International Journal of Sustainable Built Environment (2016) 5, 620–634

HOSTED BY ELSEVIER

Gulf Organisation for Research and Development

International Journal of Sustainable Built Environment

ScienceDirect
www.sciencedirect.com

Original Article/Research

Intelligent decision support system for home energy retrofit adoption

D. Duah *, M. Syal

Construction Management, School of Planning, Design, and Construction, Michigan State University, East Lansing, MI 48823, United States

Received 13 August 2015; accepted 5 May 2016

Abstract

Despite the well-established benefits of home energy retrofits (HER), its adoption has faced huge challenges. Though homeowners typically depend on energy practitioners for HER advice, previous work by the researchers has identified the inadequateness of such information as a barrier. Using an earlier developed information model, an energy retrofit intelligent decision support system (ERIDSS), that integrates expert knowledge with quantitative information to provide homeowners with accurate information for decision-making, was developed. This paper identifies the key components of the proposed ERIDSS, develops rules for relevant energy retrofit expert knowledge to be employed in the knowledge-based system of the proposed ERIDSS, develops the ERIDSS for decision-making for home energy retrofits, and demonstrates the application of the ERIDSS using a pilot system on two test homes. The quantitative information was obtained from published sources and the U.S. Department of Energy's cost database, and the expert knowledge was obtained through the application of the modified Delphi technique and job shadowing of energy auditors and retrofit contractors. The research contributes to improving the adoption of energy retrofits by homeowners, assisting industry practitioners with the corroboration of knowledge/information they provide to homeowners in order to reduce homeowner bias, providing a good understanding of available implicit domain knowledge through the development of six knowledge-based modules, and the development of a system and approach that may be replicated in other domains.

Keywords: Intelligent decision support system; Home energy retrofits; Expert knowledge; Quantitative information

1. Introduction

The importance of energy efficiency (EE), defined as reducing the amount of energy needed to perform a task by incorporating more effective systems (IEA, 2011; LBNL, 2012; Limerick & Geller, 2007), has been well established in literature. For instance, EE is viewed as a critical step in achieving sustainability in buildings by helping to control rising energy costs, reducing environmental footprints, and increasing the value and competitiveness of buildings (Johnson Controls, 2012, 2013). In addition, EE is the most abundant, cheapest, and fastest approach to significantly reducing greenhouse gas emissions (LBNL, 2013). As a result, increasing investments in EE in buildings is seen as one of the most constructive and cost-effective ways of addressing challenges with sustainability due to the economic, social, and environmental benefits

* Corresponding author at: Department of Architecture, College of Art and Built Environment, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

E-mail addresses: duahdani@gmail.com (D. Duah), syalm@msu.edu (M. Syal).
Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2016.05.003
2212-6090/

that can be accrued (Johnson Controls, 2012; USEPA, 2006).

A growing area of application of EE to buildings is the focus on existing homes, which dominate the current housing stock. Since majority of existing homes is largely energy inefficient, retrofitting them to improve their EE increases the likelihood of achieving the benefits of EE including the potential for tremendous economic, health, social, and environmental gains (Syal et al., 2014; USEPA 2010). Despite the fairly well established benefits and opportunities of energy retrofitting of existing homes, its adoption and wide scale application has faced obstacles. One estimate of market penetration for home energy retrofit (HER) programs puts it at less than 2% (Neme et al., 2012). The lack of information to homeowners in a format not easily understood and used was identified as barriers to energy retrofit adoption resulting in low uptake (Syal et al., 2014). The research team embarked on a series of steps to investigate and solve the barrier issue. Previous works by the researchers that address different aspects of the identified problem include:

1. Information framework for intelligent decision support system for HERs (Syal et al., 2014 – published).
2. Expert knowledge elicitation for decision-making in HERs (Duah et al., 2014 – published).
3. Role of Expert knowledge in HERs (Duah et al., 2015 – under review).
4. Intelligent decision support system framework for HERs in existing homes (Duah, 2014 – published doctoral dissertation).

This paper presents the culmination of the above noted building blocks by presenting an energy retrofit intelligent decision support system (ERIDSS).

1.1. Information Barrier to Home Energy Retrofit (HER) adoption

Challenges with the adoption of HER despite the well-established benefits continue to be a concern for the drive toward achieving building sustainability. For instance, out of the approximately 150 energy efficiency-related loan programs in the U.S. in 2007, less than 0.1% of their probable customers were reached (Fuller et al., 2010; Ho and Hays, 2010; USC-OTA 1993). Reviewing 85 programs that offer audits based on data from Electric Power Research Institute, Berry (1993) established a very low average annual participation rate of 3.2%. The Office of Energy Efficiency and Renewable Energy assert that less than 1% of homes have had energy retrofits exclusively to save energy (Lee, 2010).

Generally, homeowners seek information from various sources such as word of mouth, retail and lumberyard employees, cost databases, retrofit contractors, energy auditors, utility companies etc. Earlier work by the researchers put these information sources into two broad categories of information: quantitative information and expert knowledge (Syal et al., 2014). Quantitative information, typically found in published sources, includes information related to the domain and commonly agreed upon by domain experts. Expert knowledge, however, denotes information considered as knowledge of good practice, good judgment, and credible reasoning in the domain (Palmquist, 2001; Turban, 2005; Warszawski 1985). Even though majority of homeowners typically depend on energy experts, such as energy auditors and trade contractors, for assistance with decision-making when they want to retrofit their homes, Syal et al. (2014) noted that the information provided by such professionals can lack comprehensiveness, accuracy, and consistency. This research seeks to understand the information barriers to the adoption of HER and to develop a system that can assist with overcoming the information barriers.

1.2. Intelligent decision support systems (IDSS)

A decision support system (DSS) is defined as an interactive computer-based information system intended to help users make decisions by retrieving, summarizing, and analyzing decision-relevant data (Arnott, 2004; Druzdzel and Flynn, 2002; Power, 1998). Three major components of a DSS are: database management system, modelbase management system, and dialog generation and management system. In order to provide intelligence to the three components of a DSS, an optional fourth component, the knowledge-based management system (KMS) (such as an expert system), can be included (Turban et al., 2005). A DSS with KMS is referred to as knowledge-based DSS or intelligent DSS (IDSS) (Vohra and Das, 2011).

Expert systems (ES) basically capture and organize the task-specific knowledge derived from the experts (expertise) into a computer program. Users are able to provide specific advice to solve a problem by recalling stored expert knowledge. In order to provide a specific conclusion, inferences are used to provide a logic similar to how a human expert would (Liao, 2005; Warszawski, 1985; Turban et al., 2005; Syal et al., 2013). The IDSS envisioned for this research had a KMS that incorporated the model based features into an ES (Basen and Dutta, 1984 cited by Turban and Watkins, 1986; Özbayrak and Bell, 2003; Shannon, 1985 cited by Turban and Watkins, 1986).

2. Research goal and methodology

Comprehensive and easy-to-use information is essential to decision-making for HER. The comprehensiveness of this information requires an integrated approach to harnessing the two identified information sources: expert knowledge in conjunction with vast amount of quantitative information. The goal of this research was to develop an IDSS that could integrate these information types in order to provide energy retrofit information to users with the aim of improving HER adoption rates.

In order to achieve this goal, a structured process involving breaking down of the goal into methodological and work steps is indicated below (Fig. 1):

1. Identification of key components of the proposed IDSS.
2. Develop rules for relevant energy retrofit expert knowledge to be employed in the knowledge-based system of the proposed IDSS.
3. Develop IDSS for decision-making for HERs.
4. Demonstrate the application of the IDSS with a pilot system.

3. Key components of proposed IDSS

Previous works by the authors have addressed two of three key components of the proposed IDSS: the energy retrofit decision process model and quantitative information (Duah et al., 2014; Syal et al., 2014; Duah et al., 2014b). A third key component, expert knowledge, is highlighted in the following sub-sections. Such knowledge was combined with the quantitative information and was used in the development of the IDSS.

3.1. Determinants of Home Energy Retrofit (HER) expert knowledge

Expert knowledge has been identified as a major component of the development of the proposed IDSS. As a result of the intuitive nature of such knowledge, it was important to identify what constitutes HER expert knowledge. Using qualitative methods, Duah et al. (2014) examined the determinants of expert knowledge in the HER industry. Analysis of data, collected from 19 industry experts based on the Delphi technique, contributed to the understanding of expert knowledge in the industry. An energy retrofit identification system was developed to serve as an effective metric for determining an industry expert. This is particularly important in the era where non-experts or pseudo-experts are becoming "visible" on the Internet and social media. In addition, since the success of any DSS depends on the quality of expertise/heuristics used, it was important to ensure that the knowledge of competent professionals was selected for elicitation in developing the IDSS by investigating the determinants of expert knowledge in the HER industry. Armstrong (2012) has argued that the difference between expert and novice performance cannot be reduced to experience but must include qualitative differences. Cognitive psychology literature differentiates expert performance from novices using a number of elements (Armstrong, 2012, Cellier et al., 1997; Farrington-Darby and Wilson, 2006; Glaser and Chi, 1988; Shanteau, 1992):

- Experience
- Automaticity or doing by intuition
- Representation of task domains
- Ease of encoding new information
- High developed attention abilities
- Ease of adapting to exceptions
- Self-confidence in decision-making
- Willing to back ideas
- Perceive meaningful domain pattern
- Global and functional view of situation
- Speed and accuracy in problem solving
- Superior short and long term memory
- Strong self-monitoring skill
- Great anticipation skills
- Extensive and latest content knowledge
- Domain excellence

Following the differentiating qualities of experts and novices, Duah et al. (2014) developed the following 17 industry expertise attributes for determining industry-based expert knowledge (Table 1). These were used to select HER experts whose knowledge was elicited and included in the proposed IDSS (Duah et al., 2014):

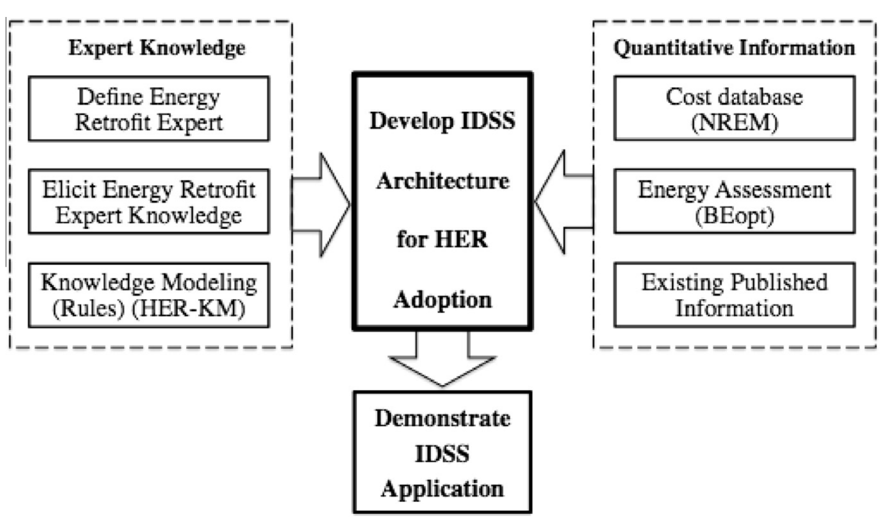

Figure 1. Research methodology.

Table 1
Attributes for energy retrofit expertise determinants (Duah et al. 2014).

No.	Energy retrofit expertise determinants attributes
1	Construction and Building Science Knowledge
2	Construction and Building Science Knowledge – Example
3	Building Science Knowledge – Post Occupancy Health Issues
4	Building Science Knowledge – Whole House System
5	Construction Knowledge – Installation Advice (Do-it-Yourself)
6	Construction Knowledge – Installation Advice (Professional Work)
7	Energy Assessment Knowledge
8	Number of Years in EER Industry
9	Number of Audits/Retrofits
10	Justifying/Explaining Decisions/Actions
11	Construction and Financial Knowledge
12	Break From Industry
13	Knowledge Update Frequency
14	Available Financial Aid Knowledge
15	Return on Investment Knowledge
16	Retrofit Benefits Knowledge
17	Retrofit Measures Knowledge

3.2. Expert knowledge

Having identified the determinants of HER expert knowledge, the oft-cited bottleneck in the development of IDSS, expert knowledge, was the next focus. Specifically, the problems associated with the elicitation of expert knowledge an important component in the development of an IDSS, were analyzed. Duah et al. (2015) noted that the tacit nature of expert knowledge that is knowledge typically committed to automaticity and is difficult to articulate, adds to the elicitation challenge.

As a result, a consensus-based expert elicitation strategy for the energy retrofit industry, that encourages experts to describe their knowledge in a way most natural to them, relates to specific problems, and reduces bias, was developed. This strategy was used to elicit and compile the knowledge of 19 HER industry experts. Such knowledge, suitable for decision-making in this domain, can be incorporated into an IDSS using Boolean logic in the form of If-Then-Else rules. It can assist homeowners with energy retrofit decision-making and industry practitioners and academia with corroboration and enhancement of existing knowledge. A preliminary application of the elicited knowledge using Boolean logic was demonstrated by Duah et al. (2015).

A major aspect of incorporating expert knowledge in an IDSS platform involves its development into a usable format. The earlier building blocks of this research provided the definition of HER knowledge and knowledge elicitation (Duah et al., 2014). The elicited knowledge needed to be modeled by developing knowledge-based rules that can be used by the IDSS.

3.3. Knowledge modeling methods development of rules

This research used a combination of the manual and automatic methods of knowledge modeling. The manual method was interview-based, and involved the use of the Delphi process, observations, and protocol analysis. Protocol analysis, based on data obtained from the job shadowing of 3 industry experts, led to the generation of protocols. In addition, a typical method for knowledge discovery using the automatic method of knowledge modeling, inductive learning, was employed. Rules were induced from existing cases whose results are known and stored in the knowledge base for future reference (Turban et al., 2005). Thus, inferences from induction learning were combined with those obtained through the manual process, and integrated with available published or quantitative information to generate a comprehensive rule-based system that was used in the proposed IDSS.

The combination of these two methods of knowledge modeling minimized the challenges with the manual method such as slowness of the process, high cost involved, and accuracy issues. In addition, the difficulty in finding experts, their unavailability, challenges with remuneration, the innate difficulty of some experts explaining what they do and how they do it due to the cognitive principle of automaticity, warranted the need to complement the knowledge obtained via manual means with that gained through the automatic process.

Data for the automatic method of knowledge modeling were obtained from the Alternative Energy Engineering Technologies Program of Lansing Community College. Twenty reports spanning a period of five years were obtained for the analysis. Internet-based housing information and data gathering resources such as Michigan Housing Locator, zillow.com, realtor.com, and trulia.com were used to complement data about the homes obtained from energy assessment reports. Based on the analysis of all recommended energy retrofit upgrades, a consistent hierarchy evolved: thermal envelope measures were always applied ahead of HVAC measures, an assertion corroborated by other published literature (ACEEE, 2002; Gellings and Parmenter, 2004; Hershfield, 2013; Krigger and Dorsi, 2009; Lstiburek, 2006).

Data for both knowledge-modeling methods (manual and automatic) led to the development of preliminary rules. Based on thorough input from an industry expert, the rules were refined and finalized in a format suitable for use in the proposed intelligent system. Specifically, the rules were developed by representing the knowledge in the form of condition-action pairs: IF this condition (or premise or antecedent) occurs, THEN some action (or result or conclusion or consequence) will (or should) occur (Leishman, 2005; Singhaputtangkul et al., 2013; Turban et al., 2005; Vohra and Das, 2011). For instance: IF *the home has had no insulation,* THEN *install appropriate insulation*.

The overarching logic for the rules was based on the energy retrofit expert knowledge elicited and corroborated by quantitative information, which followed the ensuing suggested hierarchy:

1. Thermal envelope measures
2. HVAC measures
3. Hot water heating measures
4. Lighting measures
5. Stand-alone/energy saving measures

The basis for the hierarchy is that the installation of thermal envelope measures (air sealing and insulation) greatly reduces the rate at which conditioned air leaves the home (exfiltration) or unconditioned air enters the home (infiltration). As a result, the heating and cooling loads will have to be recalculated and subsequently, appliances resized. For instance, homes with oversized furnaces perform poorly, are uncomfortable, and cost more to purchase and run. The suggested hierarchy also considers rare instances where there is an immediate need. For instance, the need to replace a broken down heating system before the winter conditions set in. This becomes a priority and is addressed after an energy simulation of the home has been performed and the effect of proposed upgrades on the thermal envelope, subsequently determined.

Hot water heating systems account for 15–25% of energy costs in a home (Energy Saver, 2012a) necessitating the installation of energy efficient upgrades of such systems. The hierarchy ensures that water-heating systems are upgraded before lighting. This is because, even though lighting has shorter payback periods in residential homes compared to commercial properties, it accounts for a minor proportion of the energy costs. Finally, stand-alone measures can be applied at any time during the retrofit process since they do not have a direct effect on the other measures. These include the installation of appliances such as dishwashers, clothes washers and dryers, and refrigerators.

4. Energy retrofit intelligent decision support system (ERIDSS)

Fig. 2 represents the architecture of the energy retrofit IDSS (ERIDSS). There are 3 major components: the knowledge-based management, data management, and the user interface subsystems. A key component of the ERIDSS is the knowledge-based management subsystem (KMS) which provides the heuristic/implicit knowledge elicited from the energy retrofit experts and is complemented by quantitative information from the data management subsystem in order to assist users with energy retrofit decision making.

4.1. Knowledge-based Management Subsystem (KMS)

Earlier work by the researchers led to the development of an energy retrofit decision process (ERDP) model (Samuel, 2011; Syal et al., 2014). This model consisted of three main parts: (1) identify retrofit measures, (2) shortlist and prioritize measures, and (3) provide expert advice on installation. Based on this model, the determinants of energy retrofit expert knowledge and the elicitation of such knowledge; the following knowledge-based modules in the KMS for the proposed IDSS were developed:

1. Knowledge-based thermal envelope measures (KB-Therm) module.
2. Knowledge-based heating, cooling, and air conditioning measures (KB-HVAC) module.
3. Knowledge-based hot water heating measures (KB-HWH) module.
4. Knowledge-based lighting measures (KB-Light) module.
5. Knowledge-based stand-alone and energy saving measures (KB-SES) module.
6. Knowledge-based expert advice on installation (KB-EAI) module.

4.2. Knowledge-Based Thermal envelope measures (KB-Therm) module

When carefully designed and well maintained, thermal envelopes can minimize energy used by HVAC and lighting systems. The correlation between the thermal envelope and other building systems has been highlighted in the whole house systems approach of buildings. Thus, thermal envelope measures take precedence in most energy retrofits. The integration of expert knowledge and quantitative information led to the identification of influential architectural variables that determine high energy consuming buildings and makes them candidates for energy retrofits (Hendron and Engebrecht, 2010; Kim et al., 2013): (1) size of house, (2) number of stories, (3) age of house, (4) presence of basements, (5) presence of fireplace, (6) visible moisture issues, (7) attached garage or carport, (8) comfort complaints, (9) main heating/cooling system, (10) visible health and safety issues, and (11) appliances and lighting characteristics.

Additional considerations in energy efficient thermal envelopes are energy codes and standards, which set lowest efficiency requirements for new and renovated buildings and assure reductions in energy use and emissions over the building life, increases building EE, and results in significant cost savings (United States Department of Energy, 2013a,b). Despite the importance of energy codes, they were only established in the late 1990s, thus, a majority of housing built prior to the 1970’s and have undergone limited upgrades are energy inefficient. Also, one and a half story homes, such as Cape Cod homes, constructed between 1930 and 1960 have particular insulation challenges. Finally, majority of house types with basements, irrespective of the year they were built, are high on energy consumption (Kim et al. 2013). In terms of age, houses built before 1930 have an energy-inefficient balloon frame system of construction compared to those built beyond this period which employs the more energy efficient platform frame system of construction. Other considerations for the development of the logic for the rules for thermal

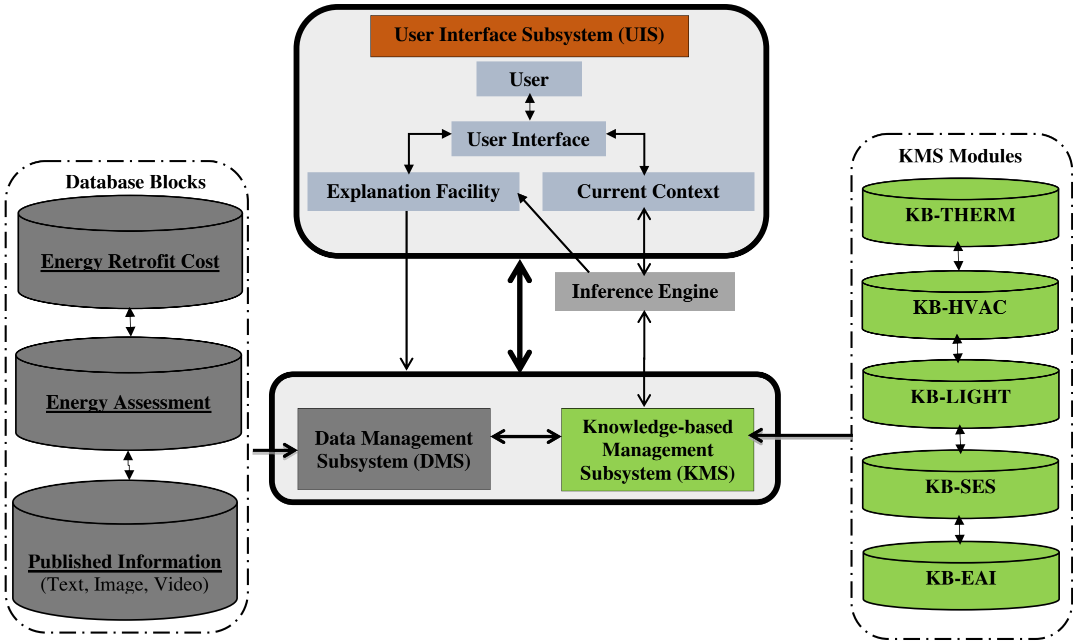

Figure 2. Energy Retrofit Intelligent Decision Support System (ERIDSS).

envelope measures include: air leakage/flow/drafts of the home, window type, external appearance of home, condition of basement/crawlspace, performed upgrades, condition of lower level of home, and duration of occupation of the home each year. The rule below demonstrates an example of the logic development for thermal envelope measures:

IF the house was built before 1970
AND is a Cape Cod style home
AND has had no thermal envelope upgrades
AND has a vented crawlspace,
THEN perform the following upgrades.

1. Air seal and insulate the house in the following order: (attic, crawlspace, conditioned space).
2. Upgrade vented crawlspace to a conditioned crawlspace.

4.3. Knowledge-Based HVAC measures (KB-HVAC) module

The analysis of data for the rule development for the heating, cooling, and ventilation is discussed separately.

4.3.1. Heating measures

Even though there are a variety of technologies that can be used to heat a home (furnaces and boilers, electric resistance heating, heat pumps, boilers, wood and pellet-fuel stoves, and solar), furnaces are the most common way to heat a home. Majority (65%) of single-family homes in the U.S. have a central forced-air furnace that distributes heated air throughout the house using ducts, the bulk of which are fueled by natural gas (Baechler et al., 2011; Energy saver, 2012b). The efficiency of a furnace or boiler is measured by annual fuel utilization efficiency (AFUE), a measurement of how efficient the appliance is in changing the energy in its fuel to heat over a typical year (USDOE, 2013b). Baechler et al. (2011) have noted that low efficiency furnaces have AFUEs of less than 78%, mid-efficiency furnaces have AFUEs of 80–82%, and high-efficiency furnaces have 90–98% AFUE. Replacing an old furnace with a new energy efficient one leads to financial savings on heating and air conditioning, fuel conservation, and the maintenance of consistent warm winter and cool summer conditions in a home.

Since ducts channel conditioned air to warm conditioned spaces, there will be financial losses if such air is lost or cooled before reaching the conditioned space. Thus, ducts must be installed inside conditioned spaces and be sealed and insulated in order to minimize conductive heat losses, especially in forced-air systems. Baechler et al. (2011) have suggested a general rule of thumb in the decision to invest in higher efficiency furnaces: the higher the heating load and fuel price, the better the justification for this investment. Age of appliances is another consideration for energy retrofits for heating measures. While older furnaces (15–20 years) must be replaced, the distribution system (ducts) of newer furnaces (less than 15 years) and the actual units can be repaired. According to Krigger and Dorsi (2009), if the cost to repair the furnace is more than half the cost of replacement, upgrading to a new energy efficient system is economically viable than investing in the old system. The rule below demonstrates an example of the logic development for heating measures:

IF the current heating system is a central forced-air natural gas system

AND it is 30 years old
AND has an AFUE of 72%
AND has a size of 150kBtuh

THEN perform the following upgrades:

1. Upgrade current 30 year old system with a new energy star labeled central forced-air heating system with an AFUE of more than 90%.
2. In order to determine the proper sizing for the heating system and to perform a health and safety test before and after the installation of a new system, consult an energy retrofit professional.

The THEN part of the logic accounts for health and safety hazards associated with the installation of heating systems that necessitates the need for the user to consult an expert. An example of such hazards is backdrafting of carbon monoxide, which can cause death. The financial, health, and safety benefits will, however, be provided by the system.

4.3.2. Cooling measures

Typical cooling systems used in most homes are: air conditioning, heat pumps, evaporative cooling, radiant floor cooling, and dehumidifiers. The focus of the research is based on data from the Mid-West region of the U.S. where the cooling load is minimal compared to the heating load. As a result, the dominant cooling system in the region, air conditioning, is discussed. Specifically, the following four types of cooling systems were analyzed: central air conditioning (AC), ductless mini-split air conditioners, room air conditioners, and natural ventilation or cooling. Since the majority of homes use central ACs where cooled air is provided throughout the home usually by combining it with central furnaces in order to use the same ducts and blower, they are addressed in this section. Compared to room ACs, central AC systems are more efficient and can save energy, money, are very quiet, and convenient to operate. To install a central AC, however, there must be available ductwork. Replacing a 10-year-old AC with a newer, more efficient model may save 20–40% of cooling energy costs (Energy Saver, 2012c).

Rating of central ACs are based on their seasonal energy efficiency ratio (SEER) which specifies the relative amount of energy needed to provide a specific cooling output. Even though many old systems have SEER ratings of 6 or less, the allowable minimum SEER today is 13. In addition, if an AC was manufactured after January 23, 2006, it must achieve a SEER of 13 or higher by law. In terms of age, central ACs typically last for about 15–20 years and there are replacement parts available to meet new standards (Energy Saver, 2012c). The rule below demonstrates an example of the logic development for cooling measures:

IF the current cooling system is a central air conditioning (AC) system
AND the AC system is more than 16 years old
AND AC has a SEER rating of 10
AND AC is used regularly

THEN perform the following upgrades:

1. Upgrade current system to a new Energy Star labeled central air conditioning system with SEER rating of 13 or more.
2. In order to ensure that the system is properly installed, there are no issues with the ducting system, and the precise sizes have been chosen, consult an energy retrofit professional.

The THEN part of the logic was based on the premise that there was a central heating system with existing ductwork, a prerequisite for a central AC system. The current system was a pre-2006 AC and had a SEER rating of 10 or less, thus, it had to be replaced with an energy efficient counterpart. Since the user uses the AC regularly, an energy efficient upgrade was suggested.

4.3.3. Ventilation measures

Ventilation ensures that there is good air quality in a home. This is achieved by bringing fresh air inside the home and removing stale air, including indoor contaminants (house cleaning chemicals, off-gassing paints, and plastics), excess moisture (showering and cooking), and pollutants (carbon monoxide). Mechanical means of maintaining a good air quality can be used to properly ventilate a house (Baechler et al., 2011; Metoyer, 2013). Even though most home heating and cooling equipment, including forced-air heating equipment, are not manufactured to be used for ventilation, they can be combined with a ventilation system or have a separate ventilation system installed. This research assumed that both home heating and cooling systems integrated a ventilation system and/or used natural means of ventilation.

4.4. Knowledge-Based Hot Water Heating Measures (KB-HWH) module

Though a variety of water heating systems are available (conventional storage, tankless or demand-type, heat pump, solar, and tankless coil and indirect water heaters), storage type water heaters are the most common. Depending on the location in the U.S., available fuel types are: natural gas, electricity, propane, fuel oil, geothermal energy, and solar. Since water heating for domestic use accounts for between 15% and 25% of the energy consumed in homes in the U.S., it is important to apply cost effective measures for systems including the following: lowering the thermostat (ideally 120°F) to lessen safety fears such as scalding and yet high enough for activities such as dish and clothes washing and bathing (EERE, 2001). In addition, pipe insulation installation, especially in unconditioned spaces such as garages, attics, crawlspaces, and for a distance of at least six feet from the tank, is an effective energy saving and cost effective measure. In terms of age, old conventional storage water heaters (about 10 years) are inefficient and eventually leak due to rustiness and holes. The rule below demonstrates an example of the logic development for hot water heating measures:

IF home is heated with a condensing boiler.
AND the water heating system is the conventional water heater (natural gas).
AND it is more than 30 years old.
THEN upgrade to energy efficient tankless or demand type water heater.

The logic for the THEN part of the rule is that since conventional water heaters last about 10 years, a 30 year old system must be replaced with a more energy efficient tankless or demand type water heater.

4.5. Knowledge-Based Lighting Measures (KB-Light) module

Compared to their energy efficient counterparts, traditional incandescent lights are known to be energy inefficient. Energy efficient lights such as energy-saving incandescent lights, compact fluorescent lamps, and light emitting diodes typically use about 25–80% less energy and last 3–25 times longer. Though the initial cost is high, energy efficient bulbs have lower operating costs and last longer, thus are financially beneficial over the bulb's life (Energy Saver, 2012d).

Even though lighting loads are significant in commercial buildings, the reverse is true in residential homes. Compared to other energy upgrades in a home such as heating or cooling system installation, the payback on lighting upgrades is short and relatively inexpensive. The rule below demonstrates an example of the logic development for lighting measures:

IF all the light bulbs in your home are traditional incandescent.
THEN upgrade to compact fluorescent light bulbs. Consider installing dimming switches, timers, or sensors.

4.6. Knowledge-Based Stand-Alone and Energy Saving Measures (KB-SES) module

The use of the whole-house approach in the analysis and installation of EE upgrades basically operates on the premise that all systems in the home interact and this interaction affects the energy performance of the home. Baechler et al. (2011) have highlighted the importance of using the whole-house approach as: ensuring the health and safety of the homeowner and achieving cost-effective energy savings. Stand-alone measures are those that have limited or no interaction with the energy performance of other systems. Examples include major non-HVAC appliances or appliances such as refrigerators, clothes washers and dryers, and dishwashers. Finally, some measures have minimal effect on the reduction in building energy consumption. Such measures, referred to as energy saving measures, include water heater pipe insulation, water saving showerheads, furnace filter change, and faucet aerators.

Energy star labeling is a good indicator of the efficiency of appliances. Appliances with energy star labeling, such as refrigerators, clothes washers, clothes dryers, dishwashers etc., use 10–50% less energy, save energy, money, and help reduce greenhouse gas emissions and air pollutants. Fridges and freezers made before 1993 cost more than $100 per year in electricity, twice as much as new models from energy star, thus are inefficient. In addition, old fridges and freezers (1970 s) cost four times more to operate (Energy star, 2013a,b). About a third of the estimated 170 million refrigerators and refrigerator-freezers currently in use in the U.S. are over 10 years old and costs consumers $4.4 billion a year in energy costs. Replacing such old appliances with new energy star models can save consumers from $200–$1,100 on energy costs over the lifetime of the appliance (Energy Star, 2013c). As a result, the threshold for old refrigerators for the development of the logic for the rule was set at more than 10 years old. The rule below demonstrates an example of the logic development for stand-alone and energy saving measures:

IF the refrigerator has a standard rating.
AND is 15 years old.
THEN upgrade to an Energy Star rated refrigerator.

4.7. Knowledge-Based Expert Advice on Installation (KB-EAI) module

This last module recognizes the importance of expert energy retrofit advice during the installation of recommended measures. In each of the 5 modules developed previously, corresponding expert advice for installation was elicited and combined to create a separate module. Typically, the expert advice provided under this module is directly integrated with available industry advice from published databases and literature and this is provided to the user. For example, under the hot water heating module, IF the home has a hot water heating system, which can be maintained, the information about actions to have an efficient system running will be provided. A demonstration of the information is indicated below:

It is advisable to set the water heater thermostat at 120 °F in order to slow mineral buildup and corrosion in your water heater and pipes, reducing standby losses and consumption losses from water demand or use in your home. Water heated at 140 °F also poses a safety hazard, such as scalding, and can waste between $36 and $61 annually in standby heat losses and over $400 in demand losses. For more information *go to:* http://energy.gov/energysaver/projects/savings-project-lower-water-heating-temperature.

All modules are integrated with each other and also linked to the data management subsystem through the knowledge-based management subsystem (KMS), and this ensures the interaction of expert knowledge and existing quantitative information (data management system), in order to assist users with energy retrofit decision-making.

4.8. Data Management Subsystem (DMS)

The database of the ERIDSS was meant to store appropriate energy retrofit data and supported the other knowledge-based modules. Database information in the DMS was configured into 3 database blocks: (1) energy assessment software from Building Energy Optimization (BEopt), (2) energy retrofit cost database from the national renewable efficiency measures (NREM) database, and (3) other published text, images, and videos primarily from government and additional scholarly documents. All three database blocks can be run in any sequence or period based on the information to be processed and the logic generated from any of the modules either individually or in conjunction with any of the KMS modules. Data in the third database block (published texts, images, and videos) and expert advice on installation blocks in the data management system can be edited individually without the need for a comprehensive data record. Data entered in the energy assessment software and energy retrofit cost database blocks are, however, edited based on the master edits from the database system administrators.

4.9. User Interface Subsystem (UIS)

The ERIDSS user interface subsystem incorporated the functions of the user interface of an expert system: (1) user, (2) user interface, (3) explanation facility, and (4) current context. The individual seeking advice for energy retrofit decision-making is referred to as the *user*. The proposed system was designed for the use of homeowners and energy retrofit professionals such as energy auditors and certified energy retrofit contractors, among others. The *user interface*, the accessible medium for interaction of the user with the system, has two functions: receive user information and translate into the system and providing system information to user in an easily understandable format, usually in texts, images, and videos. The *explanation facility* is responsible for explaining output logic in the form of rules in the KMS. This is achieved by identifying and demonstrating in an easy to understand format to the user, the steps used in the reasoning process. Since reasons for decision-making are explained, reliability of information provided is increased.

Producing a relevant decision/solution without the integration of quantitative information and the expert knowledge is challenging. Since user knowledge of their existing situation may be limited, providing specific information into the system may be unachievable. Thus, the *current context* function attempts to develop a decision/solution based on the available information. Finally, data from the DMS are integrated with knowledge from the KMS to provide information to help users with decision-making. The *inference engine* is the software system that performs the reasoning process and infers new decision-making options based on system expert knowledge. By providing the system with the ability to infer new knowledge to respond to different situations, the system is fortified. Data in the DMS and knowledge in the KMS are not useful without the *inference engine*.

5. Demonstration of ERIDSS application

The following explains the stages involved in the demonstration of the ERIDSS application.

5.1. Obtain Expert System

The ERIDSS was implemented as a pilot application using an Expert System shell from Exsys Corvid. The primary reason for this choice was based on the over 28 years of enhancement, refinement, and application of Exsys Corvid systems to real-world problems, capabilities, powerful but easy-to-use tools able to handle most demanding tasks, numerous case studies, and the use of the system by non-programmers (Exsys.com, 2011).

5.2. Select and obtain data from test homes

For the purposes of demonstrating the capability of the ERIDSS, two test homes were selected using the purposive sampling technique. Unlike probability sampling where generalizations can be made based on a selection of units from a population, purposive sampling has a primary goal of focusing on particular characteristics of a population with knowledgeable experts, to answer research questions. Since it is a form of non-probability sampling technique, there are a variety of criteria that can be used to include specific sample participants in purposive sampling. This includes specialist knowledge of research issue, capacity and willingness to participate in the research, and reliability and competence of participants (Lund Research, 2012; Oliver, 2013; Tongco, 2007). Test homes for this research were selected based on: (1) the capacity, availability, and willingness of homeowners to participate in the study, (2) unique homeowner characteristics (knowledgeable and novice homeowners to provide relevant home details and to gauge applicability of system respectively), and (3) location of test home in study area. As a result, two test homes from the Mid-West region of the U.S. were selected and data obtained (Table 2).

Table 2
Data obtained for test homes.

No.	Data requested	Data for test home #1	Data for test home #2
Thermal envelope			
1	Number of stories	One	Two
2	Year home was built	1970 – 2000	One
3	Approximate home size	901 – 2500 sq. ft.	1929 or before
4	Performed upgrades	Crawlspace and basement air sealing and insulation	901 – 2500 sq. ft.
5	Lower level of home description	Unconditioned basement and crawlspace	Crawlspace air sealing and insulation
6	Period of home occupation	All year round	Conditioned basement/unconditioned crawlspace
7	Basement/crawlspace description	Crawlspace has no insulation/has moisture issues	All year round
8	External home appearance	Winter – usually snow on roof	Basement: visible moisture issues
9	Type of windows	Majority single pane storm windows	Usually snow on roof in the winter
10	Doors/windows air leakage	A lot of draft	Majority are double pane
Heating and cooling system			
1	Main heating system	Central forced-air furnace	Central forced-air furnace
2	Fuel type	Natural gas	Natural gas
3	Age of heating system	10 years or less	11–29 years
4	Efficiency of heating system	90% AFUE (Annual Fuel utilization efficiency)	81%–89% AFUE (Annual Fuel utilization efficiency)
5	Size of heating system	90–119 kBtu/hr	89 kBtu/hr or less
6	Changing furnace filter	Regularly changed	Regularly changed
7	Control system for heating	Vary temperature on programmable thermostat	Vary temperature on programmable thermostat
8	Main cooling system	Central air conditioning	Central air conditioning
9	Age of cooling system	8–15 years	7 years or less
10	SEER rating of cooling system	SEER 13 or more	SEER 13 or more
11	Cooling system use rate	Rarely or never	Sometimes
Hot water heating system			
1	Main hot water heating system	Conventional storage water heating system	Conventional storage water heating system
2	Age of hot water heating system	15 years or less	15 years or less
3	Insulating blanket installed	No	No
Appliance use			
1	Clothes washer efficiency	Energy star rated	Standard rating
2	Clothes dryer efficiency	Energy star rated	Standard rating
3	Number of refrigerators	1	1
4	Refrigerator efficiency	Energy star rated	Energy star rated
5	Refrigerator: over 10 years	No	No
6	Stand-alone freezers	None	None
7	Dishwasher efficiency	Energy star rated	None
Water use			
1	Energy saving features installed	Low flow energy saving showerheads and water saving aerators	Low flow energy saving showerheads and water saving aerators
Lighting			
1	Type of lights used in home	Majority compact fluorescent or LED light bulbs	Majority compact fluorescent or LED light bulbs

5.3. Capturing the decision-making logic

Similar to the process described in section 5, Exsys Corvid provides Boolean logic in the form of IF-THEN rules to describe the decision-making process. The rules typically represent a section in a decision; thus, a complex system can be built by combining many rules. To develop rules, the first step involves the identifying suitable variables.

5.3.1. ERIDSS variables

Since most problems can be broken down into rational pieces, each can be represented as a variable. Based on the decision-making logic described earlier, the variables can be used to develop the rules and used in the system. When the system is run, users are asked to provide specific responses. The responses are used to assign values to the variables, derive values from other rules, or external sources such as another application or database is used. For instance, if the decision-making logic for identifying an energy retrofit measure must include the age of the home, "Age of Home" can be a suitable variable. Based on the elicited expert knowledge and relevant quantitative information, appropriate values such as 1900–1970, 1971–2000, and 2001–2013, can be provided to the user

Table 3
Variable types developed for the system (Duah, 2014).

ID	Name of variable	Variable type
Thermal envelope		
A1	Home Description	Static
A2	Architectural Characteristics	Static
A3	Age of Home	Static
A4	Performed Upgrades	Static
A5	Condition of lower level	Static
A6	Duration of Home Occupation	Static
A7	Basement or Crawlspace Features	Static
A8	External Appearance of Home	Static
A9	Window Condition	Static
A10	Draftiness of Home	Static
A11	Main Heating System	Static
Heating, ventilation, and air conditioning system		
B1	Main Heating System	Static
B2	Type of Furnace or Boiler	Static
B3	Furnace or Boiler Fuel Type	Static
B4	Electric Resistance Heating Type	Static
B5	Wood and Pellet Heating Type	Static
B6	Space Heater Type	Static
B6A	Heat Pump Type	Static
B7A	Age of Heating System	Static
B8	Efficiency of Main Heating System	Static
B9	Size of Main Heating System	Static
BB1	Furnace Filter Change	Static
BB2	Main Heating Control System	Static
BB3	Cooling System	Static
BB4	Age of Cooling System	Static
BB5	SEER Rating of AC	Static
BB6	Cooling System Use	Static
Hot water heating variables		
C1	Water Heating System	Static
C2	Age of Water Heating System	Static
C3	Water Heater Insulating Blanket	Static
Energy saving measures (appliances and water saving)		
D1	Clothes Washer	Static
D2	Clothes Dryer	Static
D3	Refrigerators	Static
D4	Refrigerator Rating	Static
D5	Refrigerator Age	Static
D6	Stand Alone Freezers	Static
D7	Stand Alone Freezer Rating	Static
D8	Stand Alone Freezer Age	Static
D9	Dishwasher	Static
E1	Low Flow Showerheads	Static
Lighting		
F1	Type of Light	Static
Energy retrofit advice		
G	Advice 1	Confidence
G	Advice 2	Confidence
G	Advice 3	Confidence
G	Advice 4	Confidence
G	Advice 5	Confidence
G	Advice 6	Confidence

to make a choice. Thus, a value will be assigned to the variable, and used in building the logic of the system (Duah, 2014). A total of 47 variables were developed for the ERIDSS (Table 3). Majority of the variables (41) were static variables and this helped in simplifying the system through the provision of options for each variable from which a user could make a choice. The remaining were confidence variables (6) and these helped in identifying suitable preferences for the user.

5.3.2. ERIDSS logic block

The logic for the system is developed in Logic Blocks and this provides a unique way of defining, organizing, and structuring rules into logically related blocks. The rules are organized using a tree structure and this allows related rules in the system to be grouped appropriately. Based on the series of logic developed for the ERIDSS in each module, appropriate rules were developed in Exsys Corvid using the variables. Fig. 3 shows a screen shot of part of the Logic Block. Each green square bracket indicates the IF part of the logic and the yellow arrows pointing to the right, the THEN part of the logic. The brackets specify a group of logics that use the same variable in the system even though they have different values. In instances of two "IF" parts of a logic, one is indented under the other and are combined with a logical "AND" to indicate that both parts of the logic are true. For the "THEN" part of the logic, the IF parts of the logic under which the "THEN" part falls must be true. "IF" parts of the logic that are associated with the "THEN" part of the logic are shown in the bold magenta color.

5.4. ERIDSS command block and inference engine

Every Exsys Corvid system must have a Command Block in order for it to function. Described as the "trigger block", the operational commands used for this system instructs Corvid to perform specific operations (Exsys, 2007). A single "DERIVE" command to run the rules was used in this system. With the exception of result display, the "DERIVE CONF" instructs the system what to do and when to do it. As a result, the "RESULTS" command was added. Relevant text and how they appear was modified under the command block. Having developed the Variables, Logic, and Command Blocks, the system was ready to run. Exsys Corvid does so using the Corvid Runtime Applet, which is displayed in the Corvid Browser window. The Inference Engine ensures that actions designed in the Command Block are adhered to using the developed Logic Blocks, thus serving as the "reasoning capacity" of the system (Exsys, 2007).

5.4.1. System user interface

The system structure allows for the interaction of the user with the system once the logic is working. The system can be run either using the system *inference engine* as a Java Applet, or as a Java Servlet Runtime program. Appearance features such as fonts, colors, positions, images, etc., similar to formatting a Microsoft Office Word document, are set in the default Applet mode. This allows the system designer to control how questions are asked and how results are displayed using the Corvid Runtime. Data from

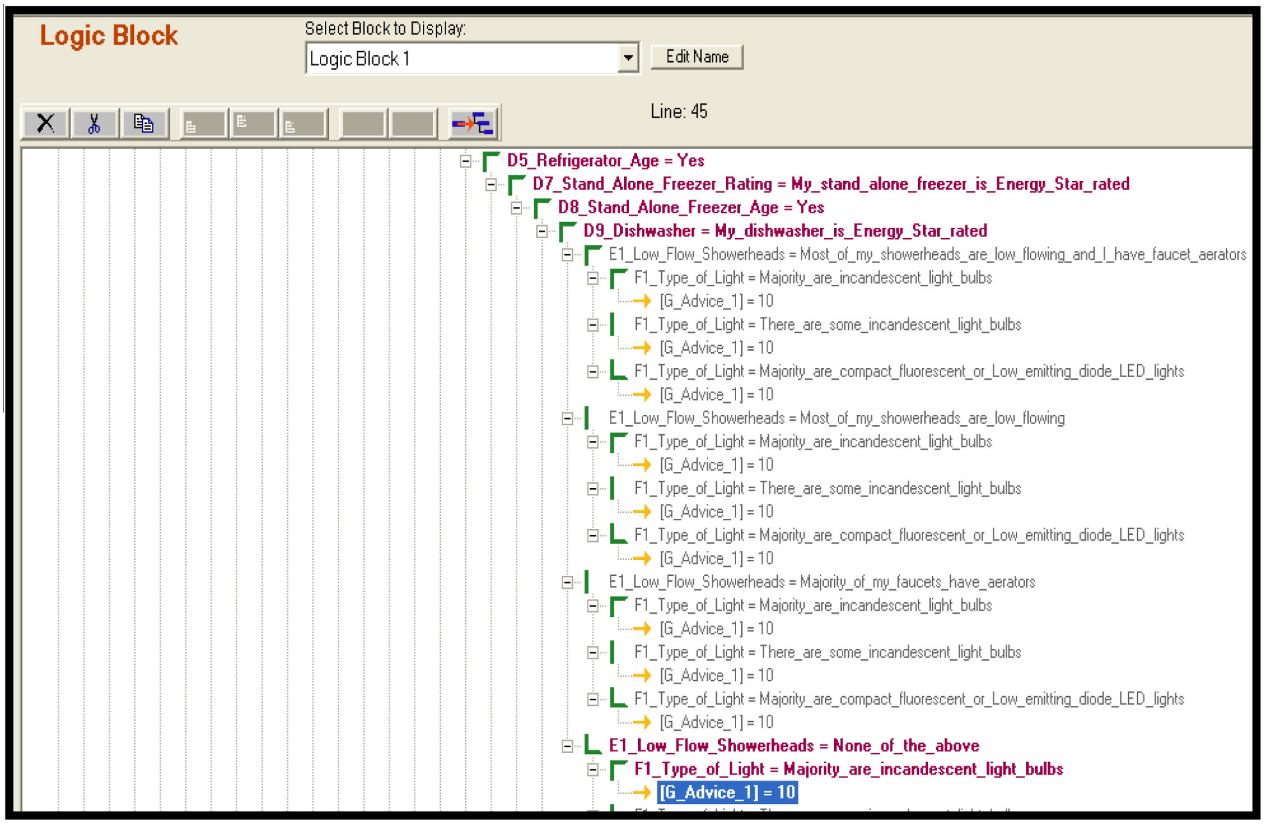

Figure 3. Screenshot of the energy retrofit logic block.

Table 4
Home energy retrofit advice for test home #1.

Test home # 1	
Thermal envelope	
Retrofit advice 1a	Upgrade energy inefficient main entrance door and window with energy efficient counterpart.
Retrofit advice 2a	Air seal door leading to garage
Retrofit advice 3a	Air seal door leading to crawlspace
Retrofit advice 4a	Air seal single-pane windows
Heating, cooling, and air conditioning system	
Retrofit advice 5a	Insulate heating ducts in basement
Windows	
Retrofit advice 6a	Upgrade windows to double-pane counterparts or better (note that the performance of this measure has very long payback periods)

Table 5
Home energy retrofit advice for test homes #2.

Test home # 2	
Thermal envelope	
Retrofit Advice 1b	Perform remedial action to solve moisture issues in basement walls Consult an industry expert for detailed cost information
Heating, ventilation, and air condition system	
Retrofit advice 2b	Upgrade existing furnace to energy efficient counterpart at $1100 with a lifetime of 20 years. More information: http://www.nrel.gov/ap/retrofits/measures.cfm?gId=2&ctId=308
Appliances	
Retrofit advice 3b	Upgrade standard clothes washer to energy efficient counterpart at $880 with a lifetime of 14 years. More information: http://www.nrel.gov/ap/retrofits/measures.cfm?gId=4&ctId=293
Retrofit advice 4b	Upgrade standard clothes washer to energy efficient counterpart at an average cost of $1,000 with a lifetime of 13 years. More information: http://www.nrel.gov/ap/retrofits/measures.cfm?gId=4&ctId=374

other resources can easily be integrated into Exsys Corvid through the provision of database connection. The system is able to read data files, or streams, and can also send information to a wide range of programs. Due to the ease and flexibility of setting up interfaces to external resources, the three components of the DMS found in the ERIDSS were incorporated into the system: energy assessment of homes software (BEopt), the NREM database, and published information in the form of text, images, and videos. Based on the data obtained for both test homes and entered into the system, Tables 4 and 5 indicates the retrofit advice offered for each of the homes by the system.

This paper demonstrates the development of an IDSS for HER that can assist consumers with decision-making. Using the expert system platform obtained from Corvid Exsys, data were obtained from 2 test homes in the state of Michigan, USA. Advice to improve the energy efficiency of both homes was provided and it yielded positive feedback.

6. Summary and conclusions

Based on the understanding of the information as a barrier to adoption of energy retrofits despite its well-established benefits, the relevance of an IDSS in supporting the consumers' decision-making process has been emphasized in this paper.

The research identified a comprehensive format that can be used to represent energy retrofit expert knowledge in order for it to be effectively used on an IDSS platform. Using knowledge models, IF-THEN-ELSE rules were developed by representing industry-based expert knowledge in the form of such condition-action pairs. As a result, series of rules were developed for the available expert knowledge obtained for this research. Additionally, in order to provide users with appropriate information to help with decision-making in this domain, an ERIDSS with the following major components was developed by the researchers: knowledge-based management subsystem (KMS), data management subsystem, and the user interface subsystem. The KMS was the central component and was emphasized. Finally, the applicability of the ERIDSS using an expert system platform obtained from Exsys Corvid was demonstrated using two test homes where results led to the refinement of the system. It also indicated a strong potential for extending the use of the system to a wider population since advice to improve home energy efficiency obtained positive feedback. There were, however, challenges with cost of measures and a detailed estimation on the return on investment, an aspect not comprehensively covered in the cost database available.

This research has significant benefits regarding improving the uptake of energy retrofits particularly by homeowners. As an attempt at solving the information barrier to the adoption of energy retrofits, the ERIDSS can be useful in assisting industry practitioners with the corroboration of knowledge and information they provide to homeowners. This can result in the reduction in the perception of bias homeowners have about industry practitioners. In addition, the development of the six knowledge-based modules provides a very good understanding of the available implicit knowledge in the energy retrofit industry. Finally, the system and approach developed and used in this research can be replicated in other domains.

Acknowledgements

The funding for this research is provided by the National Renewable Energy Laboratory (NREL) as part of the Building America (BA) Program in conjunction with U.S. Department of Energy (DOE). In addition, several energy auditors and trade contractors provided industry input. The authors gratefully acknowledge these contributions. The opinions and findings expressed here, however, are those of the authors alone and not necessarily the views or positions of NREL, BA Program and DOE.

References

American Council for an Energy-Efficient Economy [Internet]. Washington: Building envelope; c2002-2013 [cited 2013 Nov 11]. Available from: http://aceee.org/consumer/building-envelope.

Armstrong JK. [Internet]. Albuquerque: Notes on the psychology of expertise; c2012 [cited 2012 Feb 14]. Available from: http://www.unm.edu/~jka/courses/archive/expertise.html.

Arnott, D., 2004. Decision support systems evolution: framework, case study and research agenda. Eur. J. Inform. Syst. 13 (4), 247–259.

Baechler, M.C., Gilbride, T.L., Hefty, M.G., Hand, J.R., Love, P.M. [Internet]. Washington: HVAC: A guide for contractors to share with homeowners; c2011 [cited 2013 Oct 12]. Available from: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/hvac_guide.pdf.

Berry, L., 1993. A review of the market penetration of U.S. residential and commercial demand-side management programs. Energy Policy 21 (1), 53–67.

Cellier, J., Eyrolle, H., Marine, C., 1997. Expertise in dynamic environments. Ergonomics 40 (1), 28–50.

Druzdzel, M.J., Flynn, R.R. [Internet]. Pittsburgh: Decision support systems; 2002 [cited 2012 Feb 1]. Available from: http://www.pitt.edu/~druzdzel/psfiles/dss.pdf.

Duah, D.Y.A., Ford, K., Syal, M., 2014. Expert knowledge elicitation for decision-making in home energy retrofits. Structural survey. J. Build. Path. Refurb. 32 (5), 377–395.

Duah, D., Ford, K., Syal, M., 2015. Role of expert knowledge in home energy retrofits. IJAEC, Forthcoming 2015.

Duah, D.Y.A., 2014. Intelligent Decision Support System Framework for Home Energy Retrofits in Existing Homes [Dissertation]. Michigan State University, East Lansing (MI).

Energy Efficiency and Renewable Energy [Internet]. (2001). Water heating: Energy efficient strategies for supplying hot water into a home; c2001–2013 [cited 2013 Oct 14]. Available from: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/26465.pdf.

Energy Saver [Internet]. Selecting a new water heater; c2012a–2013 [cited 2013 Sep 13]. Available from: http://energy.gov/energysaver/articles/selecting-new-water-heater.

Energy Saver [Internet]. Heat distribution systems; c2012b–2013 [cited 2013 Sep 9]. Available from: http://energy.gov/energysaver/articles/heat-distribution-systems.

Energy Saver [Internet]. Central air conditioning; c2012c–2013 [cited 2013 Sep 12]. Available from: http://energy.gov/energysaver/articles/central-air-conditioning.

Energy Saver [Internet]. How energy-efficient light bulbs compare with traditional incandescents; c2012a-2013 [cited 2013 Oct 16]. Available from: http://energy.gov/energysaver/articles/how-energy-efficient-light-bulbs-compare-traditional-incandescents.

Energy Star [Internet]. Energy star qualified appliances: save energy through advanced technologies; c2013a [cited 2013 Oct 16]. Available from: http://www.energystar.gov/ia/new_homes/features/Appliances_062906.pdf.

Energy Star [Internet]. Make a cool change: recycle your old fridge; c2013b [cited 2013 Aug 23]. Available from: http://www.energystar.gov/index.cfm?c=recycle.pr_refrigerators.

Energy Star [Internet]. Freezers for consumers: about energy star refrigerators; c2013c [cited 2013 Aug 23]. Available from: http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=FRZ.

Exsys.com [Internet]. Albuquerque: Exsys Corvid advanced tutorial; c2007 [cited 2013 Nov 23]. Available from: http://www.exsys.com/PDF/ExsysCorvidAdvancedTutorial.pdf.

Exsys.com [Internet]. Albuquerque: Exsys Inc. – The expert system experts; c2011–13 [cited 2013 Jul 9]. Available from: http://www.exsys.com/.

Farrington-Darby, T., Wilson, J.R., 2006. The nature of expertise: a review. Appl. Ergon. 37, 17–32.

Fuller, M., Kunkel, C., Ziming, M., Hoffman, I., Soroye, K.L., Goldman, C. [Internet]. Driving demand for home energy improvements: Motivating residential customers to invest in comprehensive upgrades that eliminate energy waste, avoid high bills, and spur the economy. C2010–12 [cited 2012 Oct 6]. Available from: http://escholarship.org/uc/item/2010405t#page-1.

Gellings, C.W., Parmenter, K.E., 2004. Building envelope efficiency measures. In: Gellings, C.W. (Ed.), Efficient use and conservation of energy. EOLSS Publishers, Oxford, pp. 55–78.

Glaser, R., Chi, M., 1988. Overview. In: Chi, M., Glaser, R., Farr, M. (Eds.), The nature of expertise. Lawrence Erlbaum, New Jersey, pp. xv–xxxvi.

Hendron, R., Engebrecht, C. [Internet]. Building America house simulation protocols; c2010–13 [cited 2013 May 22]. Available from: http://www.nrel.gov/docs/fy11osti/49246.pdf.

Hershfield, M. [Internet]. Building envelope continuity: Part 1 – building science basics; c2013 [cited 2013 Nov 11]. Available from: http://www.peci.org/sites/default/files/building_envelope_continuity_-_part_1_-_building_science_basics.pdf.

Ho. S, Hays, J. [Internet]. Increasing demand for home retrofits: Community-based outreach and mobilization; c2010–12 [cited 2012 Oct 6]. Available from: ttp://www.skill-works.org/documents/FinalCommunityMobilization4HomeRetrofits-1_6-10.pdf.

International Energy Agency [Internet]. What is Energy Efficiency?; c2011-12 [cited 2012 May 25]. Available from: http://www.iea.org/efficiency/whatisee.asp.

Johnson Controls [Internet]. Milwaukee: Building energy efficiency and sustainability; c2013 [cited 2013 Oct 3]. Available from: http://www.johnsoncontrols.com/content/us/en/products/building_efficiency/service-and-solutions/energy_efficiency.html.

Johnson Controls [Internet]. Milwaukee: Building energy efficiency and sustainability; c2012 [cited 2012 Sep 15]. Available from: http://www.johnsoncontrols.com/content/us/en/products/building_efficiency/energy_efficiency.html.

Kim, Suk-Kyung, Mrozowski, T., Harrell-Seyburn, A., Ehrilich, N., Hembroff, L., Lieburn, B., Mazor, M., Mclntyre, A., Mutton, C., Parsons, G., Syal, M., Wilkinson, R., 2013. Market characterization project. Building Technologies Program, U.S. Department of Energy. Final Report submitted in November 2012 and being reviewed.

Krigger, J., Dorsi, C., 2009. Residential energy – cost savings and comfort for existing buildings, 5th ed. Saturn Resource Management Inc., Montana.

Lawrence Berkeley National Laboratory [Internet]. Berkeley: What's Energy efficiency? c2012 [cited 2012 May 20]. Available from: http://eetd.lbl.gov/ee/ee-1.html.

Lee, D. [Internet]. Better buildings 2.0; c2010–11 [cited 2011 Sep 15]. Available from: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ns/plenary_3_betterbuildings.pdf.

Leishman, J. [Internet]. Decision support systems; c2005–12 [cited 2012 Nov 6]. Available from: *www.freequality.org/documents/Training/DecisionSupportSys.ppt.

Liao, S., 2005. Expert system methodologies and applications – a decade review from 1995 to 2004. Expert Syst. Appl. 28 (1), 93–103.

Limerick, P., Geller, H. [Internet]. What every westerner should know about energy efficiency and conservation – a guide to a new relationship; c2007-12 [cited 2012 Nov 12]. Available from: http://www.centerwest.org/publications/pdf/energycons.pdf.

Lstiburek, J. [Internet]. Conditioned crawl space construction, performance, and codes; c2006–13 [cited 2013 May 23]. Available from: http://www.buildingscience.com/documents/reports/rr-0401-conditioned-crawlspace-construction-performance-and-codes.

Lund Research [Internet]. Purposive Sampling; c2012–13 [cited 2013 Oct 28]. Available from: http://dissertation.laerd.com/purposive-sampling.php.

Metoyer, M., 2013. Expert interview conducted for the development of rules. Construction Management Program, School of Planning, Design, and Construction, p. 2013, Sep..

Neme, C., Gottstein, M., Hamilton, B. [Internet]. Residential energy efficiency retrofits: a roadmap for the future; c2011–12 [cited 2012 Oct 5]. Available at:" www.raponline.org/document/download/id/918.

Oliver, P. [Internet]. Purposive Sampling. c2013 [cited 2013 Oct. 28]. Available from: http://srmo.sagepub.com/view/the-sage-dictionary-of-social-research-methods/n162.xml.

Özbayrak, M., Bell, R., 2003. A knowledge-based decision support system for the management of parts and tools in FMS. Decis. Support Syst. 35 (4), 487–515.

Palmquist, R.A. [Internet]. AI and expert systems. c2001 [cited 2011 Sept. 23]. Available from: http://www.ischool.utexas.edu/~palmquis/-courses/ai96.htm.

Power, D.J. [Internet]. What is a decision support system? c1998 [cited 2012 Jun. 6]. Available from: http://dssresources.com/papers/whatisadss/.

Samuel, S., 2011. Information framework for residential energy retrofit [dissertation]. Michigan State University, East Lansing (MI).

Shanteau, J., 1992. The psychology of experts: an alternative view. Expertise and decision support. In: Bolger, F. (Ed.), Wright G. Plenum Press, New York, pp. 11–23.

Singhaputtangkul, N., Low, S.P., Teo, A.L., Hwang, B., 2013. Knowledge-based decision support system quality function deployment (KBDSS-QFD) tool for assessment of building envelopes. Automat. Constr. 35, 314–328.

Syal, M., Duah, D., Samuel, S., Mazor, M., M, Y., Cyr, T., 2014. Information framework for intelligent decision support system for home energy retrofits. J. Constr. Eng. Manag. 140 (1).

Syal, M., Duah, D., Samuel, S., Mo, Y., Cyr, T., Alcott, J., Kim, S., Lieburn, Mazor, M., McIntyre A, Mrozowski, T. Information framework development for retrofit technology measures. Golden (CO): National Renewable Energy Laboratory Residential Buildings, United States Department of Energy (Accepted 2013 Nov 2).

Tongco, M.D.C., 2007. Purposive Sampling as a tool for informant selection. ERA 2007 (5), 147–158.

Turban, E., 2005. Decision support and intelligent (expert) systems. Prentice Hall, New Jersey.

Turban, E., Aronson, J.E., Liang, T., 2005. Decision support systems and intelligent systems, 7th ed. Pearson, Prentice Hall, New Jersey.

Turban, E., Watkins, P.R., 1986. Integrating expert systems and decision support systems. MIS Quart. 10 (2), 121–136.

U.S. Congress, Office of Technology Assessment [Internet]. Energy efficiency: challenges and opportunities for electric utilities. c1993

[cited 2012 Sep. 13]. Available from: http://www.fas.org/ota/reports/9323.pdf.
United States Department of Energy. [Internet]. Building energy codes program: about building energy codes. c2013 [cited 2013 Aug. 20]. Available from: http://www.energycodes.gov/about.
United States Department of Energy [Internet]. Furnaces and boilers. c2013 [cited 2013 Dec. 4]. Available from: http://energy.gov/energysaver/articles/furnaces-and-boilers.
United States Environmental Protection Agency. [Internet] National action plan for energy efficiency. c2006 [cited 2012 Jan. 9]. Available from: http://www.epa.gov/cleanenergy/documents/suca/napee_report.pdf.
Vohra, R., Das, N.N., 2011. Intelligent decision support systems for admission management in higher education institutes. IJAIA 2 (4), 63–70.
Warszawski, A., 1985. Decision models and expert systems in construction management. Build. Environ. 20 (4), 201–210.