# Zero Carbon Emissions in Buildings: A Systems Thinking Modeling Approach

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## Abstract

*Empirical evidence suggests that many variables affect energy use and carbon emissions in buildings. The variables interrelate in a sophisticated manner and constitute a socio-technical problem. While previous observations about the interrelationships among the factors stem from building physics and numerical simulations, gaps exist in the articulation of the socio-technical issues. This article argues for a paradigm shift in the modeling approach through the development of a systems thinking model (STM) for evaluating carbon emissions in buildings. The methodology for this research involved using the literature and knowledge elicitation of stakeholders in the housing sector to build the initial systems thinking model (iSTM), especially where the relationships could not be established empirically. The final systems thinking model (fSTM) was developed by subjecting the iSTM to experts' review based on a focus group approach by way of knowledge elicitation of the experts. The findings indicate a population of causal variables influencing carbon emissions in dwellings and show the complexity involved among the variables. The study concludes that the approach used in building the model has the capability of improving the accuracy and credibility of the developed STM for evaluating carbon emissions for zero carbon homes.*

**Keywords:** carbon emissions; dwellings; knowledge elicitation; South Africa; systems thinking



## Introduction

Over the years, the housing sector has been at the epicenter of the sustainability agenda for many nations.[1] This is due to the enormous amount of energy use and carbon emissions that are attributed to this sector. According to the report from the United Nations Department of Economic and Social Affairs (UNDESA), about one-third of carbon emissions from all sectors is attributable to the housing sector.[2] Considering the devastating effects of human-caused climate change, the need is great to find means of ameliorating energy use and carbon emissions in dwellings.

This notion is in line with the United Nations conventions on climate change in 1992, 1997, 2009, and 2015. South Africa is one of the signatories to the agreements reached during these conventions, and through state law, has subsequently cut down on its generation of carbon emissions.[3] For example, South Africa has set ambitious targets to cut carbon emissions by 34 percent by 2020 from business as usual 1994 emissions, and by 42 percent by 2025 through the "intended nationally determined contribution" plan.[4] Reduction of the energy consumption patterns in dwellings is one of the targets for cutting total emissions. Many comprehensive studies have been conducted within the South African energy sector as demonstrated by the works of Beute,[5] Energy Research Centre (ERC),[6] Arndt, Davies, and Thurlow,[7] Alton et al,[8] and Senatla,[9] among others. However, there is limited evidence to suggest that the literature is

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keeping pace with the changes in the domain of energy studies and the attendant carbon emissions within the housing sector in South Africa.

Quite a number of studies have established that there are multiple factors affecting energy consumption and, invariably, carbon emissions in dwellings, as documented in the works of Motawa and Oladokun,[10] Gram-Hanssen,[11] Tweed et al.,[12] Chartered Institution of Building Services Engineers (CIBSE),[13] Abrahamse and Steg,[14] Kelly,[15] Yun and Steemers,[16] Isaacs et al.,[17] and Hitchcock,[18] among others. Some of those variables according to Hitchcock are dwelling size, stock of appliances, dwelling's internal temperature, hot water usage, materials, appliance use, occupants' thermal comfort, occupants' behavior, and heating system, among others.[18] Motawa and Oladokun[10] aptly mapped these variables into three systems consisting of the dwelling system, occupants' system, and environmental system. Motawa and Oladokun[19] also argued that the variables in each of the systems interact and interrelate in a sophisticated manner, which signifies the need for a suitable approach capable of capturing this kind of complexity.

The majority of energy studies in the housing sector relating to modeling have utilized approaches that involve the building physics and numerical simulations and consider the amount of hard data collected on individual dwellings as demonstrated in the studies of Mhalas et al.,[20] Jenkins,[21] Fung,[22] and Johnston,[23] among others. These approaches are quantitative and deterministic,[1] while real-world modeling with this kind of system involves capturing both the quantitative and qualitative variables. Often, however, the qualitative variables lack empirical data to support the relationships among the variables, and this has been reported to pose problems to studies within this research area. As such, this article reports the development of a causal model of variables influencing carbon emissions in dwellings using the experts' knowledge elicitation approach within the systems thinking modeling paradigm.

## Materials and Methods

The study reported here adopted the systems thinking method (STM) associated with the system dynamics (SD) modeling approach. The STM ensures that complex interactions among variables in a model are captured in an integrated manner. This method is considered adequate for better understanding of the cause and effect mechanism that enables insights into the behavior of the model. The philosophical foundation of the SD approach stems from a pragmatic worldview of research[24] and is designed to ensure that two or more research strategies are employed to solve the research problem posed by the study. The STM of the SD modeling technique employs the experts' knowledge elicitation method under the participatory SD as follows.

### *The Systems Thinking Approach*

According to Sterman,[25] the STM is capable of analyzing and drawing insights from the dynamics of complex systems. It is, indeed, one of the approaches and tools capable of modeling complex systems qualitatively.[26,27] Historically, the STM is rooted in the SD approach as propounded by Jay W. Forrester in the early 1960s.[28] The technique combines engineering and management. That is, by drawing from the concepts of control engineering and cybernetics in combination with management theory, the approach provides a formidable technique capable of analyzing the behavior of complex systems. One of the critical features of the STM is the causal feedback structure, which involves the conceptualization of the system under study through use of feedback loops to capture the interrelationships of variables in the model.[29] These feedback loops are regarded as dynamic hypotheses that produce insights about the behavior of a system. The insights produced from the feedback loops can then be used to resolve the policy problems within the research domain.[30]

Over the years, the STM has been utilized to resolve several complex problems in many subjects, including those in the housing sector.[31] For example, Forrester's renowned work, *Urban Dynamics*,[28] was the first to use the approach to address the problem of urban growth and decay within the housing sector. Since then, this approach has proved to be an essential methodology and tool with application to research related to housing problems.[31] For instance, the STM has been applied in housing energy and environmental studies,[32–35] housing energy efficiency research,[36] and housing energy policy evaluation.[37,38]

Modeling using STM can be realized in many ways. In one method, known as the participatory technique, stakeholders are involved in various stages of the modeling process.[30] This, by implication, means that the mental knowledge elicitation of those involved in the modeling exercise is conducted through focus groups that use the group model-building technique as elucidated by Forrester.[39] Through this approach, the model can be developed to identify the model variables, the model boundary, the causal loops structure, and the model parameter values estimation for those that are not available empirically. Based on this approach, a productive dynamic hypothesis can be formulated diagrammatically by using the already-structured scripts for the mental knowledge elicitation exercise.

### *Experts' Knowledge Elicitation*

As previously posited, experts' knowledge elicitation falls within the purview of participatory STM, hence, its application in this reported research. This study explored the dynamic interrelationships among the trio of the dwellings, occupants, and environmental systems in an attempt to capture the causal structure of different variables regulating energy and carbon emissions in buildings. It is important to note that while the interrelationships among those variables can be developed and verified empirically for some of the variables incorporated within the model according to building physics and numerical simulations, some of them have to evolve from the stakeholders and experts based on their experiences.

The experts' knowledge elicitation approach builds upon earlier studies of Macmillan et al.[40] and Macmillan, Davies, and Bobrova,[41] both of which used participatory STM. In those studies, a wide range of stakeholders and experts were used in the development of comprehensive causal feedback loops.

In this study, experts and stakeholders were used to develop the causal model of carbon emissions in South African homes. The causal maps were first developed by using the iSTM involving the content analysis of extant literature on the subject and the mental knowledge elicitation of the relevant stakeholders. Following on, 12 experts, purposively drawn from industry (four), academia and research institutes (four), and government agencies (four), took part in the mental knowledge elicitation process regarding the already-developed causal diagrams of variables affecting carbon emissions in dwellings through the final system thinking method (fSTM). Specifically, the iSTM was subjected to experts' review and validation in order to produce the final causal loop diagrams through the fSTM.

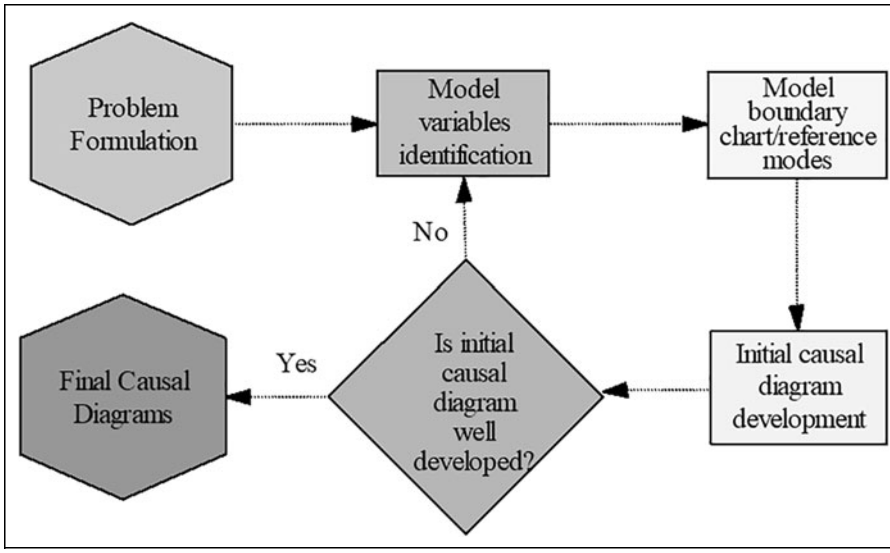


**Figure 1.** The systems thinking method used for the study

The approach followed is represented using a flowchart diagram as shown in Figure 1. In subjecting the initial causal model to experts' review, the links were examined by the experts. For each link involving two variables at a time, the experts examined the relationship between the two variables. If the experts determined that there is a relationship, then the strength of that relationship was further described as strong, reasonable, or weak. Additionally, the direction of the relationship between variables, as presented by the researcher, was examined. The experts indicated that they agreed or disagreed with the direction of the relationship proposed and also whether or not there were links not captured. To conclude the exercise, the experts were asked to suggest other variables that require inclusion in the model. Further details of this approach have been elaborated in Oladokun and Aigbavboa.[30]

## Results and Discussion

Based on the approach used for the research in this study, the following are the findings in the form model conceptualization involving the main variables influencing carbon emissions in dwellings.

### *Model Conceptualization*

The model conceptualizing the variables influencing carbon emissions in dwellings was developed using a modular system. As such, the high-level model shown in Figure 2



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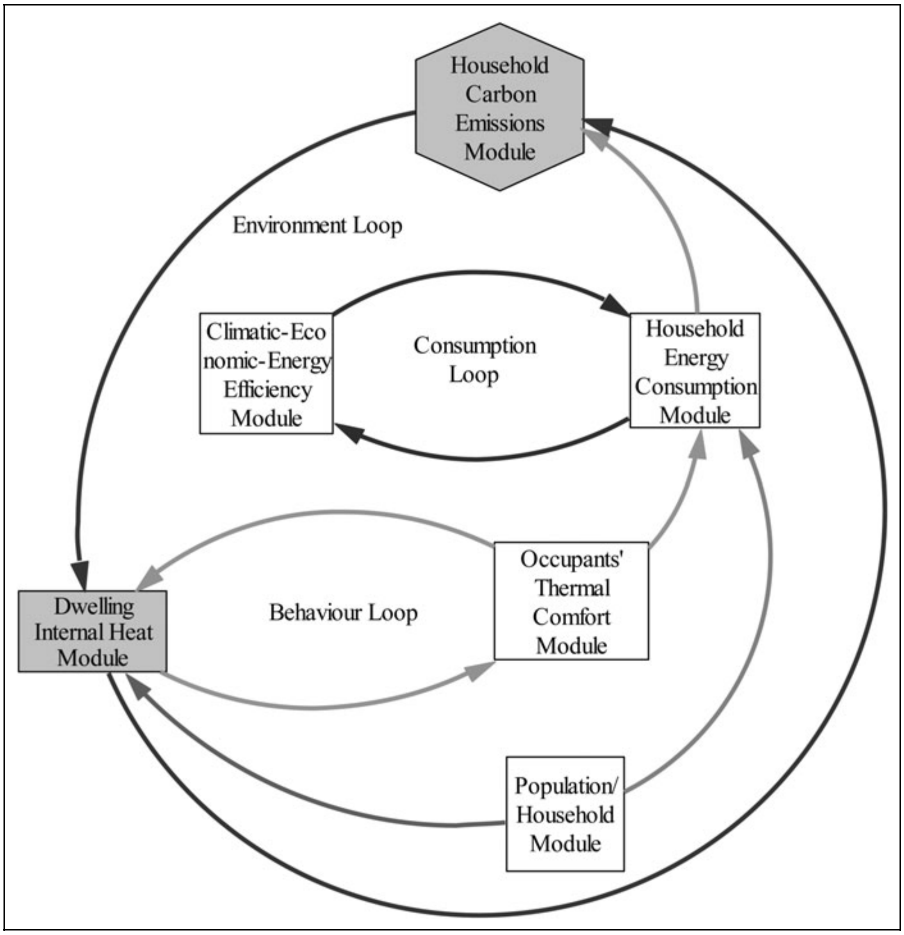


**Figure 2.** The high-level model showing the sub-models



disaggregates the dynamics of energy and carbon emissions into six different sub-models. The complexity of the interdependencies and interrelationships among the sub-models is illustrated in Figure 2. The sub-models are issues that are based on the interaction of the dwellings, occupants, and environmental systems, and the sub-models involve dwelling internal heat, occupants' thermal comfort, population and household, climatic-economic-energy efficiency interaction, household energy consumption, and household carbon emissions.

### *The Main Causal Diagram*

This study developed a population of variables influencing carbon emissions in dwellings, which was verified and validated based on knowledge elicitation from a focus group. One finding was that all experts who participated in the focus group attested to the fact that there are many variables affecting carbon emissions in dwellings. The participants based their arguments on the fact that the variables identified have complex interdependencies and interrelationships.

The causal model was developed based on different sub-models before being combined into the single holistic causal model shown in Figure 3. A causal tree (see Figure 4) was generated from the causal model shown in Figure 3 for occupants' thermal comfort as an example of the analysis that can be performed from the model.

In order to be in a position to adequately read the causal model presented in Figure 3, the causal loop diagram was developed based on different variables already identified for the study. The diagram indicates how the variables in the model are related to one another. By way of annotation, two variables are selected at a time, and the relationship between them is based on the arrow connecting them. The arrows are polarized with a plus (+) sign depicting a positive relationship, which by implication means that "an increase in arrow tail variable would cause an increase in arrowhead variable and vice-versa, whereas a minus (−) sign depicting a negative relationship, which means an increase in arrow tail variable would cause a decrease in arrowhead variable and vice-versa" according to Sterman. (p. 138)[25]

It is equally significant to note that the feedback loops (Figure 3) create the kind of complexity and dynamics in the system that was the focus of this research. Figure 3 shows both positive and negative loops with plus (+) or minus (−) signs inside a circular arrow; the former depicts a positive feedback loop, or what is known as a reinforcing loop, and the latter depicts a negative feedback loop, or what is known as balancing loop. The positive loop means that there will be an indefinite growth of decay within the system, whereas the negative feedback loop tends to balance or stabilize the system over time. In order to achieve the polarity of the loops within the model, the negative signs on the variables within the model are counted. An even number of the total negative signs gives a positive or reinforcing loop, whereas an odd number of the total negative signs gives the negative or balancing loops.

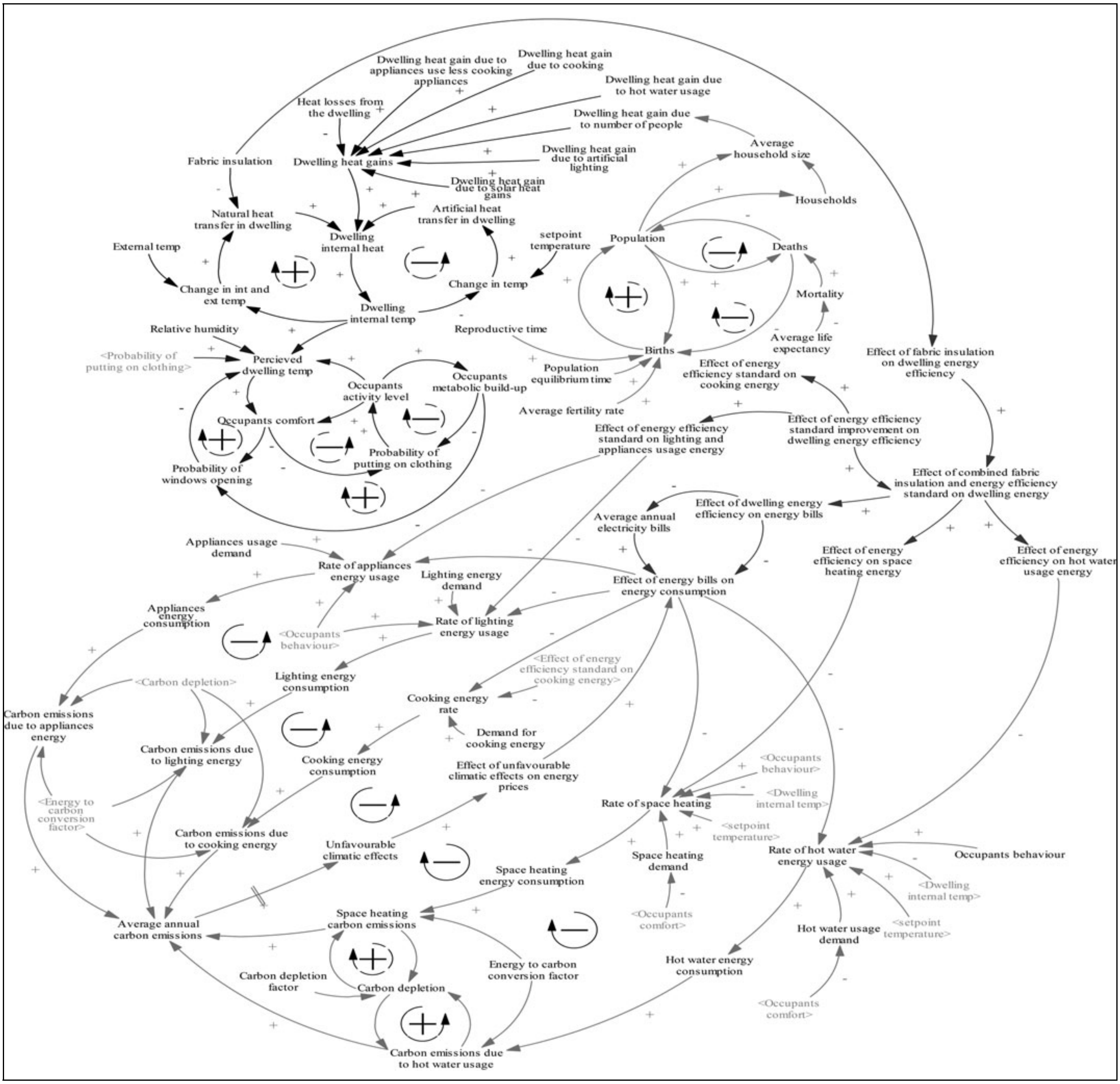


**Figure 3.** Causal model of variables influencing carbon emissions in dwellings

## Conclusions

In the midst of calls for an approach capable of modeling the dynamics of carbon emissions within the housing sector, especially by capturing both the quantitative and qualitative variables, the research reported in this article is a step forward. This study demonstrates a modeling approach that goes beyond building physics and numerical simulations by incorporating the variables that are difficult to model quantitatively. Consequently, the value and implications of the study for research and policy purposes are profound. The experts' knowledge elicitation technique within the SD approach has the capability of improving the accuracy and credibility of the theory that will eventually emanate from the causal diagrams regarding interdependencies and interrelationships of variables influencing carbon emissions in dwellings.

This study is, therefore, capable of spurring research activities within this research domain. Also, in a real-world situation, the causal tree shown in

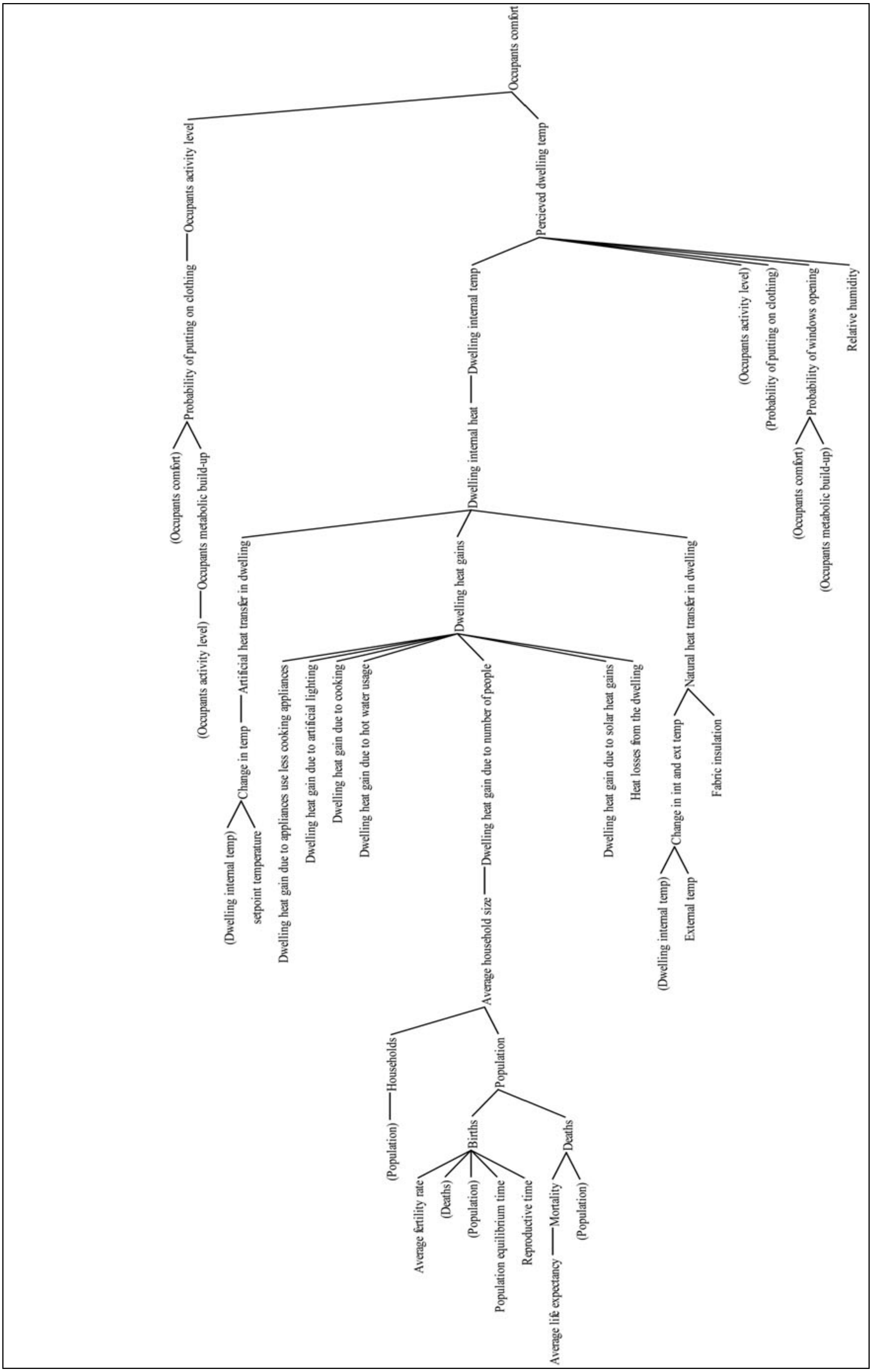


**Figure 4.** Causal tree from the causal model of variables influencing carbon emissions in dwellings

Figure 4 demonstrates that this study is capable of being used to make informed decisions regarding policy interventions about energy and carbon emissions in dwellings in the South African housing sector. This will further aid a clear understanding of the variables influencing energy consumption and carbon emissions within the housing sector by relevant stakeholders. Further work for the research would involve translating the developed causal model to a simulation model to develop algorithms for the relationships among the model variables in readiness for simulation. Afterward, the output of the simulation from the model would be presented, and validation of the model could be conducted appropriately to build confidence in the output.

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## Author Disclosure Statement

No competing financial interests exist.

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