COUPLED SIMULATION FRAMEWORK TO ASSESS LIFE-CYCLE ENERGY REQUIREMENTS IN BUILDINGS

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ABSTRACT: *The buildings sector accounts for nearly 41% of the United States' primary energy usage. These energy requirements are mainly derived from non-renewable and depleting energy sources which also results in various harmful emissions to the environment. Thus, reducing the overall energy requirements during a building's life cycle becomes critical. This can be achieved through selection of sustainable construction materials during the design phase and also by accurate estimation and control of energy use during the operational phase. Various Life Cycle Analysis (LCA) based tools are available for facilitating sustainable material selection and energy estimation especially during the design and construction phase of a building. However, for the operational phase, there is lack of a comprehensive framework that can monitor and quantify the effects of various factors such as building systems and material deterioration, dynamic occupant behavior patterns, and fluctuations in weather that can affect the operating energy and recurrent embodied energy requirements in a building. This research proposes a Life-Cycle Energy Monitoring Framework that couples LCA and energy simulation analysis using a system dynamics modeling paradigm to enable a distributed simulation platform that can monitor and control the energy requirements during all phases of a building's life cycle. Initial experimental results indicate that the proposed framework can help in understanding the optimal maintenance and replacement cycle of major building materials which in turn can result in limiting the overall energy usage and environmental impacts of a building during its entire life span.*

KEYWORDS: *Life Cycle Analysis; System Dynamics; Material Deterioration; Recurrent Embodied Energy; Life Cycle Energy Monitoring Framework; Energy modelling*

1. INTRODUCTION

The building sector continues to be a major consumer of energy in the United States with around 90% of this demand for energy being sourced from non-renewable resources (EIA 2014). Measures for reducing the overall life cycle energy requirements in a building thus becomes significant. A building typically has three main life cycle phases: design/construction phase, operational phase, and end-of-life phase. Across these phases, the energy requirements are divided into two types: Embodied energy (EE) and Operating energy (OE). Embodied energy is the energy required for production of building materials, construction of living facilities and also the energy required for demolition and disposal activities during the end-of-life phase (Dixit et al. 2010). Operating energy is the energy required for maintaining the internal environment in livable conditions during the operational phase of a building's life cycle.

Various frameworks/tools exist and are widely used for estimating the embodied energy and operating energy in a building (e.g., Athena Impact Estimator V5 2015, EnergyPlus 2014, eQuest 2014, IES VE 2014, ECEB -Moncaster and Symons 2013, Building's Energy Data Book- U.S DOE 2012, ICE Database 2008). These frameworks and tools generally assume static building parameters (e.g., material insulation performance, efficiency of heating, ventilation and air conditioning systems, number of occupants) to determine the energy demand for the building. However, the factors that can affect a building's energy performance are not always static over the life cycle and the energy projections can deviate significantly from the estimates provided by the various energy simulation programs (Azar and Menassa 2011, Yudelson 2010, Turner and Frankel 2008). Very few studies/frameworks have considered the dynamic behavior of the aforementioned factors and its subsequent effects on the overall energy performance in a building during various life cycle phases. The primary aim of this study is to develop a system dynamics framework that can analyze all critical energy requirements in a building by visualizing the feedbacks and inter-relations existing between different building components through a coupled simulation environment. Such a framework can provide efficient material maintenance and replacement guidance and more clarity on environmental emissions expected during the operational phase of a building.

2. BACKGROUND

Embodied energy can be of two types. Initial embodied energy (IEE) is the energy required to construct a building and recurrent embodied energy (REE) is the energy required to carry out the necessary material maintenance and replacements during the operational phase to keep the building performance at satisfactory levels. Studies assessing embodied energy primarily adopt a life cycle assessment (LCA) based approach. In recent years, there has been an increased focus on assessing and monitoring the embodied energy associated with building materials and also their production processes (Dixit et al. 2010). Various databases that provide the embodied energy unit values (i.e., energy that is required for producing unit quantity of a material) have been extensively used in many studies for finding out the embodied energy estimate of building materials and also for evaluating various building design options (Capper et al. 2012, Rossit et al. 2012, Shiftehfar et al. 2010, Alwan and Jones 2010, Memarzadeh et al. 2012, Asif et al. 2002, Weir et al. 1996).

In the operational phase, the main focus of prior studies has been on performing comparative analysis between REE, IEE and total energy requirements in a building (Rauf et. al. 2014, Treloar et.al. 2000, Fay et.al 2000, Cole and Kernan 1996). Even though the percentage of REE obtained across these studies varied, all of them established the fact that REE can be as significant as other energy types. In the case of high performance buildings, where the operational energy is continuously brought down by means of energy saving measures, any measure for optimizing the embodied energy during the operational phase thus becomes very important. The end of life phase has been omitted by various studies citing that it is likely insignificant when a building's entire life cycle is considered (Crawford 2011, Crowther 1999, Suzuki 1998). However, the environmental emissions associated with demolition activities can reach up to 8% of the total life cycle emissions for the building (Viera and Horvath 2008) while the embodied energy that can be recycled back through reuse of materials can range up to 37-42 % of IEE (Thormark 2002).

It can be concluded from prior studies that the principles behind calculation of embodied energy are well understood. However, the effect of incurring embodied energy on a building's performance and its consequent effects on other energy requirements have not been comprehensively analyzed so far. For instance, performing maintenance/replacement on the insulation material in an external wall assembly can increase the performance of the assembly thereby decreasing the OE requirements. The effects of various maintenance and replacement schedules on the operating energy requirements are not usually considered. Typically, maintenance/replacement schedules are decided based on the experience of building managers and also based on manufacturer recommendations.

Meanwhile, for the estimation of operating energy requirements, energy simulation programs such as IES VE, eQuest and EnergyPlus take basic details about a building as input and provide the energy consumption estimates. Some of these typical inputs include, but are not limited to: building shape, orientation, occupancy schedule, and efficiency of boilers and chillers. However, the main limitation is that, different factors affecting the energy use in a building are considered as static unless the user desired to manually perform a sensitivity analysis. However, as noted previously, the energy consumption of a building is highly dynamic and depends upon various parameters that can continuously affect the building performance during the entire life span.

Furthermore, it is a significant challenge to combine these results together to estimate the life cycle energy performance of a building. Most of the tools/frameworks presently available are developed for addressing a specific objective/problem in the building life cycle energy domain. For example, energy simulation programs estimate operating energy in buildings, while LCA databases help calculate the embodied energy during various building phases. Ideally, to offer insights about the maximum energy savings possible, any simulation framework must be able to exploit the individual benefits of all process models collectively (Pang et al. 2012). Such a capability will result in a new fully integrated building energy management infrastructure that can help facility managers and other building stakeholders to take full advantage of the fundamental process level simulation tools and components.

3. OBJECTIVES

As stated earlier, the main aim of this study is to present a new approach for monitoring the life cycle energy requirements in commercial as well as residential building sectors through a system dynamics approach. This framework can also result in cost savings due to the optimum time selection of material maintenance and replacement cycles. The primary objectives of this research can be summarized as follows:

1. Develop an extensible system dynamics modelling framework that couples and analyzes the energy requirements from different life cycle phases of a building system.
2. Validate the model by performing a case study replicating a typical life span of a building and applying the model in different scenarios of building/material deterioration patterns.

4. RESEARCH METHODOLOGY

The overall approach adopted for this research is presented in Fig. 1 below. As depicted, energy requirements such as Initial embodied energy, Operating energy, Recurrent embodied energy and End-of-life energy are assimilated into a system dynamics (SD) simulation environment that integrates various energy flows through real time information exchange between different components during the simulation.

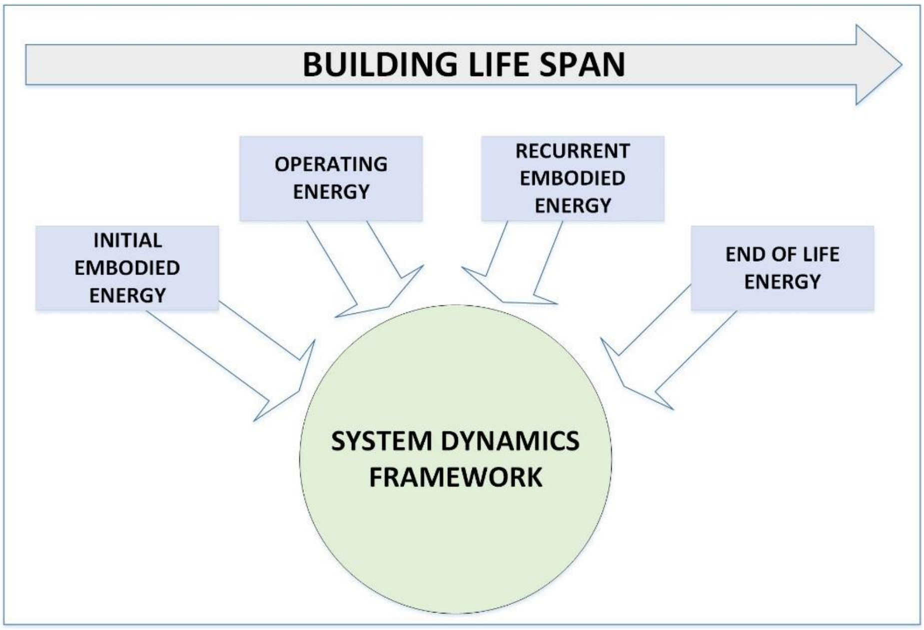


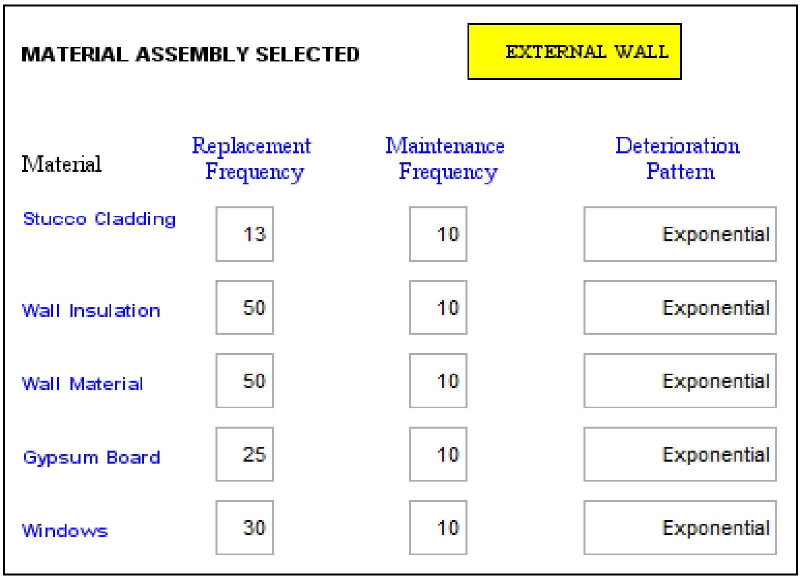
Fig. 1. Overall research approach

The proposed simulation framework is presented as a viable alternative to the traditional de-coupled energy analysis methods and is explained in the subsequent sections. Anylogic 7.0.0, a java based multi-method simulation software package is used for performing the system dynamics simulations. EnergyPlus V 7.2, an open source energy simulation software provided by the U.S Department of Energy (DOE) is used for conducting the energy simulations. Various LCA based tools/data repositories are utilized for obtaining the embodied energy unit values of different materials.

4.1 System Dynamics Simulation Framework

The system dynamics approach is based on a theory of feedback processes and inter-dependencies. A feedback system is influenced by its own past behavior which means that the results from past actions can affect the future actions (Ahmad et al 2000). Feedbacks can be positive or negative. Positive feedbacks strengthen the system behavior and negative feedbacks balance the system behavior. For instance, a high-performance building will require a higher embodied energy at the beginning for providing renewable energy generation facilities such as solar panels, and wind farms also in addition to highly efficient materials and electronic devices. However, this extra energy at the start can result in balancing the operating energy requirements during the operational phase. In addition, regular maintenance and replacement activities can increase the building performance and can be considered as a feedback that can balance the operating energy usage in the building during the operational phase. Similarly, during the end-of-life phase, embodied energy that can recovered back through recycling of materials can also be considered as a feedback that balances the total energy requirement in a building system. In summary, over the entire life cycle of a building, there are various factors that affect the energy requirements and one of the major advantages of selecting a system dynamics approach is that various feedbacks and inter-relationships can be effectively visualized and represented in the same environment to provide an overall understanding of the building's life cycle energy requirements.

Before the start of the simulation, a user will input the maintenance and replacement schedules for which the life cycle energy impact is to be assessed. Fig. 2 below illustrates a typical such user input screen for an insulation system in an external wall assembly. The insulation capacity of any material assembly is a decisive factor in determining the operating energy requirements of a building. A material's insulating performance is usually expressed in terms of R-Value (ASHRAE -2013). 'Replacement frequency' in Fig. 2 denotes the frequency at which the material is replaced and during replacement the R-Value is reinstated to its initial value. Similarly, 'Maintenance Frequency' denotes the frequency of maintenance performed on a specific material and during maintenance it is assumed that the R-Value is reinstated to a previous R-Value which the material was possessing before. The REE incurred for both cases will be based on the percentage of R-Value reinstated by the performed replacement or maintenance. Through the option 'Deterioration Pattern' users can select the pattern of material deterioration from linear, exponential, and polynomial patterns that are typically observed for building materials (Kesik and Salef 2005, Sohet et al. 2002, Harris 2001). In this specific example, the R-value variation patterns will be generated based on the maintenance and replacement schedules and also based on the exponential deterioration pattern.


MATERIAL ASSEMBLY SELECTED: EXTERNAL WALL

Material	Replacement Frequency	Maintenance Frequency	Deterioration Pattern
Stucco Cladding	13	10	Exponential
Wall Insulation	50	10	Exponential
Wall Material	50	10	Exponential
Gypsum Board	25	10	Exponential
Windows	30	10	Exponential

Fig. 2. Example User Input Screen

The system dynamics simulation window that incorporates all energy requirements is shown in Fig.3 below. The simulation is performed on a monthly basis for a period of 600 months (50 years). A building's typical life cycle starts with the design phase wherein initial embodied energy will be incurred for designing and constructing the building. As mentioned previously, a highly energy efficient building will require a higher value of IEE, but can eventually result in lesser annual operational energy requirements. 'IEE' is computed based on the building area and the average EE information obtained through data exchange from the life cycle data repository. The value of this 'IEE' will be added to the 'lifeCycleEnergy' stock as the initial value at time=0. A stock in a system dynamics simulation is a place where accumulation or storage takes place in a system (Ford 1999). All energy requirements during the life cycle of the building will be accumulated to the stock 'lifeCycleEnergy'.

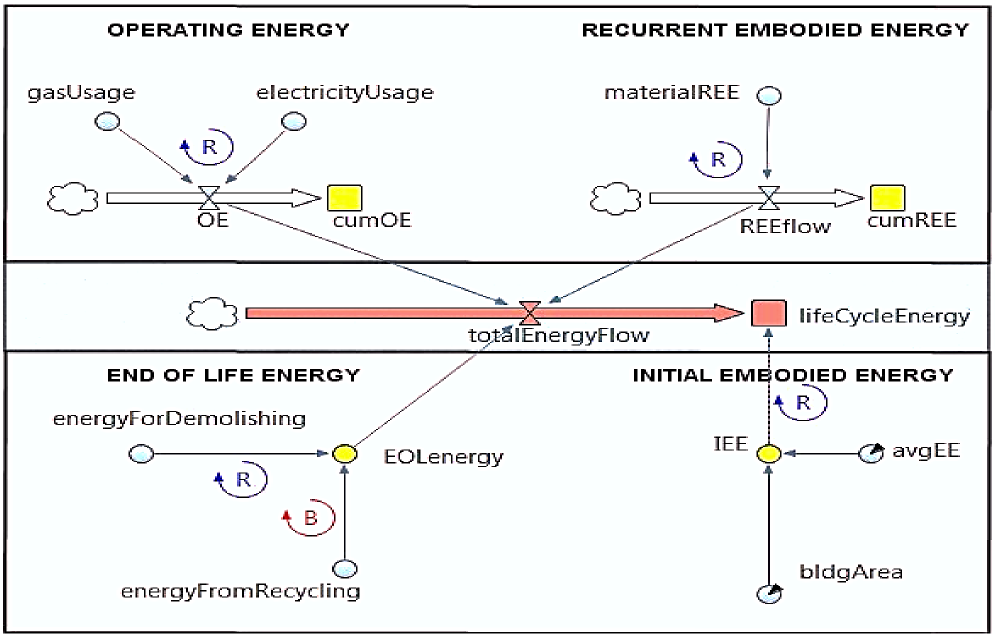


Fig. 3. System dynamics window

During the operational phase, the operating energy and recurrent embodied energy incurred are represented as two flows in the system, 'OE' and 'REEflow'. A flow in a SD simulation represents the increase of the flowing component in the system (Ford 1999). Stocks and flows are the building blocks of any system dynamics model. The electricity and gas usage requirements are calculated by performing energy simulation through EnergyPlus. From EnergyPlus outputs in the building energy performance data repository, the dynamic variables 'gasUsage' and 'electricityUsage' will record the energy consumption details for each month. During each simulation time step, the operating energy requirement ('OE') will be calculated as the sum of 'electricityUsage' and 'gasUsage' and stock 'cumOE' represents the accumulation of these OE requirements.

Meanwhile, the maintenance and replacement schedule input by the user (Fig. 2) determines the REE to be incurred for the building and will be calculated based on the information exchanged from the life cycle data repository and will be saved to the variable 'materialREE' during each simulation step. For instance, a replacement of windows at 30 years will trigger incurring a REE during the 30th year of the simulation run. These REE values will be added to the flow 'REEflow' and will be accumulated to the stock 'cumREE' during the simulation. Incurring REE will improve the building performance by improving the R-values and this is a negative feedback in this system that balances the operating energy requirement. To reflect the actual building life cycle scenario, the modified R-values are written to the energyPlus '.idf' files and this change in material properties will have a direct effect on the operating energy consumption details every month.

During the end of life phase of the building, 'EOLenergy' is calculated by subtracting 'energyFromrecycling' (embodied energy that can recovered back through recycling) from 'energyFromDemolishing' (energy required for demolishing the building). The energy flow occurring during each step of the simulation is added to the 'totalEnergyFlow' at each time step to obtain the accumulated total life cycle energy represented by the 'lifeCycleEnergy' stock. Thus, completion of one full simulation run will provide the energy requirements for different life cycle phases and also the total energy requirements for the building.

4.2 Components of the coupled simulation framework

The four main components of this coupled simulation framework are the system dynamics simulation model developed in Anylogic, the Building energy performance data repository developed in Microsoft Excel 2013, the Energy Plus building models and the life cycle data repository developed based on LCA databases and related literature. The typical steps associated with testing one maintenance and replacement scenario is shown in Fig. 4 below. In step 1, the user's preferences about the maintenance and replacement patterns of various building materials will be gathered (Fig. 2). Once the preferences are collected, they are updated to the building energy performance data repository at step 2. In step 3, based on the user's preferences from Step 1 and the typical deterioration patterns of the materials (linear, exponential or polynomial), material performance variation patterns for the entire life span will be generated. After developing the material performance variation patterns in step 3, they will be updated to the EnergyPlus prototype models and energy simulation will be carried out in step 4 for the entire life span of the building. In step 5, the monthly operating energy values will be updated to the life cycle data repository. The final step will be the system dynamics simulation bringing all the components and the energy requirements together by interacting with the building energy performance data repository and the life cycle data repository. The interactions and nexus between different steps are established through programming scripts written in Matlab 2014. The capabilities of this proposed framework is tested on a 12 story commercial building located in Chicago which will be explained in the next section.

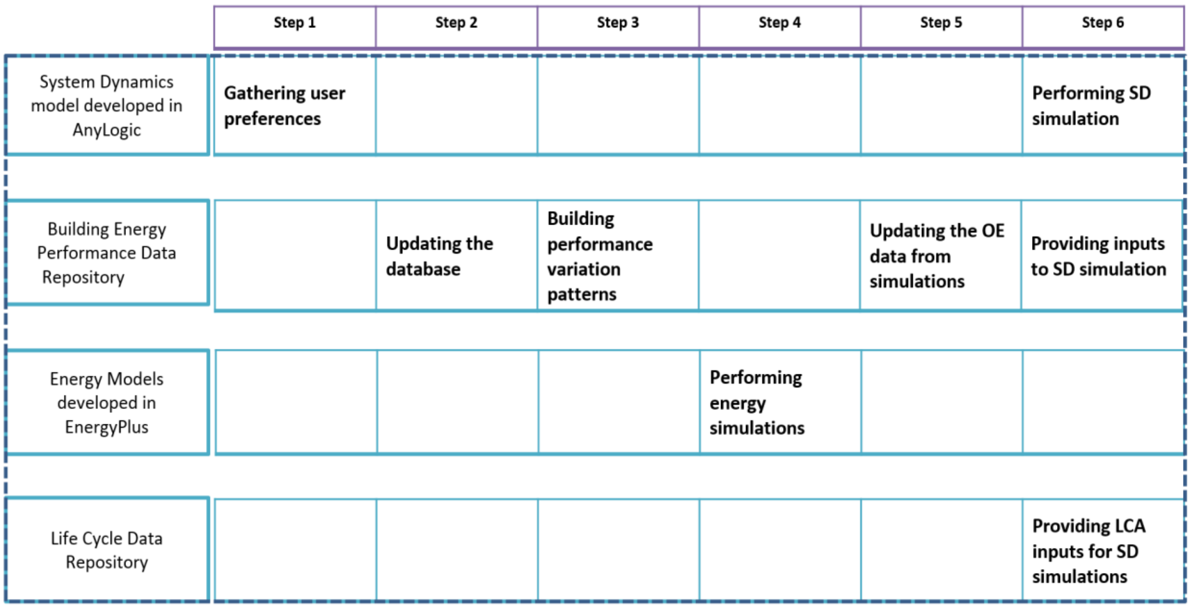


Fig. 4. Simulation time steps

5. CASE STUDY AND RESULTS

An office building located in Chicago with 12 stories and a gross area of 46,320 sqm is selected as a case study model to validate the framework. This building model is one of the EnergyPlus compatible models provided by the DOE across different climate zones in the US (DOE 2015). A life span of 50 years is adopted as the analysis period based on various similar studies (Rauf et al. 2014, Crawford et al. 2010, Fay et al. 2000, Cole et al. 1996). An external wall assembly consisting of external stucco cladding, wall insulation, concrete wall material, interior gypsum finishing and windows is selected for illustrating the framework.

Three scenarios were considered for testing the developed framework and the details of these scenarios are given in Table 1. In each scenario, the R-value of the material is assumed to be deteriorating based on the deterioration pattern initially chosen by the user (Fig. 2). In this case study, an exponential deterioration pattern is assumed for all scenarios and for all materials. The first scenario represents the base case where no maintenance will be performed on the external wall assembly during the entire life span of the building. However, when the material reaches 40% of its initial installed performance level, a replacement of that particular material is carried out. This assumption is adopted based on the study of deterioration patterns of cladding materials by Sohet et al. (2002) and also grounded on the general polynomial deterioration pattern proposed by Harris (2001). Replacement rates of materials are adopted based on various LCA based studies and building design databases (NREL 2015, RSMeans 2014, Crawford et al. 2011, Sohet et al. 2002). The replacement rate assumed for different materials for external cladding is 15 years, while for the windows a 30 year period is considered. For interior gypsum, the replacement period is taken as every 25 years. As the suggested service life of concrete wall and the insulation material is more than 50 years, no replacement is considered for both those materials.

The second scenario considers performing maintenance on windows at every 10 years and the third scenario assumes a maintenance on windows at every 5 years instead. The window-to-wall ratio for the case study model is 38% and while performing the energy simulation, windows are observed to be one of the critical component in controlling the thermal performance of the building. The details of the scenarios are summarised in Table 1 below:

Table 1: Scenario Analysis Description

Scenarios	Replacement of materials	Maintenance of Material	Material Deterioration pattern
Base Case	YES	NO	Exponential
Scenario 1	YES	YES (Maintenance for only windows at every 10 years)	Exponential
Scenario 2	YES	YES (Maintenance for only windows at every 5 years)	Exponential

For this study, the cumulative OE, difference in cumulative OE and also the REE incurred are selected for the comparative analysis. Compared to the base scenario, the only difference in scenario 1 and scenario 2 is the maintenance activity performed on the windows in the building. Hence, the variation in the cumulative OE in scenario 1 and scenario 2 needs to be compared against the share of operating energy in a building from windows. For understanding this, a separate study was conducted where the operating energy of the case study building was simulated for a year with normal window-to-wall-ratio (38%) and also by hypothetically assuming a window-to-wall ratio of zero. This analysis was performed only to understand the effect of windows in the thermal performance of a building. It was observed that around 13.3% of the operating energy can be attributed to the presence of windows. In other words, the operating energy requirement of a building having no windows will be 13.3% lesser compared to a building with normal windows.

The results obtained by performing the three scenarios are summarized in Table 2 below. As mentioned before, the savings in operating energy (Column D) was compared against the share of operating energy due the windows in the building (Column C). The percentage savings obtained are given in Column E. Column F provides the value of REE incurred for each scenario.

Table 2: Results from the scenario analysis

A	B	C	D	E	F
Scenarios	**Cumulative OE (In GJ)**	**Impact of Windows on the cumulative OE usage (In GJ)**	**Savings in OE requirement (In GJ)**	**% savings in OE**	**Cum REE in GJ**
Base Case	1,699,236	225,998	N/A	N/A	14,950
Scenario 1	1,688,075	N/A	11,162	5%	16,749
Scenario 2	1,657,411	N/A	41,825	19%	20,363

6. DISCUSSIONS AND CONCLUSIONS

A building located in Chicago was selected as a case study in this research. Energy plus V 7-2-0 was used for performing energy simulations and Anylogic 7.0.0 was used for creating the system dynamics framework that interacts with various other components. Operating energy and recurrent embodied energy usage for three scenarios based on different maintenance schedules with a base replacement pattern were plotted. It was observed that performing regular maintenance and replacement can reduce the annual operating energy in any building and the energy required for three scenarios was quantified.

On the cumulative operating energy usage, Scenario 1 reported a 5% savings and Scenario 2 reported 19% savings. This indicates that performing regular maintenance on windows every five years in the building has fetched a considerable amount of overall savings in operating energy over the entire life span. In addition, the savings obtained in Scenario 2 are more than the REE incurred for conducting the maintenance and replacement. This underlines the importance of performing regular maintenance and suggests that adopting a similar maintenance frequency on other materials can provide more savings in the cumulative operating energy. Similarly, by performing maintenance, the insulation properties of the material can always be kept under control and this can extend the service life of the material. Testing several such scenarios with varied replacement and maintenance frequencies can result in obtaining an optimum schedule that provides maximum energy savings in terms of OE and REE during the operational phase. Similarly, in the case of an energy efficient building, the IEE might be higher than a normal building but can result in lesser operating energy requirement during the operational phase because of lesser maintenance and replacement requirements and also due to better material performance.

In addition to the energy savings, regular maintenance can have other tangible benefits such as better occupant comfort, improved external appearance thereby sustaining the market value of the property, and maintaining weather tightness thereby providing better protection for various electrical and mechanical appliances inside the building. Often, maintenance or replacement is done when there is a noticeable failure or loss of function for any particular building material or assembly. In that case, the material might have already crossed the useful service life and this would have already affected the operating energy usage adversely. The framework proposed through this research can be a useful tool primarily for building facility managers who are faced with questions about the right time to conduct a maintenance or replacement of building materials.

The presented approach also has some current limitations. This study considered only external wall assembly for the simulation analysis. In reality, the performance of all materials in a building can affect the operating energy requirement and considering the effect of other materials can increase the energy performance of a building. In addition, there are many other factors such as occupant behavior, effects due to weather changes, and efficiency of equipment and systems in the building that can affect the energy use in a building. These are currently being incorporated into the model by the authors in ongoing work. Cost associated with maintenance is also an important parameter to be considered in tandem with incurring extra recurrent embodied energy. In the future, the authors will extend the scope of this research initiative by including the aforementioned factors to result in a fully developed building life cycle energy analysis tool.

7. ACKNOWLEDGMENTS

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