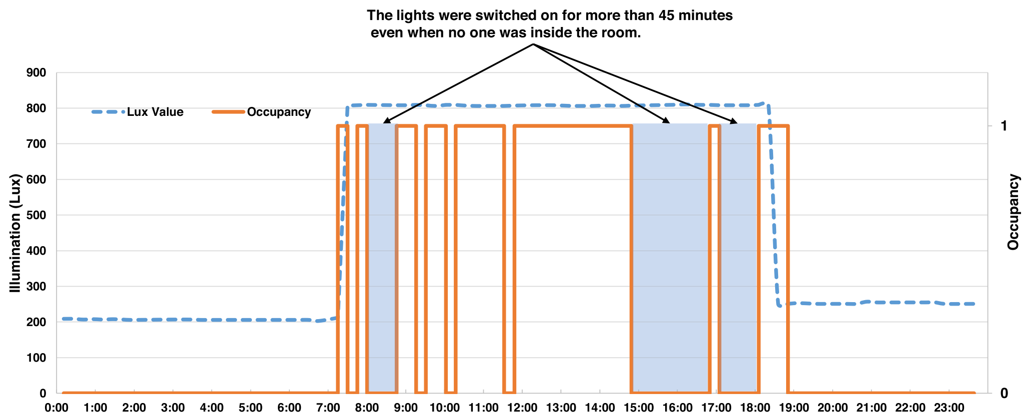


Fig. 6. This figure demonstrates a scenario, in which the lights in a selected office room was switched on even when there was no occupant within the office.

Similarly, Fig. 7 shows the room temperature and occupancy during a weekday. Based on this figure, When the occupant left the room at arount 19:00, the room's temperature was still within the comfortable range. It took more than 2 h for the room temperature to reach beyond 26°C. For some period of time, e.g., around 14:50 to 16:50, the room was empty although the AC was still operating.

2.3. Develop

The purpose of the Develop phase is to ideate, synthesize, and combine novel model design concepts based on critical opportunities and then down-select according to viability and other factors. Selected ideation methods, engineering tools and techniques, and concept filtering method in the Develop phase are explained below.

2.3.1. Ideation

Ideation is essentially a creative process of generating, developing, and communicating new ideas, where an idea is understood as a basic element of thought that can be either visual, concrete, or abstract. Three effective ideation methods are shown below.

a) Mind mapping: Mind-mapping is an ideation method that is analogous to human memory. Ideas are organized in a hierarchical structure with individual ideas under categories which in turn map to a topic [30]. For example, a mind-map is created, as shown in Fig. 8, for the design problem: *To reduce energy wastage caused by 90% in residential buildings.* There are many useful and effective online mind-mapping tools, such as Mindmup [31] and Coggle [32].
b) C-Sketch: C-Sketch is a graphical, team-based ideation technique for generating refined solutions to design problems and opportunities [33,34]. The process centers on the concept of parallel sketching by each team member, and revision after passing to the next member. For example, to solve the problem of decreasing lighting energy wastage by 70%, the drawings of the original and first pass are shown in Fig. 9. During the process, team members may find it difficult to understand other people's ideas. However, they should not ask the owner about the ideas but interpret the ideas on their own. Through this way, new ideas may be inspired and created.
c) Design by analogy: Design by analogy is a process of transferring solutions across different design domains. The process begins by abstracting the core functionality of the problem then using any of several techniques to search for related solutions based on search terms or data-mining. The techniques include AskNature [35], WorldTree [36], and TRIZ [37].

2.3.2. Tools and techniques

Three useful tools and techniques that we use for developing smart energy systems for buildings are described below.

a) Motivational psychology: We utilize the motivational psychology to design an energy management mechanism for

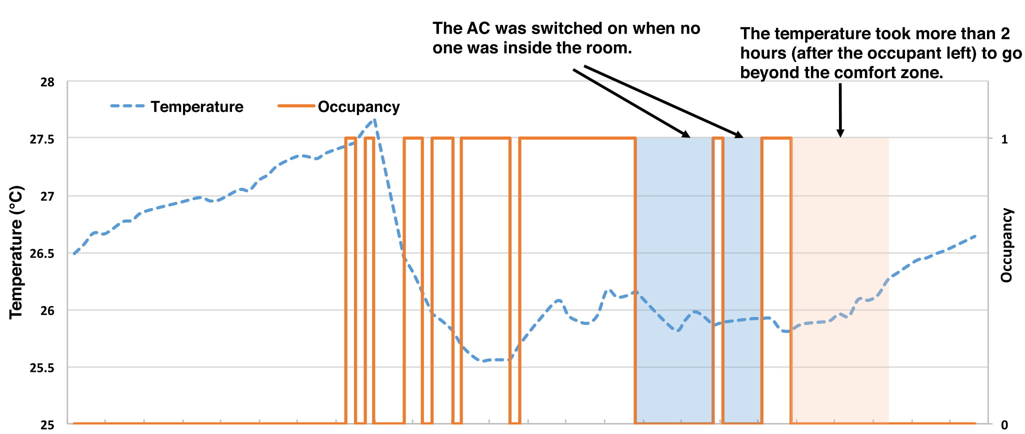


Fig. 7. This figure demonstrates a scenario, in which the opeation of an AC in a selected office room is correlated with the room occupancy.

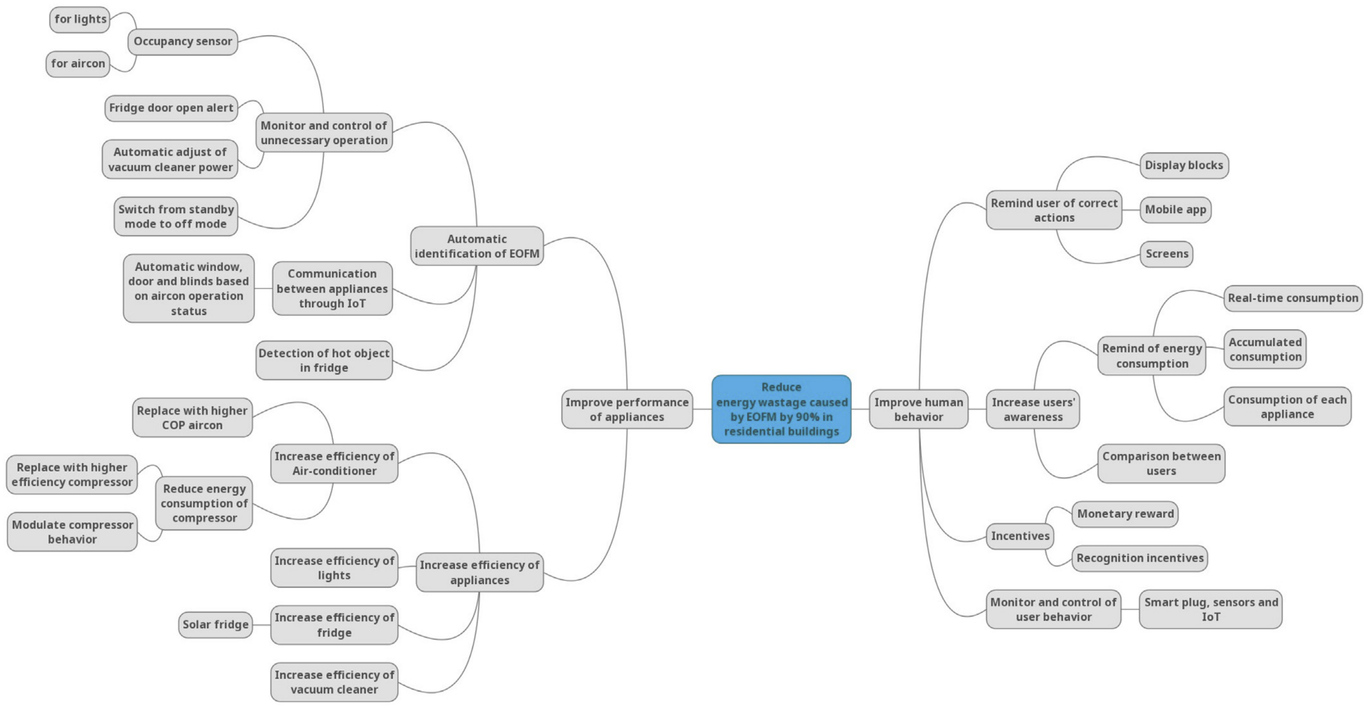


Fig. 8. Mind map of Case Study 1.

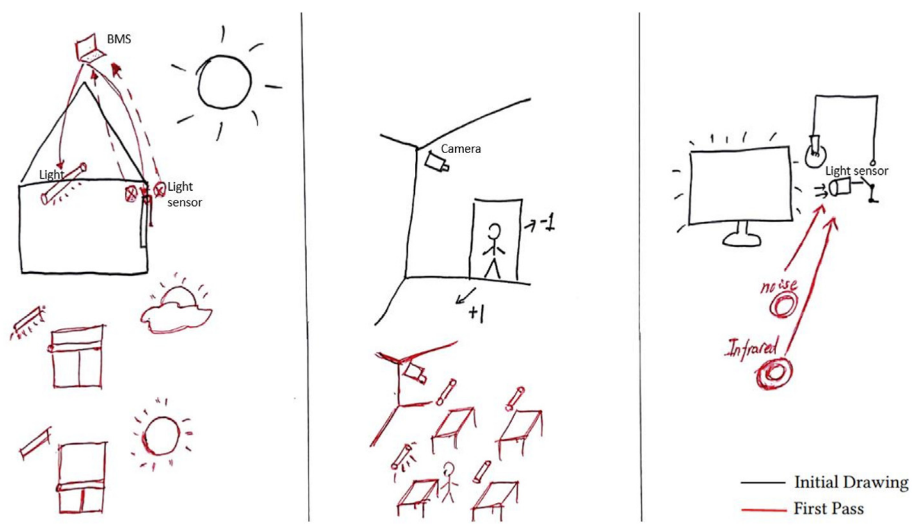


Fig. 9. C-sketch example.

buildings that encourage users' acceptance of the technology for increased environmental sustainability [38]. In order to motivate people to accept a technology, there exist a number of models that the technology needs to satisfy. Examples of such technologies include attitude model, rational-economic model, information model, elaboration likelihood model and positive reinforcement model. Thus, to use motivational psychology to attract people to accept or use a technology, the technology is developed in such a way that its outcomes satisfy the appropriate motivational models and fulfil some criteria that convinced a user to accept it and continue to use it. The motivational models are developed keeping these users behavior in mind, and therefore we find it suitable to use such models to design the energy management scheme for buildings.

b) Data driven techniques: Data driven approach is used to exploit data of a given subject to understand its behavioral pattern, for example, energy usage pattern, identify opportunities to improve energy usage behavior and then take necessary actions. Using data driven approach, more informed decision can be taken on managing energy within a building. In particular, data driven approach provide flexibility to opportunistically control appliances of a house in such a way that it does not compromise the users comfort or day-to-day activities, while, at the same time, reduce the energy usage of the house.

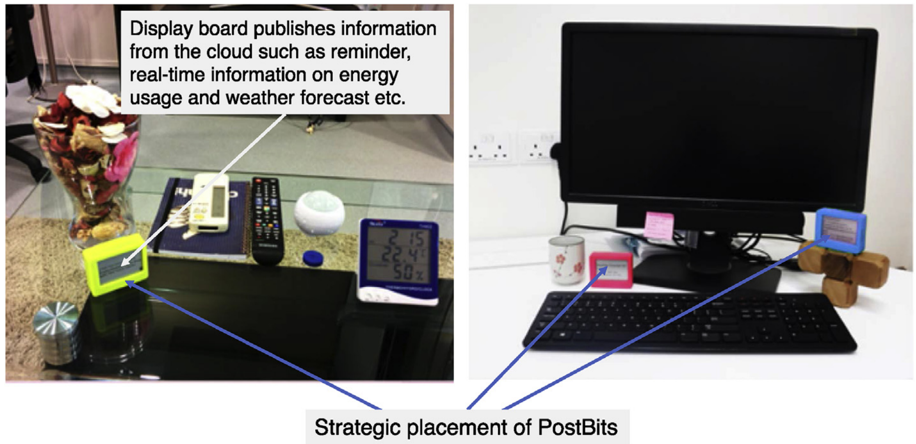


Fig. 10. Demonstration of the application that has been developed to monitor and control the lights and plug loads at IDC space in real time.

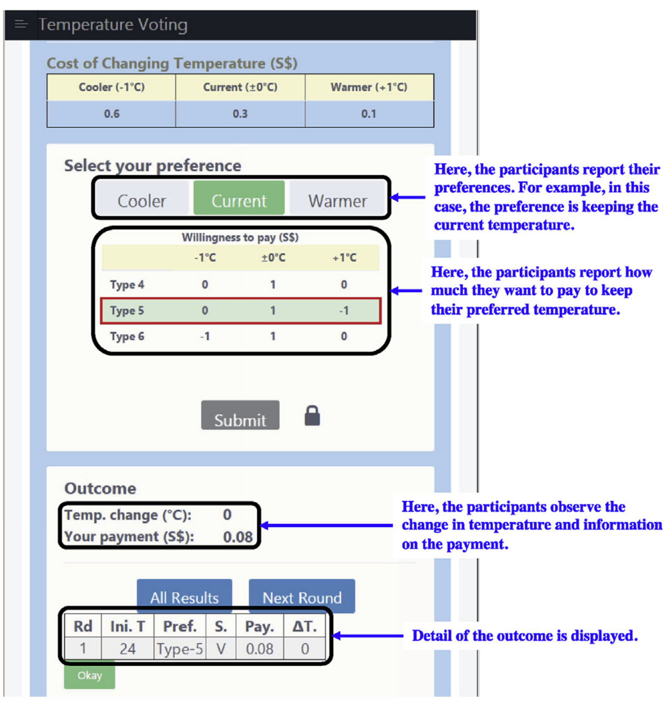


Fig. 11. Demonstration of a user-interactive smart energy interface that was prototyped via lead user test.

c) Building energy modeling: Building energy modeling can be used to evaluate the energy efficiency of potential solutions. The data obtained in the Discover phase is required as input to create a building energy model. The simulation engine performs thermodynamic simulation and building system simulations. The energy consumption and indoor environmental condition is generated as outputs of the simulation. There are many building energy simulation software available. The most commonly used two software programs are eQuest [39] and EnergyPlus [40].
d) "Real? Win? Worth it?": "Real? Win? Worth it?" is a strategy to manage risk and reward. For each concept, the energy audit team asks the questions, Is it real? Can it win? Is it worth doing? To select highly valuable and feasible concepts for further refinement [41,42]. For example, to reduce energy wastage by lighting system one solution is to ask facility manager to inspect lighting status. This solution is real but neither win nor worth it. Another solution is to install occupancy sensors for lighting control. This solution is real and worth it, but it does not win because office workers find it disturbing when motion sensors failed to detect their existence and lights are turned off.

2.4. Deliver

The purpose of the Deliver phase is to iteratively prototype and test concepts with stakeholders, explore potential risks, and deploy strategically. It also includes the architecting, embodiment, detailed design, and sustainable implementation of smart energy systems.

2.4.1. Mockup

The purpose of mockup is to emulate the function or form of a design. It is useful for communication and to prototype interaction. The process of creating a mockup is: 1) determine the focus (interface, look and feel, process), 2) sketch the form, and 3) then construct using low-cost, readily available materials [26]. For example, in the proposed energy audit process, a reminder system is developed to remind the occupants to switch off the plug loads and lights when they leave the respective rooms and to inform the users of their real-time consumption of electricity. The system is named PostBits. A demonstration of mockup of PostBits is shown in Fig. 10.

2.4.2. Lead user test

Lead user test is to iteratively prototype and test concepts with users. Through the process, the needs of users are found, and designed product, service, or system is refined. For example, in Fig. 11, we shown an example of a user-interactive smart energy interface that was prototyped and tested by the users for smart control energy consumption by shared spaces, such as meeting rooms.

2.4.3. Cost benefit analysis

Cost benefit analysis includes

a) Simple Payback Period Analysis: This method calculates the length of time required to recover the cost of an investment. The payback period of a given investment or project is an important determinant of whether to undertake the position or project, as longer payback periods are typically not desirable for investment positions.

b) Life Cycle Cost Analysis: Life-cycle cost analysis (LCCA) is a tool to determine the most cost-effective option among different competing alternatives to purchase, own, operate, maintain and, finally, dispose of an object or process, when each is equally appropriate to be implemented on technical grounds.
c) Present Worth Analysis: Present value (PV) is the current worth of a future sum of money or stream of cash flows given a specified rate of return. Future cash flows are discounted at the discount rate, and the higher the discount rate, the lower the present value of the future cash flows.

3. DI for Smart Energy Management: Case Studies

As shown in Fig. 12, this section discusses how the proposed DI framework can be applied for smart energy management. To do so, the campus of Singapore University of Technology and Design (SUTD) is used as a testbed to implement the proposed methods.

3.1. Case study 1: Residential building

3.1.1. Opportunity/problem

User behavior in end-use environment is a significant factor in deciding the operational energy consumption of appliances and remains as a significant contributor of the amount of total energy consumed through a product life cycle. The aim of this case study is to identify and solve energy overuse issues caused by user behaviors in residential buildings.

3.1.2. Methods

The 4D framework adopted in this case study is explained as follows.

a) Discover: To reveal user behavior in residential buildings, a user study was carried out as the first step of the case study. There were two phases in this user study. In the first phase, each participant was given a scenario card which stated multiple household tasks to be done. They were advised to sequence the activities according to their preference. After the first phase, as an intervention, they were shown an energy bill for the first phase and requested to lower the energy consumption in the second phase. Appliance level energy consumption data was obtained through smart plugs connected to the wall sockets. During the study, participants' behaviors were observed and recorded. Finally, interviews were conducted to get more insights about the observed revealed behaviors.
b) Define: A behavior-based framework was used to reveal causes of EOFMs. A user activity diagram was formulated by identifying the optimal approach for the activities as shown in Fig. 13. This was used to compare with each step taken by the user study participants to characterize their revealed behavior. Any deviation from the identified optimal path is considered as an Energy Overuse Failure Mode, an opportunity to improve energy efficiencies.

The user behavior categorization matrix (such as in Fig. 4) was formulated for each identified Energy Overuse Failure Mode. This matrix was used to characterize the behavior of the participants as well as to elicit underlying causes. Furthermore, inspired by the classical Failure Modes and Effects Analysis, severities and likelihoods (Fig. 14) were estimated using energy loss estimations and frequencies of failures.

It was found that the users could be far away from the expected energy saving behavior. Therefore, an opportunity statement was created as "Reduce EOFM behavior occurrence by 70% in residential buildings". Using hierarchy of purpose method, a more general statement was created as "Reduce energy wastage caused by EOFM by 90% in residential buildings", and a more specific statement was "Increase occupants' awareness of energy wastage".
c) Develop: Based on the opportunities found in the Define phase, mind map was used to generate ideas, according to Fig. 8. Multiple ideas were generated using this mind map. Then "Real-Win-Worth it?" method was used to select feasible ideas. Finally, two ideas were selected: (1) Modulate compressor on-off status via data-driven approach without affecting the end user's comfort level; (2) Use small display blocks to remind users of energy saving behavior and display real-time consumption of electricity.

The first solution focused on the performance improvement of appliance. It was a data driven approach of controlling electricity consumption of residential ACs. A control

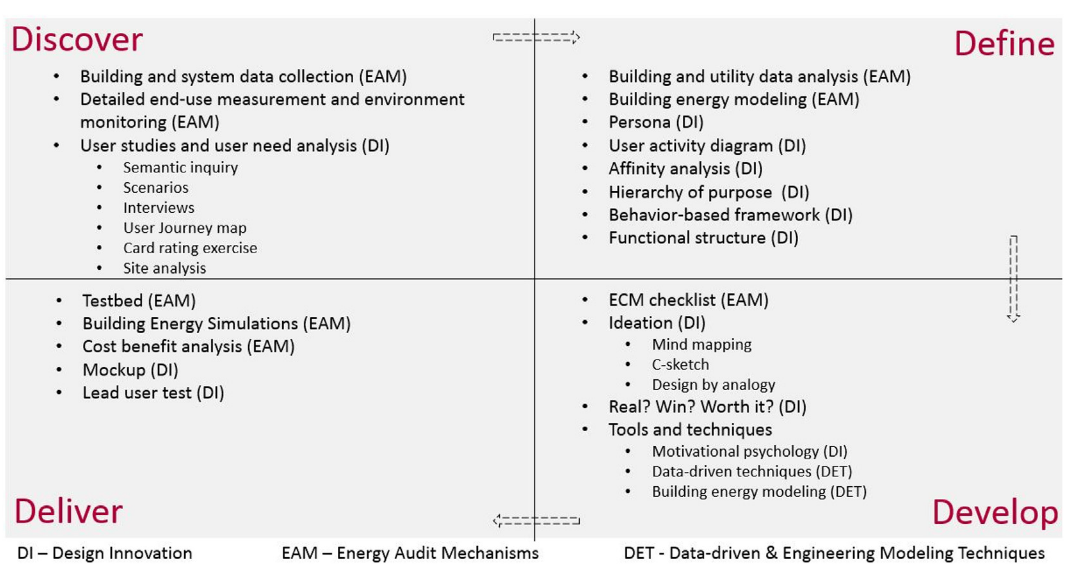


Fig. 12. The proposed 4D framework and DI methods used for designing the smart energy system for buildings.

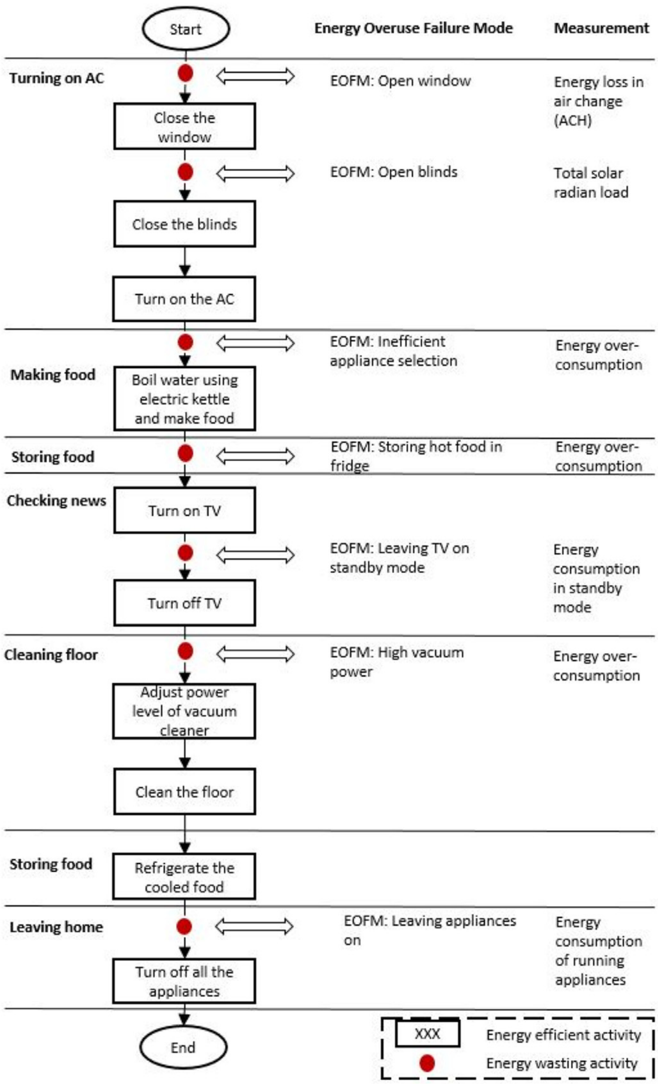


Fig. 13. Demonstration of the formulated activity flowchart.

algorithm was created to remotely control the power consumption of the compressors by controlling the set point temperature of the connected ACs. The control was conducted in such a way that the residents could not feel any changes in the indoor climate condition of their homes.

The second solution was called PostBits [43], with the purpose to remind the occupants to switch off the plug loads and lights when they leave the respective rooms and to inform the users of their real time consumption of electricity. PostBits was a system of display blocks that integrate cloud information with contextually rich physical space. The objective was to placing information at specific locations in the individual and common office spaces in order to provide the users with rich and intuitive ways to cope with different information such as energy usage, energy cost, and reminder to switch off the lights and plug loads when they leave their offices. PostBits was designed for long battery life, robust communication and simple interactions, to enable a field deployment.

d) Deliver: For the first solution, a testbed was set up in a residential building, in which the set point temperature of ACs installed within each apartment unit was controllable from a remote server. Extensive data was collected throughout the experiment. We show in Ref. [44] that the proposed data-driven approach was very effective in reducing the power consumption by the compressors as well as the potential of offering ACs as interruptible load into the market without compromising user comfort.

Fig. 15 shows how the proposed AC management mechanism exhibits these performance enhancements. In this figure, we display the power consumption pattern of a particular participant's compressor for two different days: one day with AC management (Dec 21, 2015) and one day without AC management (Dec 26, 2015). Both chosen days were chosen such that they were nearly identical to each other in terms of the user's choice of set point temperature of the AC. In other words, the user felt the same thermal discomfort on both days due to the actual room temperature. Now, according to the result demonstrated in the figure, the average energy consumption by the compressor on the day without management was

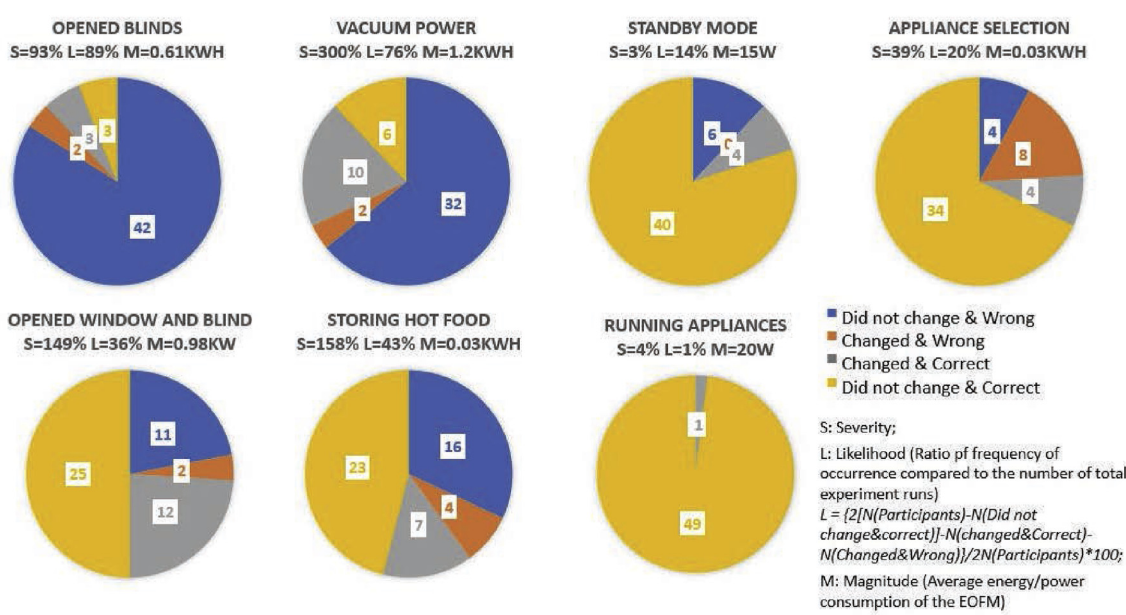


Fig. 14. Severities and likelihoods.

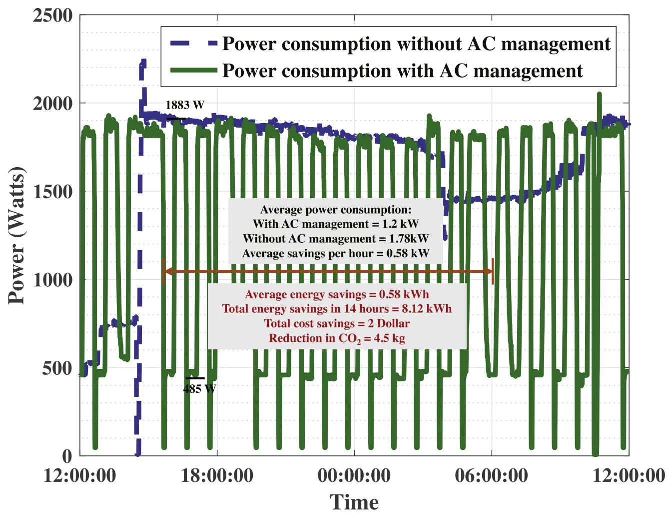


Fig. 15. Demonstration of how the designed AC management technique contributes to energy and cost savings as well as reduction in CO_2 generation by the participating household. This figure is taken from Ref. [38].

much higher than that on the day with management, which consequently demonstrates the potential, for energy saving, of the proposed mechanism. For example, consider the time span from 16 : 00 to 6 : 00. The total average energy savings during this 14 h period of time was 8.12 kWh for the considered compressor. Therefore, considering the flat rate energy price of 19.13 cents per kWh of Singapore, the total cost savings for this single compressor was $1.56, which clearly demonstrates the effectiveness of the proposed AC management technique in greatly reducing the cost of energy to the users over longer periods such as months and years. For more detail of the mechanism and how the explained results are obtained, we refer the reader to Ref. [44].

For the second solution, mock-ups were created to conduct user tests. A demonstration of strategic placement of PostBits is shown in Fig. 10.

3.1.3. Remark

The 4D framework, tools and techniques used in this case study are shown to be effective at identifying underlying causes of energy wastage in residential buildings, and providing an indication of the potential energy savings through outright product-led strategies and improving the energy awareness. This case study generated two solutions: an innovative data-driven approach of controlling electricity consumption of residential ACs and a cloud-based reminder system to conserve energy in residential buildings.

We note that there are a number of existing studies on energy consumption measures based on AC management schemes for buildings. These studies can be divided into two general categories. First category of studies, as surveyed in Ref. [45], propose physical alterations or additional to the existing system in the building such as complete replacement of the HVAC unit or a significant alteration of its control module. However, such alteration or replacement usually require a large amount of investment, which could be suitable to apply for large commercial facilities and offices, but could be hard to be implemented in residential homes where occupants may not want to make a large investment for such an alteration. The second category of energy conservation measures focus on the operation of AC system and provide optimal solutions of AC operation. These techniques are analyzed theoretically, mathematically rigorous and add great values to the literature of mathematical modeling and control. However, most of these techniques are not suitable to deploy in existing buildings due to the communication and computational resources needed to accommodate them and the necessary cost for their operation and maintenance.

Compared to the existing studies, using DI for AC management adds following new values to the AC management scheme: The proposed DI approach makes AC management more consumer-centric by taking consumers' views on the developed technology into account. The design of the AC management ensured that the outcome of the scheme satisfies some necessary conditions for attracting house occupants to use it. Detail of how it is designed can be found in Ref. [38]. Further, DI enables opportunistically control of the operation of the ACs without any need of rescheduling its operation or replacement of the unit. We report the operation of such a data-driven opportunistic control technique in Ref. [44].

3.2. Case study 2: Commercial building

3.2.1. Opportunity/Problem

Commercial buildings account for a significant amount of the

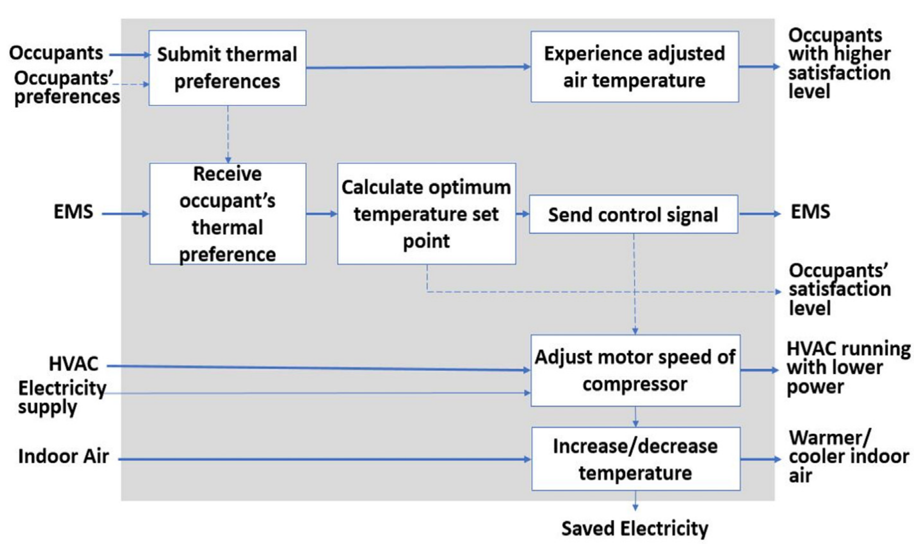


Fig. 16. Preliminary system architecture of smart energy control system in shared space.

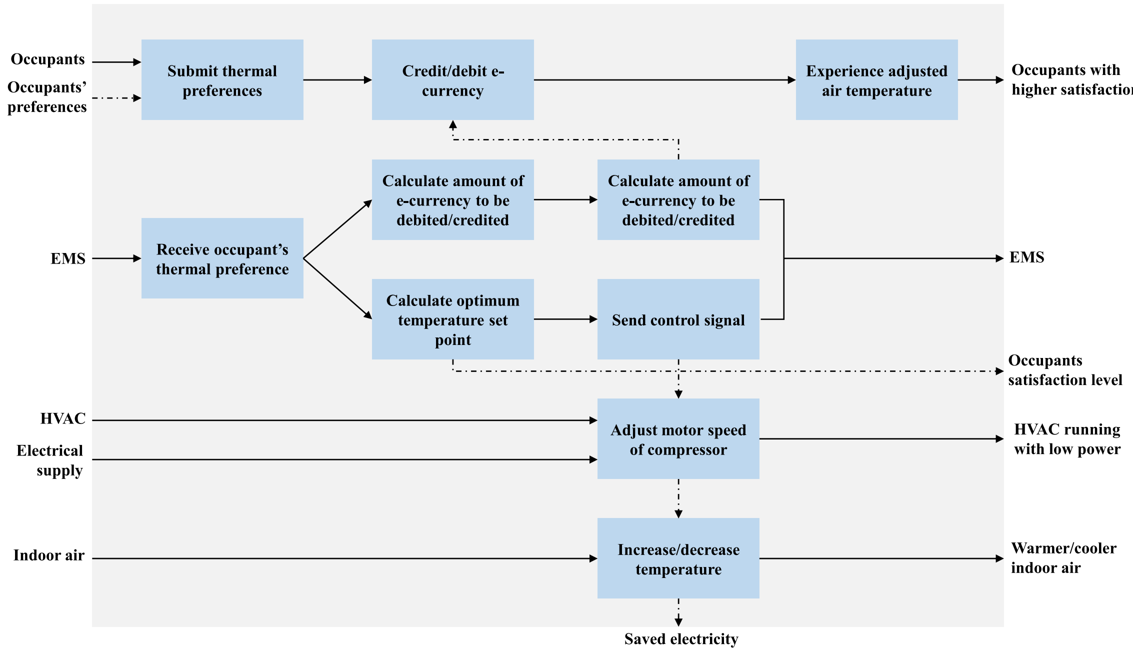


Fig. 17. Final system architecture of smart energy control system in shared space.

total energy consumption of Singapore. The case study was conducted in SUTD to closely inspect and identify the important factors influencing the energy use behaviors, and create solutions to improve energy performance in shared spaces of commercial buildings [46].

3.2.2. Methods

The 4D framework adopted in this case study is explained as follows.

a) Discover: A user study was conducted to discover important factors influencing the energy use behaviors in shared spaces. In this user study, users were involved in a competition with prizes of 400, 600, 800, and 1000 dollars worth cash vouchers. Four shared space were selected and four types of feedback displays with different intervention levels (see Table 3) were deployed in them. The selected space were equipped with smart energy meters to perform end-use measurement. Initial and Exit surveys were conducted with the feedback display introduction and one week before the competition ended. The competition was run for six weeks without any interruptions. The results of this user study is given in Table 4.

In Table 4, the lowest energy consumption of Room 4 could be a result of providing comparisons between peers (descriptive norms) and incentives. However, the increase of energy consumption shown in Room 1 could be a result of changes in workloads and other conditions "before" and "after" announcing the competition. These uncontrollable and non-uniform conditions across different groups as well as the limited number of participants can be considered as the limitations of this user study. Consequently, the reported attitudinal and behavioral data obtained through the surveys (IN and EX) are considered as the key outcomes of this case study.

Table 5 presents the bivariate correlations between IN vs. EX survey results. The questions were formulated to get behavioral and attitudinal insights. The surveys were conducted using an online platform and 0–100 sliding scales were used to get responses from the participants. As shown in Table 5 a significant improvement of behavior can be seen in the Q4 related to checking and switching off lights. Interestingly, a significant decrease of the concern about other users can be seen in Q6, where the participants were enquired about their concerns regarding the other users when they want to switch off lights. In addition, when the participants were enquired about the challenges for energy conservation, at the first phase IN survey they were more concerned about the contextual factors related to bad design of controls and bad control policies such as lack of user control, lack of accessibility to switches, lack of natural ventilation, etc. And suggested improvements for those. However, in the second phase EX survey, there was a shift towards automated solutions, in order to avoid the conflicts between users (as in the case of Q6 which can create a conflict).

This user study showed the importance of the contextual factors such as accessibility to controls, control policies for energy use interventions through design solutions in shared spaces. Especially, it is important to make those right in first place to encourage the users who are not directly paying for the energy they are using. In addition, the qualitative responses indicated the potential of smart systems to avoid conflicts between different users or user-groups.

Furthermore, regarding the AC system in shared space, conflicting needs were also found between different stakeholders (users, facility managers and building owner) from

Table 3
Feedback display design.

Room	Comparison Between Peers	Update Time
Room 1	No	Hourly
Room 2	No	Daily
Room 3	Yes	Hourly
Room 4	Yes	Daily

Table 4
Energy consumptions before and during the competition.

	Term Weekdays Average Energy Consumption			Survey Responses		
	Before (kWh)	During (kWh)	Savings (%)	Initial (IN)	Exit (EX)	Both (Repeated)
Room 1	38.3	49.1	−28	21	3	2
Room 2	57.1	50.2	12	13	7	2
Room 3	52.0	43.1	17	25	17	12
Room 4	48.1	35.3	26	22	41	21

Table 5
Comparisons of response means between the initial (IN) and exit survey (EX).

			IN vs EX surveys in general				IN vs EX surveys for repeated			
			Mean	St. D.	T	P	Mean	St.D.	T	P
I try to save energy in my day-to-day activities	Behavior	Q1 IN	68.8	20.6	−1.07	0.285	65.7	21.1	−1.73	0.092
		Q1 EX	72.3	18.6			72.6	17.4		
I always check and switch off lights, … Before leaving my residence	Behavior	Q2 IN	84	20.6	−0.6	0.55	82.2	20.7	0.17	0.864
		Q2 EX	86	19.7			81.4	22.8		
I think we waste significant amount of energy in the shared space	Attitudina	Q3 IN	59.7	30.6	1.2	0.234	60.8	29.5	0.73	0.473
		Q3 EX	54.1	27.1			56.8	26.2		
I check and switch off lights, …without any use in the shared space	Behavior	Q4 IN	69.5	29.8	−2.1	0.037	68.8	26.8	−3.16	0.003
		Q4 EX	78.4	21.8			81.1	20.2		
I switch off lights … I am the last person to leave the shared space	Behavior	Q5 IN	92.6	15.6	1.11	0.268	91.4	17.1	−0.12	0.908
		Q5 EX	89.9	15			91.7	12.3		
I am worried about switching off lights … …. Inconvenience to other occupants	Attitudinal	Q6 IN	48.8	35.4	0.69	0.488	53.8	36.3	1.74	0.091
		Q6 EX	44.7	34.9			42.4	33.8		
We do not consume a significant amount of energy …. Won't be able to save much …. .	Attitudinal	Q7 IN	31	27.5	−1.63	0.105	32	25.3	−1.26	0.217
		Q7 EX	38.2	26.5			38.8	25.4		
I can positively influence other occupants to cut down waste …. .	Attitudinal	Q8 IN	56.6	26.4	0.85	0.399	51.2	28.3	−0.87	0.391
		Q8 EX	52.9	26.9			55.1	23.3		
I want to save energy and contribute towards a greener earth	Attitudinal	Q9 IN	85.5	17.5	1.16	0.246	83.4	18.9	0.09	0.929
		Q9 EX	82.3	16.7			83.2	15.5		

interviews. Therefore, it is essential to design a smart AC control system in shared space.

b) Define: Based on the findings of the user study, a smart AC control mechanism in shared space was chosen for further development [47]. The smart air-con control mechanism was defined to increase users' accessibility to AC control, maximize the benefit of all users and avoid conflicts between different users in shared space. By using the systems functional modeling method, a black box model was created and further developed by decomposing functions into subfunctions as shown in Fig. 16.
c) Develop: To calculate the energy consumption of air-conditioner under different temperature set points, an energy model was developed using EnergyPlus. To engage users in using the system, motivational psychology were applied, and virtual currency was introduced to reward users. Virtual currencies were credit to users for facility bookings and participating in the AC control in shared spaces. An algorithm was designed to ensure that same net benefit were received by all participating users. The net benefit was defined to be thermal comfort plus payment, i.e. a user who was less comfortable would receive more payment compared to users who were more comfortable.

   The final system architecture of the smart energy control system is shown in Fig. 17.
d) Deliver: In the Deliver phase, selected users were invited to test the prototype as shown in Fig. 11. A web-based user interface was used by each participant to report his/her preference on the temperature set-point of the air-conditioner. Observations and post-experiment interview were made to gather user feedback to further refine the smart energy control system.

3.2.3. Remark

This case study inspects and identifies the important factors influencing the energy use behaviors in shared space. It generated an innovative AC control solution in shared space to both reduce energy consumption and increase user satisfaction level in commercial buildings.

3.3. Economic analysis

There were two types of cost involved in the proposed approach: initial cost and reoccurring cost. Initial cost was mainly for purchases of equipment like wireless sensor nodes, gateway, and smart plugs, which can be reused for different projects/case studies. In this analysis, this initial cost of S$3000 (here, S$ refers to Singapore dollar) was evenly distributed to the two case studies. However, the real initial cost of each case study could be lower as the equipment can be reused many times. The reoccurring cost involved in each project/case study comprised labour cost, volunteer compensation and cost of DI tools (e.g. cards, post-its). The total reoccurring costs of Case Study 1 and Case Study 2 were S$19,540 and S$15,820, respectively.

For Case Study 1, the energy savings of one household from AC control and PostBits were 8.12 kWh and 1.85 kWh per day, respectively. If the proposed solutions were installed in one residential building with 40 households, the potential energy savings would be 145,521 kWh per year. Based on the current electricity price of 19.13 cents/kWh, the annual cost saving is S$27,836, and the payback period is 0.76 year.

The smart energy system demonstrated in Case Study 2 showed a potential energy savings of 230 kWh per year for an 11.79 m^2 meeting room. If the solution was installed in all shared spaces in the building, the annual energy saving would be 31,704 kWh.

Therefore, the annual cost saving is $6,065, and the payback period is 2.86 years.

A detail of the above mentioned analysis is also shown in Fig. 18. Please note that, in this analysis, it is assumed that the facilities are ready for the installation of the solutions. Hence, the installation cost is assumed to be zero. However, installation cost may occur in other projects.

4. Summary and discussions

Through two case studies, we have demonstrated the application of the proposed design thinking approach in improving the energy efficiency of both residential and commercial buildings. The 4D framework has effectively guided the process of developing smart energy solutions by discovering opportunities, defining needs, developing concepts, and delivering solutions in the smart energy domain.

The DI methods which were integrated, tailored, adapted, and extended for smart energy system effectively contributed to each of the 4D phases. In the case studies, not all the introduced methods were used, whereas the most appropriate methods were selected based on the problem and the progress of different studies. For example, in both case studies, *user studies* were conducted at the beginning to reveal user behaviors, and discover energy saving opportunities. This fulfilled the main objective of the study to adopt a user-centered approach and integrate users views into the design of energy management systems. However, different user study techniques were used in the two case studies. Designing energy management system for residential building aimed to discover individual behaviors in a residential environment and was more scenario based. Therefore, scenario cards were used to reveal each participant's activities under a certain given condition. Interviews were conducted to get more insights of the revealed behavior.

On the other hand, energy management system design for commercial building aimed to discover important factors influencing users' behaviors in shared spaces. A large number of participants were involved and divided into four groups with different intervention levels for comparison. User surveys were conducted to obtain behavioral and attitudinal insights. Note that, although not being applied in the case studies, other user study and user need analysis methods introduced in this paper may also be useful in other studies. Each method has different focus and functions, and may be used where applicable. For example, to identify facility managers' activities and pain points, user journey maps may be created.

In the case studies, EAM methods provided basic building, system, and environment information to assist the determination of opportunities. In both studies, detailed end-use measurement and environment monitoring were conducted to assist the user studies and the analysis of relationship between user behavior and energy consumption. In the case studies, DET were also proven to be useful techniques for developing smart energy solutions, for example,

Initial Cost

	unit price (S$)	quantity	total price (S$)
wireless sensor node	100	20	2000
gateway	400	1	400
smart plug	60	10	600
software	free		0
Total initial cost			**3000**

Reoccurring Cost

Case study 1			
Cost	unit price (S$)	quantity	total price (S$)
manpower-discover (man-hour)	25	160	4000
manpower-define (man-hour)	25	40	1000
manpower-develop (man-hour)	25	240	6000
manpower-deliver (man-hour)	25	300	7500
miscellaneous DI tools (e.g. post-its, cards, paper, pens)	40	1	40
volunteer compensation (man-hour)	10	100	1000
Total cost			**19540**
Benefit	annual energy saving (kWh)	annual cost saving (S$) [base on 19.13 cents/kWh]	
AC control	2964	567	
PostBits	674	129	
Total saving of one household per year	3638	696	
Total saving of whole building per year	145512	**27836**	

Simple Payback period 0.76

Case study 2			
Cost	unit price (S$)	quantity	total price (S$)
manpower-discover (man-hour)	25	150	3750
manpower-define (man-hour)	25	40	1000
manpower-develop (man-hour)	25	180	4500
manpower-deliver (man-hour)	25	150	3750
miscellaneous DI tools (e.g. post-its, cards, paper, pens)	20	1	20
volunteer compensation (man-hour)	10	280	2800
Total cost			**15820**
Benefit	annual energy saving (kWh)	annual cost saving (S$) [base on 19.13 cents/kWh}	
AC control	230	44	
Total saving of one meeting room (11.79m^2) per year	230	44	
Total saving of whole building (offices and meeting rooms) per year	31704	**6065**	

Simple payback period 2.86

Fig. 18. Cost benefit analysis of smart energy systems explained in case studies 1 and 2.

motivational psychology and energy modeling were involved in the AC control in shared space. Furthermore, in both case studies, the economic analysis are demonstrated to show how the proposed DI based energy management can help save energy in both residential (Fig. 15) and commercial buildings (Table 4).

In summary, smart energy solutions have been created in this proposed study by integrating different DI, EAM, and DET methods, tools, and techniques. These solutions are more innovative and user-oriented compared to solutions generated from ECM checklist in traditional energy audits. By introducing the detail DI approach, the authors encourage other researchers to apply the proposed method to address more problems regarding building energy efficiency, and innovate more smart energy solutions.

5. Conclusion

In this paper, we propose and demonstrate a Smart Energy Design Innovation approach for developing a smart energy system for buildings. Smart energy systems must integrate with user needs and experiences to be adopted and be effective over sustained durations. A 4D approach, including Discover, Define, Develop, and Deliver, when significantly extended and integrated with energy audit and data-driven techniques, provides the core of the approach. By introducing a new research direction and systematic, repeatable methodology in the smart energy domain, this Smart Energy DI approach represents a significant advancement in the literature and field, and provides a basis for innovating new, user-centric solutions to energy system opportunities. By following the comprehensive discussion of the design innovation technique with necessary examples provided in this study, any researcher or practitioner working in the smart energy domain can use this study as a reference to design its own smart energy portfolio, for example, energy trading, energy security or management schemes following the 4D phases described in the paper. Finally, through two case studies, we explain how DI has been used to managing energy consumption in residential and commercial buildings respectively. Key, summarized results are shown to illustrate the effective use of Smart Energy DI, and illustrate innovative outcomes.

Please note that the approach adopted in this paper has been already used for smart energy management of large commercial spaces at a public university, a public hospital, and at defense science and technology agency in Singapore. However, due to non-disclosure agreements, we cannot release all the information publicly. Nevertheless, some findings from the application of the approach in a public university have been reported in Ref. [38]. Further, as the DI technique is developed, the proposed approach can be used to improve the energy efficiency of both old and new existing buildings.

Acknowledgement

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