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Expert Knowledge Base Development for an Industrial Energy Assessment System

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Expert Knowledge Base Development for an Industrial Energy Assessment System

by
Paolo J. Piunno

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Expert Knowledge Base Development for an Industrial Energy Assessment System

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ABSTRACT

Industrial energy management is critical to achieve and monitor industrial energy efficiency. Decision support systems enable energy managers to form effective strategies to increase profitability by eliminating wasteful practices. A well formulated knowledge base is essential for a decision support system to function. Expert knowledge must be acquired and coded into a knowledge base to be accessible to a decision support system. The primary objective is to devise a methodology to extract expert knowledge acquired through field work or archived in manually generated energy analysis reports. Once the knowledge is extracted it can be codified and stored in a knowledge base that is validated to be usable by an energy management assistant decision support system. The acquisition and codification method is demonstrated by its implementation in the REACTOR energy management software system.

DEDICATION

A fundamental principle in my life is the acquisition of knowledge which empowers me to achieve more.

I would like to dedicate this thesis to my family and mentors who nourish my creativity, motivate me to think critically, and enhance my life.

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1.0 INTRODUCTION

1.1 OVERVIEW

Industrial energy management is an effective method to eliminate unnecessary expenses and increase bottom line profits. Industrial energy efficiency is achieved by monitoring and controlling the flow of energy through a facility. Decision support systems enable industrial energy managers to make informed decisions that mitigate overconsumption. A well formulated knowledge base is required for a decision support system to assist energy managers. A knowledge base is constructed through knowledge acquisition methods that capture and codify expert human knowledge to be understood by a decision support system. Decision support systems rely on knowledge bases to deduce solutions to problems defined by various user inputs and parameters.

The primary objective of this thesis is to determine a method of extracting knowledge from experts in the field of industrial energy management and validating that knowledge once it is coded into a knowledge base. The purpose is to apply the benefits of associating a well constructed knowledge base to the REACTOR decision support system described later in this document. This will be achieved by evaluating current industrial energy conservation practices, decision support systems used in industry, and the process of constructing effective expert knowledge bases. Following the evaluation the focus is shifted to the methodology of expert knowledge acquisition, codification, validation, and storage in a knowledge base. The benefits of drawing information from knowledge bases using decision support systems are evaluated and presented.

1.2 CHAPTER SUMMARY

1.2.1 Chapter 2: Literature Review and Project Background

This chapter defines the problem space of industrial energy efficiency. The actions that are required to improve industrial efficiency are highlighted in terms of industrial energy management. The importance of a facility energy baseline for monitoring and targeting energy conservation goals is explained. The definition of energy auditing is clarified with respect to data collection and analysis methods. This leads to the requirements of energy conservation measure generation. The importance of expert intervention in audit reporting is associated to implementation rates.

These discussions lead to the integration of decision support systems into energy management. The history of decision support systems is described in terms of industrial uses. An analysis of existing energy management information systems shows the features and limitations of existing technology. This demonstrates that the similarity between various decision support systems lies in the expert knowledge base. The knowledge acquisition requirements to construct an effective expert knowledge base are described.

1.2.2 Chapter 3: Design and Methodology

This chapter provides an overview of the methodology used to develop and test the REACTOR decision support system. The system design benefits that accommodate different user types are highlighted. The different user groups are identified with their roles. The program structure is outlined to show the system components that define the

REACTOR system. Computing requirements are listed to demonstrate the framework of the system which provides insight about its functionality.

The methodology used to create the system shows how it fulfills the objective of automating the audit process. This demonstrates the benefit of the system as an industrial energy efficiency management tool for energy managers. Integrating financial models and energy conservation measures is a feature enhancement of the decision support system. Methods used to acquire knowledge to store in the knowledge base emphasize the importance of the systems diversity. The iterative design process used to build the system relies on several information sources. This process also requires continuous testing that incrementally increases in degree of complexity. The information contained within the knowledge base must be validated through a standardized process to ensure that the system achieves optimal functionality.

1.2.3 Chapter 4: Analysis of Results

This chapter gives a detailed analysis of the results obtained by implementing the methodology defined to develop the REACTOR system. The results are described in terms of the system's contribution to industrial energy efficiency evaluation and reporting. The system is then evaluated as a decision support system in terms of its features and added benefits. The system's ability to effectively capture expert knowledge is evaluated using the knowledge base editing tools that were developed to assist with knowledge acquisition. The details of the analysis are further explained in terms of the iterative system development and testing process. The knowledge base validation methodology is then evaluated for its effectiveness.

1.2.4 Chapter 5: Discussion and Conclusions

This chapter summarizes the results of the analysis of the REACTOR decision support system knowledge base construction process. It provides insight into the importance of a well constructed knowledge base for a decision support system to function properly. The system's uses for industrial energy efficiency are described which explains how the development process was influenced by the current industrial practices. The benefits of the system are listed to demonstrate how the design objectives are satisfied. The contributions of each testing phase describe the system enhancements achieved by working in the field with industry experts. The knowledge base validation process that was used in conjunction with the field testing is explained.

The importance of expert knowledge for the functionality of the REACTOR system is reiterated. This leads to a detailed methodology that can be used to construct effective knowledge bases. Details of how the REACTOR system sets itself apart from other methods of industrial energy management are described. This helps explain how the system is able to improve profits with energy monitoring and goal targeting techniques. The discussion clarifies how energy managers can expand their knowledge by using the system. The future plans for the introduction of the REACTOR decision support system into the industrial marketplace are identified.

CHAPTER II

2.0 LITERATURE REVIEW AND PROJECT BACKGROUND

2.1 INDUSTRIAL ENERGY EFFICIENCY

Energy efficiency has become increasingly relevant in industry. Market demands and economic conditions have provoked industry to increase quality, sustainability, and efficiency. Industry standards have increased the need for assessment tools and external auditing. Due to recent economic downturns, industry has to adjust expenses in order to increase or maintain profit margins while remaining competitive. Reducing operational baseline cost is an effective method to achieve this. Utility expenses account for a large part of operating cost. Reducing consumption requirements can often be done in a way that does not have a negative impact on production.

To improve energy efficiency and reduce operating cost, an energy action plan must be established according to Jutsen (2005). Targets can be set by analysing the current energy consumption and projecting the potential reductions and improvements. An energy audit is a process that involves a series of facility and process evaluations. An effective energy audit can be used to baseline the current status of a facility in a report. A baseline audit evaluates all of the consumers within a facility and their average operating times and loads. Once the facility baseline has been established the second task of an energy audit is to determine which processes or operations are not essential to the functionality of a facility. An action plan to reduce or eliminate the unnecessary consumption is detailed in a report. After the unnecessary consumers have been addressed, the third task is to evaluate the operations to develop recommendations that aim to reduce consumption. This is an iterative process that continuously strives for efficiency improvements. To ensure the energy efficiency initiatives continue to be beneficial a follow-up tracking process must be implemented to monitor program effectiveness.

Energy managers serve an increasingly important purpose as the challenge of effective industrial energy efficiency continues to grow. Ferrari (1990) said that an energy manager should be ‘a person who not only sees to the rational use of energy but who also assures a continuity of supply of energy for the production sector, considering both efficiency and assurance simultaneously’. In particular, the energy manager would have to evaluate, case by case, when one of these two approaches should prevail. Therefore, good energy management requires an interdisciplinary competence including capabilities in engineering, economics and management. This high level of competence necessarily implies a certain authority of the energy manager within the company; this authority must be transformed into power within the company hierarchy.

2.1.1 Facility Baseline

Energy consumption must be tracked in order to set new goals and achieve energy efficiency. Standard energy consumption quantifiers must be established to track industrial energy efficiency. The most fundamental quantifier of industrial energy efficiency is the facility baseline of energy consumption. Paul (2005) defines a baseline as establishing reference energy trends over a defined period of time to track the effectiveness of energy efficiency measures and programs. A baseline can be used to monitor a single facility or to identify trends across a group of similar facilities. Beyene

(2005) concluded from his research in energy efficiency and industrial classification that regulatory supports for documented energy savings, or methodology development to assess and quantify the impact of energy saving measures, are very useful to reduce energy intensity. The facility baseline documentation and methodologies have to be standardised in order to be useful. Beyene has identified the primary challenge of regulating industrial energy efficiency as the lack of in-house expertise to implement efficient and innovative energy management initiatives in small to medium size facilities. An energy management decision support system would mitigate this issue by providing any user access to expert knowledge that is required to make energy management decisions.

2.1.2 Collection and Analysis of Data

Utility consumption must be closely monitored to effectively improve energy efficiency. An operational baseline can be established by observing a facility's energy usage and comparing it to the demand of individual equipment. An energy audit is a method of establishing an energy baseline and generating recommendations to improve energy efficiency. Zingale (2005) defined an energy audit as an evaluation of the cost and benefit of implementing energy conservation measures that include behavioural or maintenance improvements, equipment replacement, facility improvement, and rate or fuel options. The goal of an energy audit is to produce a benchmark comparison by evaluating energy bills and other demographic factors on a normalized basis. This method is useful for identifying realistic and achievable energy efficiency targets. According to Paul (2005) potential areas for improvement can be defined by collecting energy usage data and comparing it to the facility energy baseline. A prioritized list of energy conservation recommendations is generated by evaluating each recommendation in terms of simple payback period which is capital cost over annual return on investment.

2.1.3 Recommendations

Studies carried out by Tonn (2000) have shown a linear correlation of monetary savings as a result of capital invested in energy conservation. He predicted that a facility may gain approximately 28% of the project implementation cost in annual savings. He also found that there is a direct relationship between expert intervention and improvements in industrial energy efficiency. These improvements can be further enhanced by utilizing decision support systems which improve the relevance of the recommended actions by basing decisions purely on facts to minimize bias. In this way decision support systems help to improve report quality which establishes more confidence in financial decision makers to further improve implementation rates.

Audit recommendations and best practice recommendations are the two primary types of energy conservation measures used in the standard energy audit reporting style as explained by Zhivov (2010). An audit recommendation is a suggested energy conservation measure that appears in an energy audit report accompanied by supporting calculations that show estimated cost of implementation, predicted annual savings, and simple payback period. Audit recommendations are most useful for financial planning because they give a clear indication of the predicted return on investment. Best practice recommendations are suggested energy conservation measures which indicate some savings are possible through implementation although there is no feasible way of calculating specific details of cost or payback. These recommendations are expected to reduce consumption but implementation is usually left to the discretion of the energy manager or auditor based on their personal knowledge or past experience. By utilizing a decision support system the decision makers are able to enhance their choices by drawing additional information from the expert knowledge base.

Recommendations that are generated through energy audit reporting must be validated before implementation as Menezes (2006) shows. This avoids costly experimentation and helps decision makers create an effective energy action plan. By collecting data from the facility operations, calculations and evaluation tests can be used to model energy consumption. The current consumption models can be modified to reflect the implementation of energy conservation measures. These calculated changes can then be compared to similar scenarios through a series of evaluation tests. An evaluation test utilizes operations that compare calculated values to predefined parameters. The parameters are extracted from experts and archived audit reports. The decision of the evaluation test can be based on a number of scenarios that include annual savings, capital cost, payback period, or implementation rates. Typically the decision is made by a financial decision maker, although Bhattacharjee (2010) explains that in recent years energy managers have taken on a more authoritative role in the corporate structure. A decision support system could assist financial decision makers and energy managers to make informed choices about implementing new energy conservation measures.

2.1.4 Reporting and Implementation

The objective of incorporating a decision support system into the process of energy auditing is to make informed decisions about project implementation from a business perspective. One of the greatest challenges for improving energy efficiency, according to Najafi (2005), is to convince management to implement an energy conservation initiative. His study focuses on the socioeconomic factors that influence decision making which he outlined in three factors that increase implementation rates. These factors are communication throughout and after the auditing process, the presentation of technical data, and the selection of recommendations that have the best probability of implementation based on client conditions.

2.2 DECISION SUPPORT SYSTEMS

A decision support system is an interactive software-based system that supports decision making activities as defined by Stefik (1995). Decision support systems rely on knowledge-based systems in order to make informed decisions. The purpose of employing decision support systems in energy management is to reduce bias and improve the efficiency of the decision making process for industrial energy conservation and planning. Decision support systems are able to identify and solve problems by using a combination of collected data, archived documents, and codified human knowledge. The system is then able to make decisions, or human decision makers are then able to make decisions, based on the results of its analysis.

Decision support systems are designed to enhance the communication of all parties involved with an energy management initiative. The decision support system allows the auditors and facility personnel to focus on the tasks at hand while they work together to provide the system with the information necessary to make informed decisions. A well constructed knowledge base is required to analyse the technical data and present it to the users in an effective way. The knowledge base contains recommendation implementation rate information gathered from previous energy audits. With this information the decision support system is able to provide recommendations that are most likely to be implemented given the situation. These features are designed to encourage management to implement energy conservation initiatives based on facts that are reinforced by continued use.

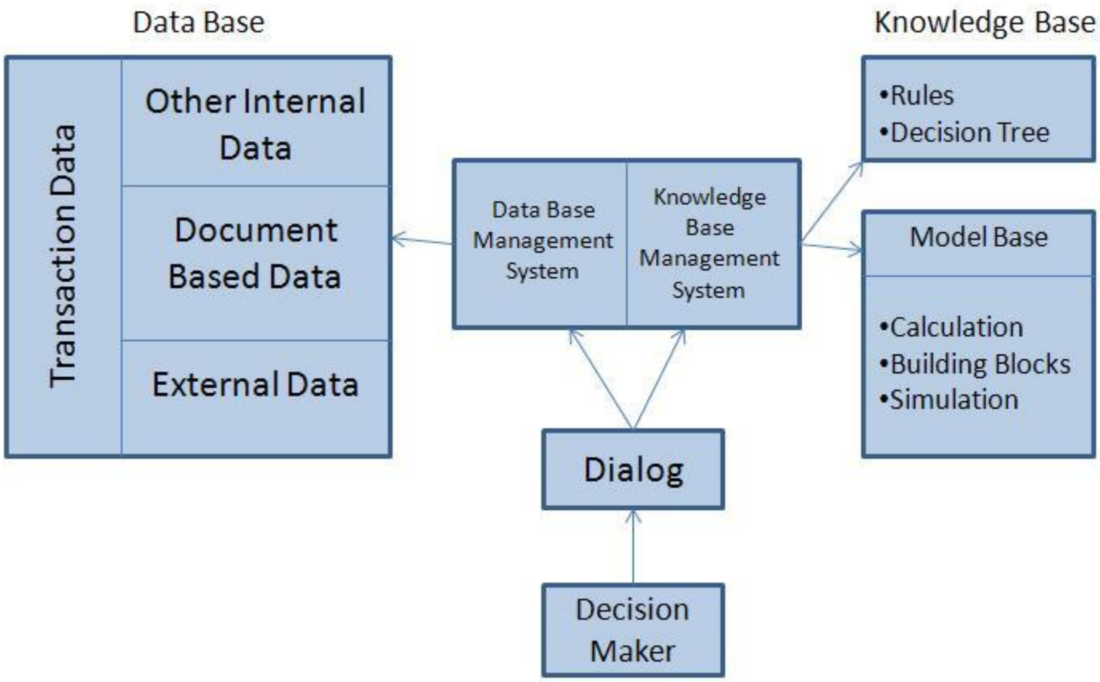

Figure 1: Decision support system framework. (Adapted from Sprague Jr. and Watson (1996).)

The basic construction of a decision support system is outlined in Figure 1 which is a modified version of the original, Sprague Jr. and Watson (1996). In this example the decision maker interacts directly with the dialog component through a graphical user interface. This interface allows the user to manipulate the data base and knowledge base management systems. The data base is used to store transaction data such as information collected by the user through site analysis, calculation results, client information, or document templates. The knowledge base management system allows the user to store information in the knowledge base. The user is able to store knowledge as a set of rules that define the path of a decision tree or as a model in the model base. Expert knowledge must be acquired, codified, and validated before the information can be stored in the knowledge base.

2.2.1 Background and Purpose

Decision support systems have been used in industry for many years. According to Gray (1987), decision support systems gained intensity as an area of research in the 1980's. They are commonly used to make financial business decisions in industry although the systems are typically process or product oriented. Due to recent economic downturns companies are looking for alternative ways to improve efficiency and reduce expenses. Rosenberg (2001) conducted an industrial energy study that demonstrates the importance of energy efficiency in terms of sustainability. He concluded that by realizing lower energy costs and implementing strategies that lower energy consumption, companies can become more competitive in the national and international markets, thus creating jobs and tax revenue. In the case of an economic downturn, plants could avoid closure and job loss. As a result, industry is beginning to focus on utility based operational expenses in addition to considering the traditional approach of comparing material and labour costs to revenue.

Decision support systems are able to identify and solve problems by using a combination of past experiences. Stefik (1995) defines an experience with regards to knowledge systems as 'a source of information that can be used in problem solving'. This information can be extracted from collected raw data, archived documents, and codified human knowledge. The system is then able to make decisions by analysing the results of past experiences and comparing them to the current situation.

2.2.2 Existing Methods

Energy managers are responsible to plan and implement energy efficiency initiatives. Knowledge and experience are critical to effective decision making. It takes time to acquire the knowledge required for an energy manager to be able to make informed decisions about process changes and project implementation. By capturing expert knowledge from external sources and coding it into knowledge bases the knowledge transfer can be implemented through a decision support system. Alternatively, those energy managers who are in demand because of their expert knowledge can assess energy efficiency cases more quickly with the assistance of a decision support system.

Industrial energy efficiency can be monitored in real time with energy management information systems (EMIS) or benchmarked and monitored with various energy auditing techniques demonstrated by Knapp (2006). Regardless of the method used for data collection and analysis the most critical aspect is ultimately the final decision. Energy audits are effective to monitor and target energy conservation measures. Various methods of energy auditing exist with many similarities in the data acquisition and analysis objectives according to Knapp. Each method typically uses the same general concept of time-point data analysis based on historical and projected future consumption.

Real time data collection with an energy management information system (EMIS) audit process is used to facilitate the assessment of an organization's current energy usage to help identify gaps and determine feasible solutions. Scott (2012) explains how information systems can be used to mitigate risk when making financial decisions that affect energy conservation. As part of her research expert knowledge was captured to describe various organizations' past encounters with energy conservation investment risk.

The transition from what Scott refers to as 'engineer-led culture of risk cognition' to 'market oriented financial risk management' revealed two distinct results. Firstly, this transition demonstrates that developing software that combines energy transaction and risk management provides access to an important learning ground, especially during periods of typical change. Secondly, it describes how the development of a risk management information infrastructure provides insights into the enhancement of various types of risk factors. Energy management information systems are useful for tracking facility health and monitoring the effectiveness of implemented energy conservation measures.

Industrial energy systems can be modelled so that accurate predictions about the effect of implementing different energy conservation measures can be analysed before investing in new equipment or altering an industrial process. Karlsson (2011) devised the 'Method for analysis of INDustrial energy systems' (MIND). The MIND method is a flexible method of decision support that is constructed for different types of analysis of industrial energy systems. The MIND method was originally developed to model various types of industrial energy systems. There are four basic steps that the model follows. The first step is to define the boundaries of the problem space for analysis. In the second step a model is built as a structure of branches and nodes that represent the various parts of an operation including utilities, resources, equipment or entire processes. These factors are used to develop a matrix of equations that define the problem space and each of its components. The third step is to optimize the matrix of equations that were defined to model the industrial energy system. The equations can be optimized to minimize any type of resource although the system cost is usually selected as the minimizing factor.

The system cost is most often selected as the minimizing factor since it includes the cost of energy, investment, and raw material which results in the most efficient solution. The fourth and final step is to represent the results of the optimization in a format that is usable by the decision makers such as a text-file that can be read in Microsoft Excel. The results are then validated by the user and a decision is made as to which energy conservation measures would be most effective. This method provides a holistic energy analysis of an industrial facility although it lacks a knowledge base so it is very labour intensive. Expert intervention is required to define models to analyse every facility.

2.3 CAPTURING EXPERT KNOWLEDGE

2.3.1 Expert Knowledge Base

The knowledge base is a critical component required by decision support systems to have the ability to make informed decisions. The impact that expert knowledge has on industrial energy efficiency is described by Tonn (2000) in terms of energy conservation opportunity identification and measures implementation. The assessment showed that the intervention of an expert substantially increases the frequency of opportunity identification by 60% and the implementation of energy conservation measures by 54%. A decision support system is an effective tool to assist energy management personnel by providing the information they require to make their own decision or provide a decision directly with reasoning.

A decision support system is able to use past experiences to assist with decision making. The experiences must be made available to the decision support system through a knowledge base. The information coded into the knowledge base is collected using various methods of knowledge acquisition such as information gathering through field visits or system modeling through expert consultation according to Gammack (1989). Experiences are codified information derived from expert knowledge. Since knowledge used by decision support systems are derived from past experiences, as a decision support system is exposed to a situation it collects information that can be saved as a new experience in the knowledge base. These codified experiences are then made accessible to the decision support system and enable the system to make informed decisions.

2.3.2 Knowledge Acquisition and Validation

Decision support systems require knowledge to make decisions. Formalizing and codifying knowledge is a major task in building a complete functional system. Rules and facts must be obtained by reviewing archived documents, interviewing experts, and testing in the field. Nilsson (1980) discussed three methods for automating the knowledge acquisition process. The first was to develop an editing system that would allow experts in the domain of the application who are not computer programmers to interact directly with the knowledge base of the system. The second would involve natural language processing techniques that allow users to instruct and teach computer systems through ordinary conversational techniques. Third was expanding the ability of the systems to learn important knowledge directly from their experiences within their operating domains.

Regardless of the method of knowledge acquisition the information must be validated before it is stored in the knowledge base. Di Biase (1998) demonstrated that if the information being used for industrial energy management is not validated the results will unreliable. A methodology for validating the information being stored in an expert knowledge base must be developed and tested. Di Baise explained that expert interaction through mathematical and statistical tools must be used to ensure that the information contained within the system is valid and usable.

2.4 REACTOR PROJECT BACKGROUND

REACTOR is the Rapid Energy Audit Collection Tracking Organization and Reporting decision support system. It assists with the collection, analysis, and reporting on information for energy auditing. The system has been designed to accommodate various needs in the field of industrial energy management. Najafi (2005) stated that the objective of an energy manager should be to convince management to implement an energy conservation initiative. His study focuses on the socioeconomic factors that influence decision making which he outlined in three factors that increase implementation rates. These factors are communication throughout and after the auditing process, the presentation of technical data, and the selection of recommendations that have the best probability of implementation based on client conditions. REACTOR has been designed to accommodate each of these factors.

The initial motivation of this project came from a collaborative program between the University of Windsor and a major utility distribution company. The program consisted of a team of engineering students who conducted comprehensive energy analysis at industrial facilities throughout southwestern Ontario. The teams worked in four month terms. At the beginning of a new term the new students entering the program had to be educated with industrial energy management practices. It was determined that a knowledge base could be used to capture and store the expert knowledge required by the team. The REACTOR decision support system could use this expert knowledge base to train new students entering the program and enhance the overall productivity, consistency, and quality of the analysis reports being generated by the program teams. The initial development of the REACTOR system intrigued the utility distribution company to continue the development of the system so that it could be used internally by their professional account managers.

2.4.1 Industrial Energy Efficiency

The most critical aspect of an effective energy management action plan is to ensure monitoring and targeting goals are set and reached as Jutsen (2006) explained. The system has the ability to store versions so new analysis reports can be easily compared with past work. The REACTOR system has been designed to assist auditors and facility personnel with their energy management tasks. By utilizing a decision support system directly in a facility, operations and processes can be monitored more effectively. REACTOR can help identify which processes or operations are not essential to the facility. Eliminating an unnecessary system is a cost effective way of reducing operational baseline cost.

Based on information provided by the user the REACTOR decision support system is able to help determine if there is a feasible energy conservation measure to mitigate overconsumption in a given situation. The system relies on its ability to derive conclusions to problems based on past experiences stored in the knowledge base. Just as the audit process itself is iterative, REACTOR iterates problem solutions allowing the system to assess and make recommendations on an increasing range of cases. Each time REACTOR is used to solve new unfamiliar problems a new experience can be saved into a knowledge base so it can be recalled in the future if similar situations arise.

Effective energy managers require interdisciplinary competence including capabilities in engineering, economics, and management. It is not practical to assume that every energy manager can be trained in each of these fields. The REACTOR system assists energy managers by accessing multiple databases simultaneously to draw on multiple information sources. This creates a network of information that energy managers can use to educate themselves. This also reduces the risk of missing opportunities that the energy manager might not yet be aware of. As a result an energy manager utilizing the REACTOR system can be granted more power within the hierarchy of the corporation enabling them to implement energy conservation initiatives with less resistance. The system provides the tools necessary to make informed decisions and present the information effectively.

2.4.2 Decision Support Systems

REACTOR is an interactive software based system that supports decision making activities for industrial energy conservation and planning. The primary objective of decision support systems is to assist a user in the decision making process by providing them with the resources necessary to find a solution to their problem. The system can reduce or eliminate bias in energy conservation recommendations by evaluating the facts without external human influence. REACTOR is able to process data that are collected by the user and conduct an analysis of the information by comparing past experiences to the current situation. The experiences are coded and stored in a knowledge base that is accessible to the system. The system has the ability to make informed decisions by extracting information from a knowledge base. REACTOR has the ability to draw information from multiple knowledge bases simultaneously which enhances its ability to make decisions. The knowledge bases are constructed from collected data, archived documents, and codified human knowledge.

Financial decision support systems have been used in industry for many years. To transition the use of decision support systems from the office to the shop floor changes had to be made. Although the purpose of the REACTOR system differs from the typical decision support systems seen in industry in the past, the concepts are not entirely new. The intention of REACTOR is to reduce the operating cost of a facility by minimizing the consumption of energy. This results in the REACTOR system using similar principles to typical financial systems with the additional integrated feature of an energy conservation recommendations knowledge base. This integration allows the system to evaluate the current circumstances, determine a list of feasible solutions, and present the best solution for the given situation based on a balance of energy conservation and return on investment. This shifts focus onto utility based operational expenses in addition to considering raw material and labour cost to revenue.

Energy managers plan and implement energy efficiency initiatives. It takes time for an energy manager to acquire enough experiences to be able to make informed decisions quickly. Their decisions often have a significant impact on the process efficiency and inadequate information of misguided decisions could have negative consequences on production. Misguided decisions often result in more incurred costs than the project is initially intended to save when an appropriate solution is eventually reached. Giving an energy manager access to a knowledge base expedites the knowledge transfer process. Using a decision support system to select energy conservation recommendations minimizes risk for financial decision makers.

2.4.3 Program Structure

The REACTOR suite of software tools is centered on the Audit Librarian which controls the communication and movement of data and information between the system components. This gives all of the system tools access to the same knowledge base and project details. The system tools access the Audit Librarian through the Internet though a constant connection is not required. Each tool has the ability to work from a local database and the information generated while the tool is offline is synchronized with the Audit Librarian once a connection is established.

Figure 2: REACTOR system structure.

AUDIT TRACKER is a component that handles the client information such as consumption data and contact information. This information is stored in the Audit Details Database and it can be accessed by the other tools through the Audit Librarian.

AUDIT ASSISTANT is used to access the Knowledge Base for onsite data collection and to run calculations and evaluation tests used to check the usability of each recommendation strategy, Figure 3. The results are stored in the Audit Details Database where they can be accessed by Report Builder.

Figure 3: Data collection.

Audit Assistant is optimised for use on a tablet with special functions like handwriting recognition and user interface controls designed for touch-screens, Figure 4. The system tool can also be used on an office workstation computer. This is useful for post processing the collected data for analysis and report generation. The system draws on information stored in an expert knowledge base to prompt them which data is required for each recommendation schema being evaluated.

Figure 4: System user interface.

REPORT BUILDER is a Microsoft Word add-in that draws on information gathered by Audit Assistant and stored in the Audit Details Database. This tool is used to help the auditor decide which energy conservation measured should appear in the analysis report. Report Builder draws on template text from the Knowledge Base to generate audit reports. Once the recommendation text has been inserted into the report it can be modified by the auditor to better reflect the conditions at the project site.

KNOWLEDGE BASE EDITOR is used to store calculation information and report text in the Knowledge Base. Knowledge can be modularised into separate knowledge bases. Each system tool has been designed to handle multiple knowledge bases simultaneously. This allows the user to access expert knowledge from multiple expert sources. Using the Knowledge Base Editor, organisations have the ability to capture their own experiences, proprietary information, and intellectual property. This allows users to construct their own Knowledge Bases and market them to other system users.

System Structure Workflow

The development of the REACTOR decision support system suite of software tools was guided by the Knowledge Base construction methodology and user criteria. The primary objective of this thesis was to develop a methodology to construct a knowledge base that could be used by the REACTOR decision support system. Figure 1 outlines the basic construction of a decision support system. In this example the decision maker interacts directly with the dialog component through a graphical user interface. This interface allows the user to manipulate the data base and knowledge base management systems. In REACTOR, as shown in Figure 2, this operation is carried out by the Audit Librarian which interacts directly with the Audit Details database and the knowledge base. The data base is used to store transaction data such as information collected by the user through site analysis, calculation results generated by Audit Assistant, client information collected by Audit Tracker, or document templates that may be used by Report Builder.

The knowledge base management system is referred to as the Knowledge Base Editor. This suite of tools allows the user to store knowledge in the knowledge base. The information stored in the knowledge base is accessible to the decision maker through the Audit Assistant and Report Builder tools. The user is able to store knowledge into the knowledge base as a set of rules that define the path of a decision tree or as a model in the model base. Expert knowledge must be acquired and codified and before the information can be stored in the knowledge base it must be validated.

REACTOR Model Base Decision Tree

An essential component of the model base of the REACTOR knowledge base is the decision tree. Figure 5 demonstrates how the REACTOR decision support system evaluates a facility component. This evaluation leads to a recommended action that can reduce the energy consumed by the facility component being analyzed.

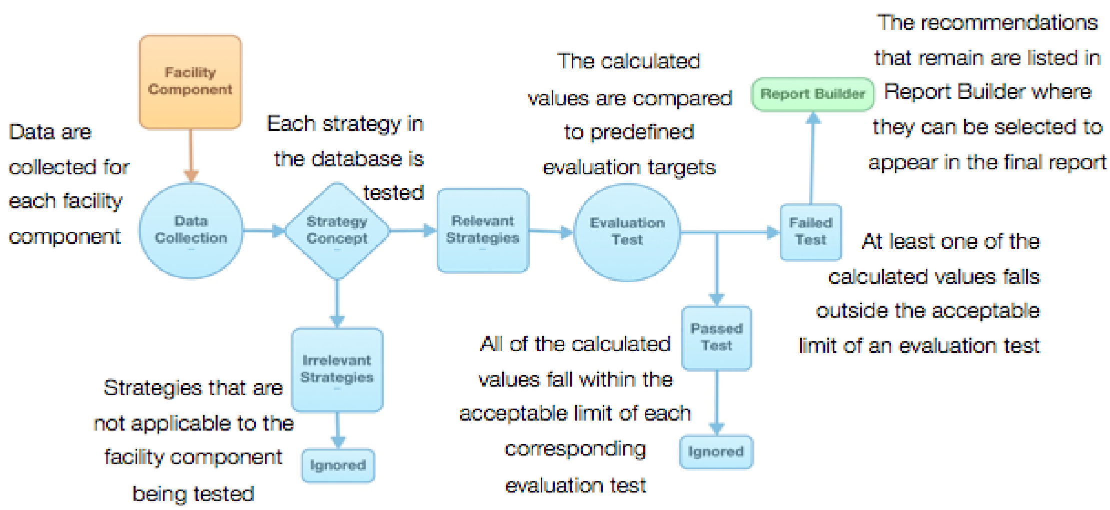

Figure 5: Evaluation of a schema stored in the knowledge base.

System User Types

Administrative User

The administrative user is responsible for installing and maintaining the REACTOR suite of software tools and managing the knowledge base. The administrative user will have to be familiar with program installation, the ‘Knowledge Base Editor’ tools, and the process for creating a recommendation. The ‘REACTOR System Requirements’ in Appendix B outlines the system requirements to install REACTOR and setup a database. The ‘Knowledge Base Editor’ is used to codify experiences and manage a knowledge base. The administrative user is required to have access to expert knowledge to create recommendations for the system to reference through the ‘Audit Assistant’. The administrator is also responsible to validate the information contained within the knowledge base.

General User

The general user is responsible for collecting data and reporting. The general user will benefit most from the 'Audit Assistant' and 'Report Builder' components of the system. The ‘Audit Assistant’ is used to prepare the system for a site visit, collect information on site, and analyse the results. The ‘Report Builder’ is used to report on the information that is gathered and analysed with Audit Assistant.

CHAPTER III

3.0 DESIGN AND METHODOLOGY

3.1 OVERVIEW

The intention of the REACTOR Decision Support System is to determine the most effective energy savings opportunities for client industrial and commercial facilities based on their individual, site-specific characteristics. The objective of the system is to automate the auditing process in order to improve consistency in energy auditing. The system was built on principles derived from various sources of expert knowledge. Each system component is intended to enhance, but not replace a user's tasks. An evaluation of existing methods and technology was done to ensure that REACTOR would effectively fill the existing market gap. The supporting methodology that REACTOR was built on are defined in terms of industrial energy efficiency requirements, the influence of decision support system characteristics, the process of capturing expert knowledge, and the method of building, testing, and validating the system.

The intention of this thesis is to develop a methodology to construct a knowledge base that the system can use to assist energy managers across industry in the decision making process to implement energy conservation initiatives. The knowledge base must facilitate the communication with clients, presentation of data, and the decision of which energy conservation measures are best suited to the project.

3.1.1 Development Phases

The development of the REACTOR knowledge base was carried out in a three phase process. The intention was to develop a methodology to construct a knowledge base that could be used by the REACTOR decision support system. Each phase focused on specific design characteristics and considerations. The objective and methodology behind each of the phases are summarized in the following sections.

Development Phase I

Objective:

- Use a valid source of expert knowledge to populate a preliminary knowledge base.
- Test the systems capability to construct a usable knowledge base.
- Verify that the system is able to generate a report that satisfies the industrial requirements in a controlled case study.

Methodology:

- Evaluate archived energy audit reports that were manually generated by a team of energy experts.
- Group similar recommendations that appeared in the reports.
- Prioritize the list of recommendations in order of feasibility to be codified into the preliminary knowledge base. Take the complexity, size, and usefulness of each recommendation into consideration.
- Represent the groups of recommendations in their prioritized order by developing a single strategy template for each recommendation schema.

- Codify the strategies into a knowledge base using the REACTOR knowledge base editing tools. Each recommendation schema includes a set of required data items, parameters, calculation sets, evaluation tests, and report text templates.
- Input the collected values that were initially used to manually generate the archived reports that were used to construct the preliminary knowledge base. This verifies the capability of the system to utilize a knowledge base to generate energy analysis reports with actual collected data.

Development Phase II

Objective:

- Verify that the system is capable of handling situations that are typical to an actual energy analysis site visit to an industrial facility.
- Ensure that employing the decision support system uses less time or adds more value to the overall project.
- Test the ability of the system to access an expert knowledge base to make informed decisions in an unfamiliar industrial setting.

Methodology:

- Asses an industrial facility by conducting an energy audit with a team of energy experts.
- Use the information gathered by the team to develop an energy audit report using traditional methods of reporting.

- After the initial field visit is completed by the team of energy experts revisit the facility to conduct another energy analysis.
- Perform the second site visit using the REACTOR decision support system to conduct the analysis and generate a report.
- During Phase II testing the system relies on the preliminary knowledge base constructed from archived audit reports in Phase I of development.
- Compare the expert written report to the report generated by the REACTOR system to evaluate the capability of the decision support system. This ensures that the system is able to collect and analyze information in real time by referencing an expert knowledge base.

Development Phase III

Objective:

- Develop a methodology to construct and validate an expert knowledge base of energy conservation measures that can be used by the REACTOR decision support system.
- Verify the value propositions that the system offers from a business perspective.
- Use the system to generate reports that are able to be sent to actual industrial clients.

Methodology:

- Work with energy experts to develop a knowledge base that is usable in industry.

- Develop energy conservation recommendations that are applicable to a specific facility type or industrial segment. Store each of the recommendations in a knowledge base.
- Conduct an energy audit using the REACTOR system with energy experts in the field.
- Work with the energy expert to evaluate the results that the system generates. Using the expert feedback finalize the recommendation template. The finalized template can then be saved in the knowledge base and made accessible to any user that requires it in the future.
- Select a facility from a different industrial segment with characteristics similar to the first facility and whose scope of equipment and operations are known to be near the edge of the extent of knowledge currently captured in the knowledge base.
- Develop additional recommendations that were not required to evaluate the first facility but may be required to evaluate facilities within the second industrial segment.
- Perform an energy audit in the second facility with an energy expert. Evaluate the workflow of the expert as they evaluate the facility.
- Generate an energy audit report and work with the expert to validate the content.
- Choose a third facility that falls in a separate industrial segment than the first two facilities that were evaluated. Similar to the first two facilities the knowledge base must be expanded prior to conducting the site visit. The report generated through the site visit can then be used to validate the information contained within the knowledge base.

Knowledge Base Construction Methodology

The knowledge base construction methodology can be described in three parts. The first part is knowledge acquisition, the second is codification, and the third is validation. Prior to collecting, codifying, and validating knowledge to be stored in the knowledge base a methodology had to be established. Figure 6 is a demonstration of the iterative auditing process that can be used to construct a knowledge base.

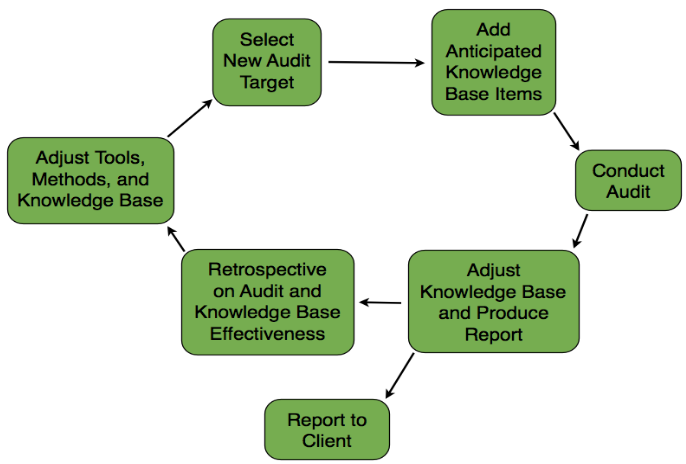

Figure 6: Iterative knowledge base construction methodology.

The process begins at the 'Select New Audit Target' step. After selecting a new client experts add anticipated knowledge base items to the system. The knowledge base is then adjusted to accommodate the information collected during the audit. These adjustments in addition to the retrospective effectiveness analysis from client feedback are used to validate the models and information stored in the knowledge base. The benefit of this method of knowledge base construction is that the clients that are involved are able to receive reports that assist in the improvement of their energy management practices. Simultaneously the knowledge base development continues and the information can be evaluated by an expert as it is introduced to the system.

3.1.2 Capturing Expert Knowledge

Expert knowledge significantly increases the identification and implementation of energy conservation measures. A decision support system is an effective tool to assist energy managers by providing the information that they require to make informed decisions or by providing a group of decisions directly with supporting explanation. A well constructed knowledge base is required for a decision support system to make informed decisions. REACTOR utilizes two primary knowledge sources. The first source of information used to build the REACTOR knowledge base are energy audit reports that were generated by expert teams in various facilities. The second information source is expert knowledge extracted directly from experienced energy auditors through consultation. Both of these methods of knowledge acquisition require manual data entry into the knowledge base through the REACTOR knowledge editor tools. In addition, as REACTOR is used and exposed to new situations in the field it has the ability to collect information that can be used to generate recommendations that do not yet exist in the knowledge base. These new experiences can be coded by the user and remain stored in the knowledge base for future reference should the situation present itself again in the future.

The objective of the REACTOR knowledge base editing tools was to develop an editing system that would allow experts who are not computer programmers to interact directly with the knowledge base of the system. The ideal user interface would allow users to educate the computer system through ordinary language techniques. Another method of knowledge acquisition would be achieved by expanding the ability of the system to learn important knowledge directly from its experiences in the field through user interaction.

Each of these methods can be employed to some degree with current computer systems. The REACTOR industrial energy management decision support system includes knowledge base construction and editing tools that are designed to be accessed by the user through the systems graphical user interface. This allows non computer programmers to codify their knowledge into the system's knowledge base though a familiar user friendly interface. The system also has limited ability to learn through ordinary conversation. A document parser has been incorporated into the system's knowledge base builder tool set which can comprehend calculation sets from archived report documents as long as the document follows specific format rules. As the system is used in the field, data is collected and processed for analysis through an evaluation test tool. In future versions the system will acquire the ability to use data to expand its own knowledge without additional user interaction.

The initial knowledge base module for REACTOR was created based on the Rutgers State University of New Jersey's Assessment Recommendation Code System for the United States Department of Energy Industrial Assessment Center Database, commonly referred to as 'The ARC' database. The ARC contains lists of recommendation codes for the enhancement of industrial energy efficiency, waste minimization, and manufacturing productivity. The ARC database is only a list of recommendation codes and does not contain any expert knowledge. The REACTOR knowledge base focuses on the recommendations for the enhancement of industrial energy efficiency. REACTOR has the ability to handle multiple knowledge bases simultaneously so although The ARC was used as the preliminary knowledge base template, additional knowledge bases have also been constructed and tested.

Past reports were used to gather information about facility types, typical equipment, and common recommendations. Energy audit reports from a major energy distributor and a team of energy auditors were used to derive the information necessary to construct a preliminary knowledge base. Once a knowledge base with recommendations was constructed experts in the field of energy management were consulted directly. The experts were interviewed or directly involved to standardize the existing recommendations. The experts also assisted to add new recommendations for topics that were not reflected adequately through the knowledge extracted from the past reports. Expert knowledge was extracted in meetings and in the field through examination and observation to ensure that the knowledge base would be diverse enough to handle the types of situations that REACTOR is intended for.

3.1.3 Knowledge Base and Tool Design in REACTOR

The REACTOR system was developed based on current industrial energy auditing methods. Following the current energy auditing practices for development simplifies the process of adoption and integration of the system into a corporate structure. As the methodology for knowledge capture and validation was developed and refined via field testing and use of REACTOR as described above, the results were used to modify the specifications for the feature set and user interaction design of the REACTOR tools. Mr. Haibin Dong, the lead programmer on the REACTOR project, used those modified specifications to refine the design and implementation of the REACTOR tools. This improved the user interaction with REACTOR through the Knowledge Base Editor, Audit

Assistant and Report Builder. This is important since each of these tools interact with the knowledge base.

The knowledge base editor tools have a user interface that is nearly identical to the data collection and reporting interfaces which enables the user to be more familiar with the tools. The tools are used to define each of the components necessary to create a recommendation template in a knowledge base. The components that define a recommendation are data items, parameters, calculations, evaluation tests, and report templates. Data items and parameters are values that are required in order to complete a calculation or perform an evaluation test. Data items are values that must be collected with the audit assistant data collection tools. Once they are stored in the audit details database they are accessible to be used in the calculations, evaluation tests, or report templates. Parameters are predefined values or constants that are required for the calculations or evaluation tests. A parameter value can be stored as local item within a single recommendation or it can be made globally accessible throughout the knowledge base.

Once the data items and parameters have been established a set of calculations and evaluation tests can be defined. The calculations are made from a combination of operations using data items and parameters which result in new variables called calculation results. The calculation results are stored in the audit details database. The evaluation tests then draw from the information stored in the audit details database and compare the data items and calculation results to parameters. The evaluation results are used to determine if an energy conservation measure is available in the knowledge base to improve the results of the evaluation. If a recommendation exists the information is saved in the audit details database. The report builder tools then use this information to retrieve the appropriate recommendation templates from the knowledge base. The values stored in the audit details database are inserted into the recommendation template that will appear in the audit report.

The knowledge base editing is intended to be regulated by a system administrator although the new recommendations will likely be established by a general user. The knowledge base editing tools fulfill the needs of both user types. One of the system administrator's tasks is to build and approve the knowledge bases. They compile information acquired from experts, archives, and personal knowledge into knowledge bases. The general user takes on the field work responsibilities for energy auditing tasks. Since the general user has the most direct exposure to industry they also have the ability to modify or add new recommendations to an existing knowledge base. Using the knowledge base editing tools they can add entire recommendations or make notes about where the knowledge base is lacking. The administrator is then responsible to validate or complete the recommendation suggested by the general user so that it is made available to all of the system users.

3.1.4 Field Testing: REACTOR Software and Knowledge Acquisition Method

The testing of the REACTOR tools and user interactions were carried out in parallel with the testing of the knowledge base development methodology. The system was tested throughout the development process using various methods. An action plan was established to effectively test the system throughout development. Once the system was operational the feature testing began by regenerating archived energy audits. The process was initially conducted in reverse order by coding the recommendations from the final versions of audit reports into a knowledge base. Once the recommendations were stored in report templates an accompanying set of calculations were developed. The development of the calculations identified gaps in the knowledge base editing tools. The calculations were then connected to the appropriate report templates with evaluation tests. The purpose of the evaluation test is to analyse the results of the calculations and compare them to predetermined parameter values. The evaluation tests are used to decide if the energy conservation measure being tested is feasible to be used as a recommendation in the final report. After the initial knowledge base was constructed the raw data collected by the energy auditors for the original reports was then entered into the system using the data collection tools in the audit assistant. The system was tested by comparing the resulting decision obtained by the REACTOR decision support system to the result of the energy auditor's analysis.

Following the initial knowledge base design the next phase of system testing involved conducting a field test energy audit. An automotive parts manufacturing plant was selected as the test site for the system's first field visit. An energy audit was conducted at the facility using the traditional approach of manual data collection and note taking that was later analysed by the team of engineers. They calculated the current energy consumption and identified potential energy conservation measures. They tested the feasibility of each recommendation by developing a calculation set from engineering fundamentals. The same facility was then evaluated using the REACTOR system. The system was linked to the initial knowledge base that was created through the study of archived audit reports. The resulting report produced using the REACTOR system was compared to the report generated through the traditional engineering approach.

The knowledge acquisition focus was shifted from archived energy audit reports to expert energy analysts to further improve the knowledge base editing tools. The intention was to follow experts through facilities and evaluate how they gathered and processed information in real time on site. This information was used to evaluate the effectiveness of the data collection tools in the audit assistant. It also helped identify weakness in their workflow and these shortcomings were used to generate ideas for additional feature development. Three facilities in the food processing, restaurant, and construction industries were used as the evaluation vehicles for this phase of system testing. Each facility identified different opportunities and presented new challenges. The experts assessed the system before, during, and after each site visit. To maximize the diversity of the site visits different levels of energy audit were conducted at each of the test facilities. The first level audit is the preliminary walkthrough evaluation. This is to assess the facility to plan for the next level of evaluation. The second level is a detailed analysis where data are collected to calculate estimates of current consumption and potential conservation. The third level is to revisit a facility to assess the effectiveness of implemented energy conservation measures. The REACTOR system was designed to handle each of these levels of energy auditing. The system is capable of handling multiple knowledge bases simultaneously so that it can evaluate a facility with various degrees of intensity. By using different knowledge bases the focus of the audit can be tailored to suit specific requirements.

3.1.5 Knowledge Base Validation

Preliminary knowledge bases created through analysis of archived audit reports and field work with expert energy analysts were most useful to develop and test the REACTOR system. Specific focus throughout the testing phase was on the knowledge base editor tools. The first knowledge bases that were created as a by product of the testing phase are usable by the system although the information contained within a knowledge base must be validated before it can be used to support decision systems. A validation process to create knowledge bases for the REACTOR system was established through engineering work with experts in the field of energy management.

Energy conservation measure recommendations that will be stored in the REACTOR knowledge base must follow a specific format. The formation of a new recommendation starts by identifying the problem space that will be addressed by the recommendation. The knowledge required for the recommendation must be acquired through one of the methods of knowledge acquisition from archived reports, field work, or an expert. Once the parameters of the problem are clearly identified the calculations can be derived from the information. The variables must be defined as data items to be collected on site or parameters that will be predefined as part of the recommendation template. The calculation results are compared to limit ranges that must also be determined from past experience or industry standard. These evaluation test comparisons will be used to decide if a recommendation is feasible to appear in the final report. Next a generic report template must be created for the recommendation. When the template is passed into the report builder it will automatically be populated with the information stored by the audit assistant in the audit details database to reflect the results of the analysis. The data collection, calculation, evaluation, and report templates must be stored together in the knowledge base so that they are accessible to the decision support system.

Each recommendation must be validated to be accurate, and reflective of appropriate engineering knowledge and practice. Each recommendation must be verified by an expert to prove that it accurately evaluates the energy conservation measure that is being investigated. Only after these steps have been satisfied may the energy conservation measure be stored as a recommendation in the REACTOR Knowledge Base.

CHAPTER IV

4.0 ANALYSIS OF RESULTS

4.1 RESULTS SUMMARY

The REACTOR System was developed and tested using an iterative three phase process. Each phase was intended to test various functions of the system. In addition to system development the knowledge base construction methodology was analyzed. The following sections outline the objectives and results of each phase of analysis.

Test Phase I

Objective:

- Use a valid source of expert knowledge to populate a preliminary knowledge base.
- Test the systems capability to construct a usable knowledge base.
- Verify that the system is able to generate a report that satisfies the industrial requirements in a controlled case study.

Results**:**

- The benefit of the Phase I method for early stage testing is that clients are not relying on the system generated reports while they are in early development, but the realistic conditions of actual client facilities may be used.
- There is no need to spend time on site as the reports contain all of the information necessary to develop, test and validate the knowledge base.

- The time to codify recommendation strategies into the knowledge base is related to the information available and the complexity of the calculator being developed. The first calculators took one to three hours to add into the knowledge base in addition to the time required to comprehend the situation and develop a calculation solution. Using the enhanced knowledge base editor tools and standardized calculation format calculation sets could be coded into the knowledge base in twenty to forty minutes.
- In the earliest version of the knowledge base design tools the user was required to manually generate a tag for each data item, parameter, or calculation value. The tags were used as placeholders in the report text. As a value was assigned to each tag the value would replace its placeholder in the report text. The primary issue with this method was the consistency of the tag throughout the entire system. This issue was resolved though tag tracking which automatically generates a tag for each value placeholder as they are required and then keeps all similar tags consistent throughout the system. If any of the tags corresponding to a strategy are modified the other tags updated to maintain consistency and greatly reduce the risk of human error.
- The time to codify a calculation is reduced with nested calculations and copy paste functionality. These features were added to the knowledge base editing tools through the construction of the preliminary knowledge base. By adding the recommendation strategies in a prioritized order the scope of the system functionality was continuously expanding.

- A failsafe has been incorporated into the knowledge base editing tools which tracks the completeness of each of the recommendation strategies under development. This system informs the user which of the components are completed or in progress. This ensures that recommendations are usable before they are stored into the completed knowledge base.

Test Phase II

Objective:

- Verify that the system is capable of handling situations that are typical to an actual energy analysis site visit to an industrial facility.
- Ensure that employing the decision support system uses less time or adds more value to the overall project.
- Test the ability of the system to access an expert knowledge base to make informed decisions in an unfamiliar industrial setting.

Results:

- The method of testing used in Phase II exposed the REACTOR system to an actual industrial facility with real client interactions.
- The primary benefit of working in parallel with a team of energy experts was that the system could be tested effectively in an actual client facility without the client having to rely on the system generated results alone.

- The field test proved that the system has the capability to access an expert knowledge base and produce results that are equal or better than those reported by an expert energy team.
- The most notable attribution of the system that was reviled through the Phase II testing is its ability to improve the quality and number of useful audit recommendations that appeared in the report.
- The manually written report was made up of four audit recommendations, which include supporting calculations, and three best practice recommendations. The report generated by the REACTOR system included six audit recommendations with supporting calculations, and two best practice recommendations. The system successfully turned two of the original best practice recommendations into full audit recommendations with supporting calculations. It also identified and added a brand new best practice recommendation to the report.
- As each recommendation was being tested the system helped to ensure that all of the data required to complete the supporting calculations would be available for analysis after the site visit was completed. This explains how the two best practice recommendations identified by the expert team could be used in the REACTOR generated report as fully supported audit recommendations.
- Since the data being collected by the system was analysed in real time the user was able to increase interactions with the facility personnel which lead to the collection of more useful data.
- The on site system testing showed increased interactions between the energy analyst and the facility personnel. These interactions play a critical role in

extracting additional information about the facility that may not have been exposed if less direct client interactions had taken place. These discoveries ultimately lead to user interface improvements that aim to further reduce the users' interactions with the software so that their time can be used more efficiently with the client.

- Phase II focused on the functionality of the system tools. The ultimate goal was to validate the system's ability to draw conclusions from collected data by extracting information from an expert knowledge base. The user interface was streamlined to allow the user to focus on client needs. Phase II testing demonstrated that the REACTOR system is able to achieve these goals. The system was used to generate a report of superior quality compared to one written by an expert team while exerting less effort and it was able to do this in an equivalent amount of time.

<u>Test Phase III</u>

Objective:

- Develop a methodology to construct and validate an expert knowledge base of energy conservation measures that can be used by the REACTOR decision support system.
- Verify the value propositions that the system offers from a business perspective.
- Use the system to generate reports that are able to be sent to actual industrial clients.

Results:

- The iterative process of continually preparing for visits to facilities in new industrial segments enhances the capabilities of the knowledge base. The information contained in the knowledge base can be validated by reviewing the reports generated by the system with an energy expert.
- In order to ensure that the energy conservation measures contained within the knowledge base are properly validated a secondary validation process was employed.
- Each of the recommendation templates were evaluated by a separate group of energy experts with technical experience in engineering. The evaluation of each recommendation was conducted using fundamental engineering principles.
- Redundant evaluation of each energy conservation measure ensures that the recommendations contained within the expert knowledge base are valid.
- By employing the system, auditors ensure they collect the information necessary to calculate the energy savings associated with each of the recommendations.
- Through analysis of energy experts auditing process the system was optimized.
- The average number of person-hours required by an energy expert to produce an audit report after a site visit is typically 150 hours. By utilizing the REACTOR decision support system the time required to generate a completed audit report was reduce significantly. The report could be generated in 2 to 4 hours. In most cases the report was ready for review by the expert in the same day as the site visit. The final version of the report could be sent to the client in one to two days after the site visit.

4.2 RESULT DETAILS

The REACTOR decision support system was designed to assist in determining the most effective energy management solution. The system is intended to automate the auditing process to enhance the decision making activities. A knowledge base had to be constructed for the system to have the ability to make informed decisions. Experts were consulted for the design and development of the knowledge base. By working with the experts a set of knowledge base editing tools were developed. The tools were then used to construct preliminary knowledge bases that could be used for system testing. The iterative process gave the expert users the ability to evaluate and enhance the knowledge base construction process. The information provided by the experts was used to verify that the system has the capabilities required to support energy conservation decisions for energy management. The REACTOR system was analysed as a decision support system tool to improve industrial energy efficiency. Its ability to capture expert knowledge was evaluated based on the system design, testing, and validation methodology.

4.2.1 Industrial Energy Efficiency

Industrial assessment and external energy auditing have proven to be effective methods of reducing industrial energy consumption according to Bhattacharjee (2010). The REACTOR system has been designed to assist with energy management decision making. The intention of employing the system is to reduce the facility baseline operational cost. The system has proven through testing that it possesses the capabilities required to meet or exceed the current industrial standards of energy auditing. This was made possible by designing the system in various industrial environments. The iterative design process has exposed the system to several sources of expert knowledge that were used to construct a knowledge base and develop the required knowledge base design tools.

4.2.2 Decision Support Systems

The evaluation of the REACTOR system revealed several effects of employing decision supports systems for energy management. Typically decision support systems are used in industry by financial decision makers to analyse financial models and make important investment decisions. The REACTOR system utilizes common decision making techniques to analyse investment opportunities. The system weighs the monetary costs and return on investment by comparing annual savings to the initial investment to calculate the simple payback period. In addition to the financial factors the system utilizes an expert knowledge base to take various energy conservation measures into consideration by comparing the benefits of each recommendation. This results in a decision that optimizes the return on investment as well as the energy conservation potential.

4.2.3 Capturing Expert Knowledge

The process of designing the system highlighted the importance of an effective knowledge base. The REACTOR system takes financial and energy related expenses into consideration to optimize the return on investment by reducing energy consumption in the most cost effective way. For the system to have the ability to evaluate a given situation effectively it relies on a well constructed knowledge base. The knowledge acquisition process is critical to the quality of the information stored in the knowledge base. When extracting information from experiences it is important that the energy conservation measure recommendation being developed does not directly reflect the scenario. By doing this the recommendation template will be usable for similar scenarios in various facility types even if the situation is not identical. This is especially important in the report text templates. The text must be generic so that it is cross compatible with several facility types, although it should be specific enough that a user can insert the text template into a report with little or no manual modifications. It is left to the discretion of the user to add additional case specific information. The recommendation schema must be customized to reflect the actual scenario under evaluation.

Knowledge base editing tools were developed to assist with the knowledge base construction. The tools were designed based on the type of information typically stored in the knowledge base. The knowledge base editing tools are intended for users of various skill levels. It is not a prerequisite for the knowledge base administrator to be a computer programmer. The knowledge base is programmed in a human language through the knowledge base editor tools which have the same user interface as the data collection tools. In addition to manually adding calculation sets into the knowledge base through the knowledge base editor tool user interface there is a calculation parser. This parsing tool has the ability to recognize calculations that follow standard formats that are nested in text documents to save them in the knowledge base. This feature was developed to assist with processing archived reports. The other system tools were tailored in similar ways based on the methods used to develop and test the system.

4.2.4 System Testing

The REACTOR system testing was intended to enhance the development process. By iteratively testing the system throughout its development the features were able to be tailored to fulfill the market requirements. The system was initially tested with information from archived audit reports. The energy conservation measures recommended in the reports were standardised by removing case specific information. The fundamental calculations were used to create an initial knowledge base to test the system functionality. The construction of the initial knowledge base was critical for the development of the knowledge base editing tools.

Once a preliminary knowledge base had been constructed the first test was to enter the data values used to generate the archived reports into the system. Theoretically the system was expected to regenerate the archived reports that were used to create the knowledge base. This process became more efficient as the method of knowledge acquisition was improved. The archived reports were examined to identify patterns. These patterns were used to categorize the energy conservation measures into groups based on the complexity of the recommendations. Knowledge base editor tools that would be capable of codifying the basic recommendations were developed and tested. As the capabilities of the editor tools became sufficient to handle the recommendations for the reports being analysed the report selection criteria was increased incrementally. Coding advanced energy conservation recommendations into the knowledge base further enhanced the capability of the editing tools.

Following the creation of a knowledge base from the archived reports the hypothesis that the system would reproduce the manually generated reports was tested. The data collected for the manually generated reports was entered into the system through the audit assistant user interface. The energy conservation measures generated by extracting information from the archived reports were not identical to the recommendations found in the reports since they were standardized to accommodate a variety of situations. The variability in the recommendation template formatting accounts for the differences that exist between the archive reports and the system generated reports for the corresponding facilities. Although the recommendation format was different the actual recommendation list matched for corresponding reports generated for each facility. This test proved that the consistency of reporting is improved by using the REACTOR decision support system for energy management reporting purposes.

To continue the iterative system testing process the caliber of testing was increased. An action plan was established to test the system in the field. An automotive parts manufacturing plant was selected as the first location for field testing. After manually generating an audit report with a team of engineers the same facility was revisited using the REACTOR system. The system was used to collect information for the energy conservation measures stored in the knowledge base generated from the standardized archive audit reports. This test was the first demonstration of the system capabilities in an industrial field setting. A notable improvement during the data collection was the interactions between the auditor and the facility personnel, Figure 7. The system prompts the user to collect specific information that is required for each recommendation being tested. This allows the user to focus on interactions on the plant floor to determine which recommendations are most likely to be beneficial to the facility rather than expending their energy on ensuring that they collect the information required to test the feasibility of the recommendations. Tailoring the recommendations that appear in the final report to the requirements of the industrial decision makers increases the probability of implementing the energy conservation measure.

Figure 7: Interactions with facility personnel.

The system enhances the data collection process by prompting the user to gather the information required to test each recommendation. This minimizes the risk of missing data that is required to fully test energy conservation measures. The report generated by the REACTOR system contained the same recommendations as the manually generated report although the system report was more complete. Since all of the required information was collected on site during the first visit the report calculations were more complete and the inconclusive best practice recommendations from the manually generated report were full audit recommendations in the system generated report.

The system also reduces the amount of time required to generate the report since the majority of the analysis is completed on the plant floor. After the field visit a brief meeting is held with the facility personnel so that the report can be tailored to their requirements by prioritizing the recommendations tested by the system. The prioritized list dictates which recommendations will appear in the final report as well as their order. The user is then responsible to import the recommendations into a report template using the report builder. Once the report template is filled in, minor formatting enhancements can be made so that the report can be delivered. In the case of the automotive parts manufacturing plant the manually generated report was ready for delivery after a two week period where as the REACTOR generated report was available the afternoon following the field visit.

4.2.5 Knowledge Base Validation

In the early stages of development the focus was improving the capacity of the knowledge base editing tools. As the system became more advanced a higher degree of testing was required. The construction of a valid knowledge base was necessary to fully test the functionality of the REACTOR system. The knowledge base had to be validated as it continued to expand. Various methods of knowledge acquisition and validation were tested to ensure the system is diverse enough to handle a wide range of facilities and report styles. The system has been designed to handle multiple knowledge bases simultaneously which improves its ability to handle various situations and user requirements. The next phase of system testing was carried out in three facilities in the food processing, restaurant, and construction industries. By working with experts in each of these facilities further improvements to the system workflow were made. These improvements were intended to enhance the knowledge acquisition process and ultimately led to the validation of the knowledge base.

The first field visit with industry experts was to a food processing facility. The objective of this visit was to analyse the expert's interactions so the system's workflow could be optimized to accommodate different user types. The system had to be fast enough to conduct a preliminary walkthrough which is intended to highlight potential areas of improvement while the knowledge base had to be powerful enough to evaluate potential energy conservation measures that could be recommended in an energy audit report. For this visit the REACTOR system was used in parallel with two experts focusing on separate levels of analysis. One of the experts had their attention on highlighting the facility from a broad perspective to learn about the process and client needs. The other expert was concerned with evaluating specific aspects of the facility to determine feasible solutions to energy consumption issues. After conducting the site visit the experts acknowledged that they believed the system would have the capability to assist them with their data collection and analysis requirements. They mentioned that the decision support system was not intrusive to their workflow and if the knowledge base was well constructed that the system would actually improve their work. The system has the potential to reduce the amount of time required to conduct a site visit and with the integration of a well formed knowledge base the audit assistant ensures the correct data is being collected.

The second field visit with an industry expert was to a restaurant facility. The objective of this visit was to ensure the system has the ability to select energy conservation recommendations that are appropriate to a particular situation. In preparation for this site visit a new knowledge base module had to be created to accommodate a restaurant facility. To begin the development of the new knowledge base module an expert who primarily deals with restaurant facilities was consulted. The information was used to create the framework of a knowledge base capable of analysing restaurants. The expert validated the list of recommendation types that were stored in the knowledge base. A series of evaluation tests were then established to check the feasibility of each energy conservation recommendation. The evaluation tests are used by the decision support system to determine if a recommendation will mitigate an issue that exists within a facility. The tests compare collected values to predefined parameters determined by an expert. All of the information required to make an informed decision is stored in the knowledge base. The system was then used to collect information at a restaurant facility. The data collected were based on the requirements of the evaluation tests stored in the restaurant module of the knowledge base. The evaluation tests processed the data collected to generate a list of recommendations that could potentially reduce the facility's energy consumption. The expert evaluated the list generated by the system. They approved the list of recommendations that the system had selected to be reasonable.

The third field visit with an industry expert was to a construction facility. The objective of this visit was to test the functionality of the REACTOR decision support system entirely. To accomplish this degree of testing the system was used to its fullest capabilities and the energy conservation recommendations stored in the knowledge base were in their most complete form. Each recommendation had data items and parameters, full calculation sets, evaluation tests, and report section templates to be inserted through report builder. The system was used to collect data on site to form a preliminary list of recommendations. This list was evaluated by the expert and the facility manager to decide which recommendations would appear in the final comprehensive energy audit report. Once the site visit was completed the report builder tools were used to automatically generate the first draft of the report. Using Report Builder, the draft was prepared and sent to the expert for revisions within hours after the site visit. Few revisions were required to customize the report to better reflect the situation at the construction facility. Following these revisions the expert approved the report and it was ready to be delivered to the client.

Along with the test facilities a comprehensive knowledge base was simultaneously being constructed with the assistance of an expert energy consultant. This process involved regular meetings with the expert. Scenarios were built to simulate theoretical energy conservation measures that could be used as generic recommendation templates. Calculation sets were developed based on fundamental engineering concepts. These calculation sets were then used as a component in a variety of recommendation templates. The recommendation templates that were extracted from the archived audit reports were also validated in a similar process. Many of these recommendation templates were in the knowledge base used to test the system through several field tests and site visits. Ultimately this process enhanced the knowledge base and the knowledge base editing tools. With the existing knowledge base and system tools the REACTOR system is capable of conducting energy analysis ranging from preliminary walkthroughs to comprehensive reporting. It has the ability to be used by different user types with a variety of skills and tasks.

CHAPTER V

5.0 DISCUSSION AND CONCLUSIONS

5.1 SUMMARY DISCUSSION

The importance of knowledge to the REACTOR decision support system has become evident in every aspect of the analysis. The system is intended to improve industrial energy efficiency. The development of the system was based on industrial needs assessments and current industrial practices. The objective was to develop a tool to assist energy managers to make implementation decisions from financial and technical information. A well constructed knowledge base is a critical aspect that enables the system to perform. The knowledge contained within the knowledge base must be validated to ensure that the system produces applicable results. This validation process involves working with industry experts in various environments. All of these considerations contribute to the development of a well rounded system capable of assisting energy managers with their tasks.

The most notable contribution of the REACTOR system is the capacity to improve consistency, speed, and quality in energy conservation monitoring and targeting. The system's capabilities have been verified through a variety of testing methods. Beginning the system testing with archived audit reports worked to add knowledge base editor tool functionality. The tests conducted during this phase confirmed that the system has the ability to improve consistency by comparing the REACTOR generated reports to the archived reports that were used to construct the initial knowledge base.

The next phase of testing was the system's first exposure to an industrial setting through an actual site visit. This test was a comparison of an audit report generated by a team of experienced energy analysts to a REACTOR generated report. For this evaluation the system relied on the initial knowledge base containing the information extracted from archived reports. The results of this test demonstrated that the system was able to enhance the user's workflow by minimizing the distractions caused by focusing on data collection. Since the system intuitively prompts the user to collect the data necessary to evaluate an energy conservation recommendation's feasibility, the user is free to direct their attention to the facility personnel. This potentially increases the probability of uncovering a solution that may go overlooked if the user was distracted with data collection. The site visit testing demonstrated these workflow improvements along with enhancements in report content. These enhancements can be partially attributed to the increased communication that was able to occur throughout the data collection process. Another contribution of the organized data collection user interface is the quality of report content. In this test some of the recommendations that appeared as inconclusive best practice recommendations in the analyst generated report were able to appear as completed recommendations in the REACTOR generated report since all of the information necessary to complete the calculations and evaluation test were collected on site during the field visit.

The final testing phase involved site visits to multiple facilities in a variety of industries. These field visits were conducted alongside experts in each corresponding facility. The intention of these tests was to ensure that the system had the capabilities required to assist the experts with their tasks without the technology inhibiting their workflow. This provides further improvements to the usability of the system which enhances the working experience. Working with experts in the field also encouraged better results for the decision support system. The knowledge base was forced to become more diverse and the energy conservation recommendations had to be more detailed to handle additional special cases. This required the knowledge base editing tool to handle advanced calculations and evaluation test criteria. The overall quality of reporting was improved by implementing the advanced system functionality such as the ability to handle multiple knowledge bases simultaneously.

While the system testing was being carried out the knowledge base capabilities were being enhanced in parallel. These enhancements were achieved by consulting with an expert energy analyst. The work done with the expert resulted in new types of calculators that could be nested into existing recommendation calculation sets. This improves the workflow and efficiency of knowledge base construction. Validating calculator blocks to incorporate into existing recommendations improves the consistency and quality of the energy conservation measure recommendations stored in the knowledge base by standardizing the format. These characteristics have been tailored to accommodate the needs of energy managers that will use the system. The objective of designing the knowledge base editor tools around the user is to create an intuitive user interface that allows the knowledge base construction to follow a natural development process.

5.2 CONCLUSIONS

The development of a well constructed knowledge base is vital to the functionality of the REACTOR decision support system. The ideal methodology to construct an effective knowledge base begins with the quality of the energy conservation measure recommendations that it contains. The ultimate process of building a knowledge base follows a pattern that starts with the identification of the problem space. Expert knowledge must be acquired in order to identify which recommendations are feasible. Once the issues are prioritized a list of solutions can be established. The list can then be itemized to identify similarities between each of the potential recommendations. The similarities can be addressed by creating calculation sets that satisfy a portion of the required solution. After these blocks of calculations are validated by an expert they can be assembled to represent the full calculation sets that make up each individual recommendation. This codification of expert knowledge must be accompanied by a series of evaluation tests that are capable of assessing the viability of the proposed energy conservation measure. The calculation sets and evaluation tests are then paired with appropriate report text templates. The text templates can be populated by the calculation results and inserted into the report if the evaluation tests reveal that the energy conservation measure is applicable to the given situation. Following the codification of the expert knowledge the entire recommendation must be approved through an expert evaluation. If the recommendation is valid, then it can be stored in the knowledge base and made accessible to the REACTOR decision support system.

The framework of the system is based on standard decision support system models typically used in financial decision making. The REACTOR system also takes technical factors into consideration when evaluating different scenarios. This unique characteristic of balancing financial and technical factors sets the system apart from other industrial information systems currently available. The REACTOR system utilizes these factors to determine the ideal energy conservation measure for each scenario that it encounters. The user is then tasked with evaluating the information provided by the system to take action in implementing the best energy conservation measure. The objective is to reduce the facilities energy consumption to maximize the bottom line profits. Additional to reducing costs associated with energy consumption the system helps monitor facility health to establish maintenance action plans.

REACTOR assists with targeting energy conservation goals that work toward achieving continual improvement. The information contained within the knowledge bases aims to accelerate the learning process for energy managers that employ the system in their operations. The increased knowledge mitigates investment liability that can result from deciding to implement new energy conservation measures. Informed energy managers are empowered with the support of the REACTOR system to make difficult decisions that may fall outside the scope of their knowledge. Referencing the knowledge base helps support their choices which increases the probability of project implementation. The personnel that are directly immersed in a facility can easily become overburdened by the paradigms of their daily tasks. The system ultimately encourages the people that are most familiar with the facility to identify solutions to reduce the overconsumption of energy. This process eventually transforms these people into innovative energy managers with greater insight of energy conservation initiatives.

Industry needs an energy management decision support system like REACTOR. The REACTOR system has been designed to cater to the needs of the people that are responsible for managing energy conservation. The system has been made easily adoptable given its intuitive and user friendly configuration. The objective moving forward is to introduce the system into the industrial marketplace. The value will be in assisting companies to construct their own expert knowledge bases that will mitigate their energy management challenges. As the system gains momentum in industry it can be implemented to qualify companies for financial incentive programs or energy certifications. The REACTOR decision support system promotes an energy conscious culture that has the ability to work together by sharing information about energy conservation measures through publically accessible knowledge networks.

APPENDICES

APPENDIX A

GLOSSARY OF TERMS

Audit recommendation – Suggested energy conservation measure that appears in an energy audit report accompanied by supporting calculations that show estimated cost of implementation, predicted annual savings, and simple payback period.

Best practice recommendation – Suggested energy conservation measures which indicate some savings are possible through implementation although there is no feasible way of calculating specific details of cost or payback.

Calculation Set – Component of a recommendation template supporting calculations developed based on fundamental engineering concepts that show estimated cost of implementation, predicted annual savings, and simple payback period.

Codification – The process of storing expert knowledge into a knowledge base for use through a decision support system.

Data Item – Component of recommendation templates that represent the data values that must be collected to populate calculation sets, evaluation tests, and report text templates. Data items are variable values used in recommendation schema.

Decision Support System – Interactive software-based system that supports decision making activities by accessing expert information in knowledge bases which enable users to make informed decisions.

Energy action plan – Evaluate energy consumption to set targets that aim to reduce or improve energy usage.

Energy audit – A series of facility and process evaluations that identify energy consumers and potential areas of savings through the implementation of recommended energy conservation measures.

Energy baseline – A summary of a facility's energy consumers that are defined by energy usage trends over a specific period of time.

Energy Conservation Measure (ECM) – An action that, when implemented, has the potential to reduce energy consumption.

Energy Manager – A person who is responsible to manage the rational use of energy and ensure continuity of supply.

Evaluation Test – Component of a recommendation template that evaluates the feasibility of implementing energy conservation measures by comparing calculated values or data items to parameters.

Expert – A person with capabilities in engineering, economics, and management who provides information that can be codified into a knowledge base. A person that is able to validate information contained in a knowledge base based on their fundamental knowledge and experience.

Implementation rates – A record of the number of times an energy conservation measure has been implemented. Used for statistical analysis to determine the probability of a recommended energy conservation measure being implemented.

Industrial energy efficiency – The effective use of energy in industrial facilities. A combination of facility and process energy conservation.

Industrial energy management – A field of work or research that is focused on improving industrial energy efficiency.

Industry Expert – A person who is knowledgeable in their field of work or research. An energy analyst is an expert in the specific industry of energy management.

Information System – A system that utilizes various data items to assist a user with the decision making process. The system has the ability to evaluate a situation using a combination of collected data and expert knowledge stored in an expert knowledge base.

Iterative design process – The development of a system by creating a preliminary model that is used to test the system that is being developed. Modifications to the system are made based on the initial test results and the system is tested again. This process is repeated until the results of the testing satisfy the initial intent of the system.

Knowledge Base – The storage of codified expert knowledge that can be used by an information system to make informed decisions. The REACTOR knowledge base of energy conservation measures is made up of data items, parameters, calculation sets, evaluation tests, and report text templates. These components are used by the REACTOR decision support system to evaluate the feasibility of each recommendation to find the ideal solution for a given situation.

Knowledge acquisition – The capture of expert knowledge to be codified and stored in a knowledge base that can be accessed by a decision support system to make informed decisions.

Knowledge codification – The translation of expert knowledge from human language to a format that can be understood by an information system.

Knowledge validation – The verification of expert knowledge that has been acquired, codified, and stored in a knowledge base.

Parameter – Component of recommendation templates that represent the predefined parameter values that are required to populate calculation sets, evaluation tests, and report text templates. Parameters are constant values used in recommendation schema.

Parser – A software tool that is used to analyse a text file and extract useful expert knowledge and store it in a knowledge base. The REACTOR system has a parser that is capable of extracting calculations from text files and forming recommendation templates from the collected information.

Problem space – The representation of the domain of study. The problem space of the REACTOR system is industrial energy management.

REACTOR – Rapid Energy Audit Collection Tracking Organization Reporting decision support system.

Recommendation Template – Knowledge base component that represents an energy conservation measure with data items, parameters, calculation sets, evaluation tests, and report text templates

Report Text Template – A standardized text template that is associated with an energy conservation measure stored in a knowledge base. The generic text can be applied to a specific recommendation regardless of the facility type. The intention is that the generic text is used as a framework that includes all of the information necessary for a client to understand the recommendation. The report text can be enhanced by the user to more accurately reflect the specific situation.

Simple payback period – Capital cost over annual return on investment. Used to demonstrate the value of implementing an energy conservation measure.

APPENDIX B

REACTOR SYSTEM REQUIREMENTS

Windows Operating System

- Windows XP, Windows Vista, or Windows 7 is required to run the REACTOR System Suite including AuditLibrarian, AuditAssistant, and ReportBuilder.

Microsoft Office

- Microsoft Word 2007 or Microsoft Word 2010 is required to run ReportBuilder.

Internet Connectivity

- A connection to the Internet will be required during installation to download or update any required components of Windows Installer, .Net Framework, IIS, or SQL Server Compact.
- If a connection is not available during the installation process and the required components are not up-to-date the system may not run correctly until all of the updates are completed.

The components listed below are installed and updated automatically. In the event that the program does not install or run correctly the user is responsible to confirm that the correct versions of the following critical components are installed and up-to-date:

Windows Installer

- Windows Installer 4.5 is required for the system installation, maintenance, and removal.

Microsoft .Net Framework

- .Net 3.5 is required for the functionality of AuditAssistant and ReportBuilder.
- .Net 4 is required for the functionality of AuditLibrarian.
- ASP.Net 4 Version 4.0.30319.0 is required for the functionality of AuditLibrarian web services and database synchronization.

Microsoft Internet Information Services (IIS)

- Microsoft IIS Version 5.1 or later is required for the functionality of AuditLibrarian web services and database synchronization.

Database Server

- SQL Server Compact 3.5 SP2 is required for the systems web services and synchronization.

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