A SYSTEM DYNAMICS MODEL FOR THE SELECTION OF CONSTRUCTION PARAMETERS IN ENERGY EFFICIENT HOUSING

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ABSTRACT

The design of Energy Efficient Housing is an iterative process that requires the participation of experts in different fields while consuming time and human resources, thus increasing the cost of the final product. The development of tools that allow a more efficient design process can have a positive impact in the reduction of costs associated with designs, and it might incentivize the implementation of sustainable practices for the construction of new homes or retrofitting of existing ones. The challenge for this situation is to find a method that allows the use of existing detailed simulation tools starting with early design stages when some variable values for the technical sub-systems of the home are not yet available. This paper proposes the use of System Dynamics (SD) as a methodology for the integration of different simulations that take place during the design of energy efficient housing propositions and the cost estimate associated with the selection of materials for construction. The current research presents previous uses of SD as well as a model that integrates simulation tools for the design, analysis and cost estimate of energy efficient housing.

Keywords:
System Dynamics, Energy Efficient Housing, construction parameters, design modeling.

1. Introduction

Since the 1960s, sustainable development has received a lot of attention and has become a dominant topic in the agenda of local and national governments, especially after the United Nations Conference on Environment and Development (UNCED) held in 1992 in Rio de Janeiro. The continuous growth of the worldwide population and the depletion of the natural resources are having a direct impact in securing the wellbeing of future generations. The dependence to non-renewable resources makes our modern society more vulnerable to social, economic, and political conflicts associated with the production of those resources.

The implementation of sustainable practices in construction have a high impact in the economic, environmental, and social dimensions of sustainable development. The fact that actual energy consumption by the residential sector is two-fifths of the total energy consumption of the United States is enough reason to give special attention to importance of achieving sustainable practices in the homebuilding industry.

Notwithstanding the existence of computational tools and the availability of new materials, the integration of food, energy and water systems in sustainable housing are far of being the norm in new constructions. While the practice can be seen as an opportunity in the market, researchers affirm that current tools are inadequate, complex, user hostile (Attia et al., 2012), they required a high level of expertise, they are costly in terms of money and time, and during the decision making, the designer cannot easily predict the impact of decisions on building performance and cost.

The design of an energy efficient house is an iterative process that requires the participation of experts in different fields while consuming time and human resources, thus increasing the cost of the final product. The development of tools
that allow a more efficient design process can have a positive impact in the reduction of costs associated with designs, and it might incentivize the implementation of sustainable practices for the construction of new homes or retrofitting of existing ones. The challenge for this situation is to find a method that allows the use of existing detailed simulation tools starting with early design stages when some variable values for the technical sub-systems of the home are not yet available (Brahme et al., 2001).

The design process is a component that greatly influences in achieving construction of sustainable housing. However, a tool capable of analyzing all the subsystems involved in the performance of a home does not exist. Usually there is a different tool for each type of specialty, and often the interfaces do not allow to import information from one tool to another. Consequently, the project has to be modeled again in each software, and often the model is repeatedly created from scratch. Additionally, since changes cannot be automatically updated, a great amount of work and coordination with experts is implied. The research question to be answered is whether it is possible to construct a model that integrates different parts of a house system during the design stage. The model should be capable of generating results for a more effective way to study the impacts and interactions of elements that are part of an energy efficient system.

This research intends to use system dynamics to propose a model that integrates different design aspects and allows to determine the impact in a previous design stage. The model should allow defining design parameters from the beginning of the process. As a result, the model will be an additional tool for reaching goals while reducing the number of iterations. The selected parameters can be given to the architect as an input for the design, and as a consequence, the final product can meet expected goals in less iterations and in less time.

2. Background

Traditionally, the process of creating sustainable housing begins with the site selection, followed by planning and programming in accordance with the requirements of the client. One of the first deliverables is the preliminary design, which becomes an important input for the subsequent simulation processes. Then, the design is evaluated using different tools that are used to determine aspects such as heating and cooling demands of the designed residence. After that, the search for the ideal solution to minimize demand becomes an iterative process in which design and analysis stages are repeated until the best solution is found by the design team. The team has to reach a solution that meets requirements from different codes and specifications, along with certain goals specified by the project (e.g., PV panels, natural lighting, rain water harvesting). Besides this, generating an energy efficient design is a difficult task due to aspects that vary from project to project such as orientation, location, shading, and weather.

Every decision made during the design process will later impact the construction cost and house performance; hence, it is imperative to pay special attention to this project phase. Nowadays, in the building industry, experts from different areas can be integrated through contractual agreements or delivery methods such as Integrated Project Delivery (IPD) or procurement methods like Design – Assist. For residential design, the additional high costs associated limit the use of these practices.

The use of System Dynamics (SD) as a methodology for the integration of different simulations that take place during the design of sustainable housing is studied in this article. A literature review was conducted in order to identify similar uses of SD. The methodology is studied for the purpose of integrating different tools taking into consideration that a building system's simulation is well-suited in situations where the system to be modeled is extremely complex, highly dynamic or contains a large number of feedbacks (Thompson and Bank, 2010). The selection of this methodology is based on the capability of SD to model the building as a feedback system in order to simulate the interactions among various building sub-systems (Thompson and Bank, 2010).

2.1. System Dynamics

The SD methodology is a mathematical modelling technique can be applied to understand the performance over time of a complex system, and it can be implemented to the modelling of systems in various disciplines, besides the ones that are related to social sciences. The approach of SD is different to other modelling techniques concerning the use of stocks, flows, feedback loops and time delays. The model can be represented graphically in different software packages developed for model solving by updating all the variables in small time increments. A simple model for housing demand and supply was created as example (see Figure 1). The model represents a scenario where a builder has 10 units ready to be sold, and is planning to build 30 more units. Each month, 25% of the houses under construction are completed and 33.33% of the inventory is sold.

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The “houses completed” flow element represents the flow of stock from houses under construction to inventory of houses. The stock of houses under construction is reduced from its initial value of 30, until it reaches the final value of 0. It is important to notice that the number of houses completed is a function of the number of houses under construction; also, the number of houses under construction is the difference of the initial value and the number of houses completed.

The model is simulated for 30 months, and the results from the simulation allows to visualize the changes in the flow of houses completed and sold houses, and the changes in inventory of houses under construction and completed houses. Figure 2 presents the graphical results from the simulation of the model. Once the model has been created it is simple to analyze the impact of changes in any of the parameters of the model. For example, if the housing demand changes from three to ten, the inventory of houses increases and the number of houses sold decreases.

2.2. Applications of SD in civil engineering and building construction

SD modelling has been used in a variety of applications. One of the first applications was the model proposed by Chasey et al. (1997) to study the relationships between the comprehensive level of service and the effect on the socioeconomic system for civil infrastructure systems. The model studied the complex interrelationships between the transportation system, their construction and maintenance, and the impact on the user. The approach was used due to the feedback attributes of the problem (Chasey et al., 1997). Another contribution to the area of transport infrastructure is the decision support system for road maintenance budget allocation that consists of four sub-systems. This model was made to provide a decision tool while the behaviour of the system was studied for several combinations of budget allocation (Bjornsson et al., 2000).

SD methods have been used to study waste management and waste generation. Causal loop diagrams are developed for wastewater collection networks to identify complex interactions and feedback loops among physical, financial, and social sector, resulting in a support tool that can be used for financially sustainable management of wastewater collection networks (Rehan et al., 2014). Waste generation models have been developed for the analysis of waste generation in an urban setting having a high economic growth potential with regard to alternative policies in the problem (Dyson and Chang, 2005). Similarly the model developed by Van Vuuren et al. (1999) simulates long-term trends in the production and consumption of metals in relation to impacts such as ore-grade decline, capital and energy requirements and waste flows (Van Vuuren et al., 1999).
The area of building construction has used the SD method to study the effects of project personnel changes with a model of the design process which looks at the causes behind erosion for design productivity arising from staff changes, and the identification of those issues which aggravate the assimilation period of new recruits (Chapman, 1998). The design build process was analysed with a dynamic project plan for design/build fast-track that can absorb changes in the project schedule without creating major interruptions. The methodology used integrated SD with the graphical evaluation and review technique (GERT), axiomatic design concepts, and concurrent engineering concept. The SD was applied to analyse the causality links of relevant factors in the construction system, and to identify the important variables that determine the success of a particular overlapping strategy (Peña-Mora and Li, 2001).

The dynamic behavior of project performance and the cause effect relationships that may be responsible for responsible for time and cost over-runs in infrastructure projects was explored with SD (Ogunlana et al., 2003). Love et al. (2002) used SD to understand change and rework in a construction project management system by taking into consideration that project managers have to integrate the work activities of consultants, subcontractors and suppliers. Park and Peña-Mora (2003) proposed an enhanced version of the dynamic planning and control methodology (DPM), and Lee et al. (2005) proposed a framework for quality and change management model that evaluates the negative impacts of error and changes on construction performance for negative iterative cycles.

The delay and disruption claims and the dispute resolution applied to construction projects have been analyzed with a model that is useful for acceleration, delay, and disruption claims, quantifies and portrays indirect productivity losses, determines which activity causes the largest amount of delay and which activity is delayed most in a particular project (Ibbs and Liu, 2005), a conceptual and mathematical model to evaluate alternative dispute resolution (ADR) investments by drawing an analogy from theories of financial and real option pricing. The model provides a decision framework that accounts for the uncertainty in estimating the ADR investment cash flows during the project planning phase (Menassa et al., 2009), and a model adopted to represent the dynamic complexities in the origin and escalation of conflicts, and the interaction between conflicts and dispute avoidance and resolution techniques (DART) (Ng et al., 2007).

For the error and change management using SD a model focuses on the economic and environmental impacts for construction process for the change management and error. The research explores the use of SD in identifying multiple feedback processes and softer aspects of managing errors and changes. The study concludes that the SD approach can be an effective tool in the understanding of complex and dynamic construction processes and in supporting the decision making process of making appropriate policies to improve construction performance. (Lee and Peña-Mora, 2005).

SD can also be implemented for modeling reservoir operations, and simulate them for flood management purposes (Ahmad and Simonovic, 2000), and integrated with geographic information system (GIS) in a new approach called spatial system dynamics (SSD) (Ahmad and Simonovic, 2004).

2.3. Applications of system dynamics for design and simulation

Although SD has not being implemented for the design of residential construction, it has being implemented in some situations that are closely related to the design of buildings in three main areas: life cycle assessment, integration with other tools, and building’s system interaction.

The models developed towards the study of the life cycle assessment have been developed to analyse the performance during the expected time of occupancy of the facility. A first research uses building design strategies to predict and reduce the environmental loads for the several types of construction and building materials. For this model, the simulation accomplished results for a long-life and energy efficient house more effective in regard to life cycle assessment (LCA), and allowed the possibility to address a life cycle cost (LCC) of the houses and a carbon dioxide flow SD model (Matsumoto, 1999). A second research demonstrated that the contribution of a project to sustainable development can change largely due to the impact of various dynamic variables throughout its life cycle. The project’s sustainable performance was examined using three factors: economic development, social development, and environmental. (Shen et al., 2005). Finally, a model based on the analysis of the construction life cycle of residential buildings was developed using SD. The model consist of three components: material input data, STELLA simulation model, and decision-making process (Marzouk et al., 2013).

The available tools used for the implementation of the SD methodology have been integrated with other software in some cases. An example of this integration is the proposed approach for sustainability assessment of urban residential development using Geographical Information System (GIS), SD, and 3D Visualization. With the integration of this tools, the model allows to explore the housing equilibrium using sustainability indicators, explore economic, social, and
environmental features on residential buildings, and to visualize the simulation data in GIS technology (Xu and Coors, 2012). Similarly other simulation used a Shared Object Model (SOM) to incorporate the information needed for the configurationally definition of the building early in the design process (Brahme et al., 2001).

The interaction of the subsystems that belong to the general system of the building has a considerable impact in the final performance of the building. The study of interaction of systems was used to create tools such as the evacuation simulation model (ESM). ESM is a tool for simulating the evacuation in building fires. The tool predicts the evacuation performance of a building and not only is capable of tracking the occupants and flow rate profile inside the building; it also can estimate the possible victims by giving the tenable duration for any compartment (Shen, 2005). Another example of subsystem interaction is the study of the mid and long term impacts of green buildings related policies on the greenhouse gas (GHC) emissions stock. The objective of the study was to find best policy options which can stabilize the exponentially increasing trend of GHC emissions stock configured from the energy use in the US residential buildings (Onat et al., 2014). A third paper demonstrates the use of the SD method for the analysis of a building subject to a bioterrorist attack. The model is used to study three major categories of building variables: performance of the air handling system, physical building security modifications and occupant behavior modification. It uses the output data to improve decision-making in building design, retrofit, and operation and links an electronic building information model (BIM) of the building to enable the electronic capture of the relevant building features in the system (Thompson and Bank, 2010).

3. Methodology

An expected result from the proposed research is the development of a model that can be used to provide feedback to the design team. During the design phase it is important to provide feedback of the building performance to the designer as early as possible. But many aspects of building performance are significantly affected by the design of the building's technical systems, which are typically configured in detail only in the later stages of design (Brahme et al., 2001).

With the aim of allowing an expedited process for the design of sustainable housing, it is important to select the best tool for the elaboration of the model. SD has been used as a tool to analyze complex systems and the impact of the elements within the system. In the area of design integration, some authors have been able to integrate SD with other tools, and in some areas the area of management has presented satisfactory examples, like the generic model generated for a design and build construction project that included five subsystems: the employer, the design, the procurement, the construction and the financial subsystem which was successfully created using SD (Chritamara et al., 2002).

The evidences shows that SD can also be used for the integration of different elements that have an impact in the performance of the final product, but it is necessary to build the model and evaluate if the methodology of SD is the most suitable for this purposes. For the actual research the process consists of four steps: literature review, selection of the system components that affect the energy performance of the building, selection of the tools that are used for the evaluation of the components, and design of causal loop diagram with the elements.

From previous experiences in the area of building simulation design, the components that affect the energy performance of the building have to be included in the proposed model because they influence the results (i.e., stock and flows) of the simulation. These elements are: geographic location, building orientation, building materials, area and orientation of windows and doors, geometric characteristics of the building, building ventilation, characteristics of the zones of the building, building occupancy, heating and cooling systems type and configuration, existing elements on the surrounding areas (e.g., adjacent buildings, trees), building type and use.

The analysis of the influence of these elements is a difficult task itself. Due to the complexity of the mathematical equations used to predict the results in terms of energy consumption for the house some of the existing tools only perform calculations for one parameter at the time (i.e., one tool is required to measure the sky view factor, a different tool is used to perform the ventilation analysis). The result is a set of models, and results, from each one of the software. This process requires individual input of the information and separate analysis of the results. The tools that can be used for the evaluation of the components listed previously are: software for computer aided design (e.g., AutoCAD, SketchUp, Revit); software for solar radiation analysis (e.g., Ecotect); Software for wind pressure analysis (e.g., CP calculator); software for heating and cooling needs (e.g., EPC, eQuest); energy simulation programs for modelling building heating, cooling, lighting, ventilating, and other energy flows (e.g., EnergyPlus + DesignBuilder); or software for multizone indoor air quality and ventilation analysis.

The proposed diagram that includes the elements that participate in the design process are presented in Figure 3 (left). This diagram will be used as an input for the creation of the causal diagram (see Figure 3, right) and the SD model.
The figure shows the flow of information from one tool to the other, the results are analyzed and compared until they are satisfactory, when the design meets the goals and requirements the final model is released and it is materialized during the construction phase.

![Design process diagram and design process causal diagram](image)

Figure 3. Design process diagram and design process causal diagram

4. Anticipated results

The expected result from this research is a model that integrates different aspects of the design requirements for a sustainable housing. The model should allow to determine the impacts from the elements with less interactions and in a shorter time compared to an analysis performed in a traditional process. The results from the model should allow to establish the parameters for the final design, almost from the beginning of the process, as a result the model would be an additional tool for meeting the goals while reducing the number of iterations.

The selected parameters could be given as an input for the final design and as a consequence the design can meet the goals with less iteration and as consequence, in a shorter time. The models would have the ability to properly function as an evaluation tool due to the option of changing the inputs to the model while maintaining the structure of the relationship among the elements that are part of the system.

5. Conclusions and future work

The use of SD as a method for analyzing complex systems and for making decisions was presented in this paper. A review of previous uses of the method in the field of civil engineering and design was discussed, and the literature review showed why the SD method can be applicable to solve the research problem.

The design of sustainable housing is a complex process that requires a considerable amount of human resources and time. The additional cost added by the design process is a barrier for the final users to have access to sustainable housing. While the public and private sector have a notable interest in exploring options that encourage the reduction of energy in residential housing, the existing process for sustainable design are expensive for the budget of most of owners.

The main contribution of this work to the body of knowledge will be to contribute with a model that integrates different systems in residential housing. It is expected that this model could be used as a building design strategy to predict and reduce the environmental loads for construction and building materials. Also the model could be used to accomplish results for a long-life and energy efficient house more effective in regard to life cycle assessment (LCA), and should allow the possibility to address a life cycle cost (LCC) of housing propositions. The study is limited to housing design and construction, but future work could include commercial buildings.

Future research includes the selection of system components that affect the energy performance of the building. The next stage of the research is to identify the elements that have higher impact on the energy performance by performing first a literature review, and then the analysis of a prototype house. In order to simplify the SD model only the elements with the higher impact are going to be included, for that reason, the results from the analysis of the prototype are going to be organizing and selected using the Pareto principle, also known as the 80–20 rule.
Once the elements have been selected, the model is going to be proposed and then calibrated using results from existing buildings. One of the challenges on this phase is the limited amount of information available for residential housing.

6. References


