A CRITICAL REVIEW OF MODELLING TECHNIQUES FOR THE SOCIO–TECHNICAL SYSTEMS OF HOUSEHOLD ENERGY AND CARBON EMISSIONS

Michael G. Oladokun*[1] and Timothy O. Adewuyi[1]
[1]Department of Building, Faculty of Environmental Studies,
University of Uyo, Uyo, Nigeria

*Corresponding author:
Michael.G.Oladokun@uniuyo.edu.ng

ABSTRACT

The purpose of this paper is to identify the most suitable modelling approach to conceptualise the complex socio-technical systems (STS) of household energy consumption and carbon emissions (HECCE). The literature review approach was adopted for the study. Before the review of literature for modelling techniques of STS, the paper first reviewed literature on systems-based approach of scientific inquiry as they form the theoretical knowledge base underpinning the STS. This is mainly to give the philosophical backgrounds of STS. Literature search was then conducted. The results of the review were analysed for the modelling techniques for STS and the following techniques were identified: actor network theory, agent-based modelling technique, Bayesian belief network, configuration modelling, fuzzy logic, morphological analysis, social network analysis, and system dynamics. These techniques were further probed for their capability in capturing the problem of modelling HECCE against a set of criteria. A careful appraisal of all the techniques suggests that the system dynamics approach is the most suitable technique capable of conceptualising the problem under investigation in the context of this paper. The study complements the body of knowledge by adding to building physics, econometric, and regression-based approaches that have traditionally in existence for capturing the HECCE issues. The study is original in that it identified novel approaches capable of exploring the complex intrinsic interrelationships existing among the STS of dwellings, occupants, and environment as relates to HECCE.

Keywords: Carbon emissions; household energy; modelling; socio-technical systems

1. INTRODUCTION

The menace posed by carbon emissions and other climate change related effects have created extreme difficulty to accurately predict the energy and carbon emissions performance of dwellings once occupied (Stevenson and Rijal, 2010; Bordass et al., 2004). Way and Bordass (2005) posit that dwellings are not only becoming more complex, but also tighter energy and other environmental regulations are increasing pressure regarding their greater predictability. Undoubtedly, integration of dwellings occupants' aspect with that of dwellings characteristics/parameters regarding energy consumption in buildings sits squarely within the socio-technical systems (STS) approach of systems-based methodology of scientific inquiry. Dwellings as a system are seen to comprise two subsystems: physical subsystem that relates to dwellings characteristics/parameters (technical system) and human subsystem regarding occupants' actions within the dwellings (social system). Dwellings are affected should there be any change to both the technical and social systems. Invariably, any change to technical system will have effects on physical subsystem; likewise any change to social system will have corresponding effects on human subsystem. On one hand, some changes to technical system may have indirect influence on human subsystem, while on the other hand, some changes to social system may have indirect influence on physical subsystem as well.

Importantly, dwellings as a system relates with the outer environment, which has both direct/indirect influence on both the technical and social systems. Any change in the outer environment elements will definitely influence the behaviour of these technical and social systems. This will consequently have effects on household energy consumption and associated carbon emissions. This then presents a kind of complex system that calls for an approach that is able to cope with this type of situation. It needs to, however, note that engineering models can only deal with the changes to technical system alone and social models can as well cope with the changes to social system alone. For example, within the energy sector, modelling energy consumption and carbon emissions has been purely based on econometric (FitzGerald et al., 2002), statistical (Fung, 2003), or building physics (Shorrock and Dunster, 1997) method. These methods have received widespread criticism from researchers due to (1) lack of transparency in the model algorithms, (2) inability to account for the complex, interdependencies, and dynamic nature of the issue of energy consumption and carbon emissions, (3) limited evidence to show for the occupants-dwelling interactions, and (4) lack of enough capacity to accommodate qualitative data input (Oladokun, 2014). And as such, there is the need to scout for more robust and sophisticated modelling approaches that take into consideration the kind of complexity involved and bedevilling the issue of HECCE due to high inter-dependencies, chaotic, non-linearity, and qualitative nature of some of the variables involved. It is on this basis that the paper conducts a critical review of the modelling techniques for capturing the STS of HECCE with a view to proposing a novel approach capable of testing different strategies and interventions for reducing household energy consumption and carbon emissions.

2. SYSTEMS-BASED APPROACH OF SCIENTIFIC INQUIRY

The STS cannot be discussed without first making an exposition into the systems idea of scientific inquiry. The systems idea of scientific inquiry came into limelight not until in the fifties, when the main concepts and principles relating to the general systems theory were formulated. Banathy (2000a) noticed that the systems ideas of different fields share a common ground on systems orientations as those ideas embrace research/professional activities in the area of "system engineering, operations research, system dynamics, cybernetics and information science, general theory of systems, living systems and evolutionary theory, soft systems and critical systems theory, and chaos and complex systems theory" (Banathy, 2000a). As a result of this, these researchers now recognise the necessity of an interdisciplinary research field with the capability of coping with ever increasing complexities that fall beyond the scope of a single discipline. The systems-based approach of scientific inquiry that emphasised the intrinsic order and interdependence of the complex problem in all its ramifications is therefore born.

Systems-based approach of scientific inquiry, however, incorporates systems theory, systems philosophy, and systems methodology; as three main inter-related domains of disciplined scientific inquiry. While the systems theory and philosophy provide the philosophical basis for the systems-based approach, systems methodology gives the sets of methods, strategies, models and tools for the systems-based approach of scientific inquiry. The rest of this section discusses the rationale behind the systems-based approach of scientific inquiry, its concepts, and components and characteristics of systems-based approach.

2.1 Rationale Behind the Systems-based Approach to Scientific Inquiry

Science is a way of acquiring testable knowledge about the world (Clayton and Radcliffe, 1996). The classical method of scientific inquiry has played prominent role in understanding and treating complexities in the 'world of science' and came into luminance during the last 17th and 18th centuries based on Descartes' analytic-deductive method which was used in studying complex phenomena. Clayton and Radcliffe (1996) argue that science has a number of defining characteristics of which three are particularly important to include 'replicability', 'refutability', and 'reductionism'. Descartes, however, bolstered reductionism by publishing 'Discourse on Method' in 1637 and this publication gives four precepts which influence science for years (Capra, 1996). These precepts according to Capra (1996) are:

- Accept only that which you are certain of,
- Divide topic into as small parts as possible,
- Solve simplest parts first,
- Make as complete lists as possible.

The method breaks down the complex entities into small parts and studies them separately in order to gradually have the understanding of the whole, which forms the philosophical basis of classical view of scientific inquiry that born the technological and industrial revolutions in the globe (Panagiotakopoulos, 2005).

Panagiotakopoulos (2005) reports that by the end of the 19th century and during the 20th century complexity in 'real world' expanded in such a way that the classical method of scientific inquiry reached its limits in explaining the world. Due to this fact, Banathy (2000a) contends that the reductionist approach was no longer able to explain 'wholeness' which results from the mutual interaction of 'parts'. Premise on this, Skyttna (2006) submits that to have a full understanding of the reason why a particular problem occurs and still persists, there must be a savvy of the parts in relation to the whole. This argument is, however, absolutely against the classical view of scientific reductionism and philosophical analysis as promulgated by Descartes (Capra, 1996). In view of this, there is no doubt that simple tools cannot be used to capture ever increasing complex problems in the world that is embedded in interconnected systems which are operating in dynamically changing environments (Banathy, 2000a). This therefore necessitates the needs for a shift in classical approach paradigm to systems approach of scientific inquiry.

Systems approach of scientific inquiry, therefore, represents a kind of paradigm shift which is now changing the emphasis from 'parts' to the study of 'whole' (Banathy, 2000a) since it is difficult to observe properties of the whole bit by bit. Systems approach of scientific inquiry, hence, provides a multi-dimensional framework in which information from different disciplines and domains can be integrated without being forced into a one-dimensional mapping, which is not possible from the view of classical approach.

2.2 The Basic Concepts of Systems-based Approach to Scientific Inquiry

Banathy (2000b) regards researchers like Ashby, Bertalanffy, Boulding, Fagen, Gerard, and Rappoport as the pioneers that set forth the basic concepts and principles of the general theory of systems that metamorphosed into systems-based approach today. The concept of systems approach advocates that the properties and characteristics of the whole, which is the systems itself, is quite different from summing up the parts in such a way that properties of a whole cannot be observed bit by bit as against the view of classical, traditional method of scientific inquiry that studies parts with linear cause and effect. Banathy (2000a) argues that deterministic, linear cause and effect is practically inadequate in dealing with many interactive variables of complex, dynamic systems. In contrast, the systems-based approach is able to capture the dynamics of multiple, mutual and recursive complex causation (Banathy, 2000a) and sees the behaviour of the systems as non-linear, non-deterministic and expansionist in nature as negates the reductionist approach of classical science. Based on the ideas of the pioneers of the systems-based approach, Banathy (2000a) proposes an overview of the key distinctions between the classical view of scientific inquiry and systems view of scientific inquiry. These distinctions are based on what they 'focus on', their 'mode of inquiry', the way they 'reason', the 'rule' guiding them, 'goal' and finally 'control' as shown in Figure 1.

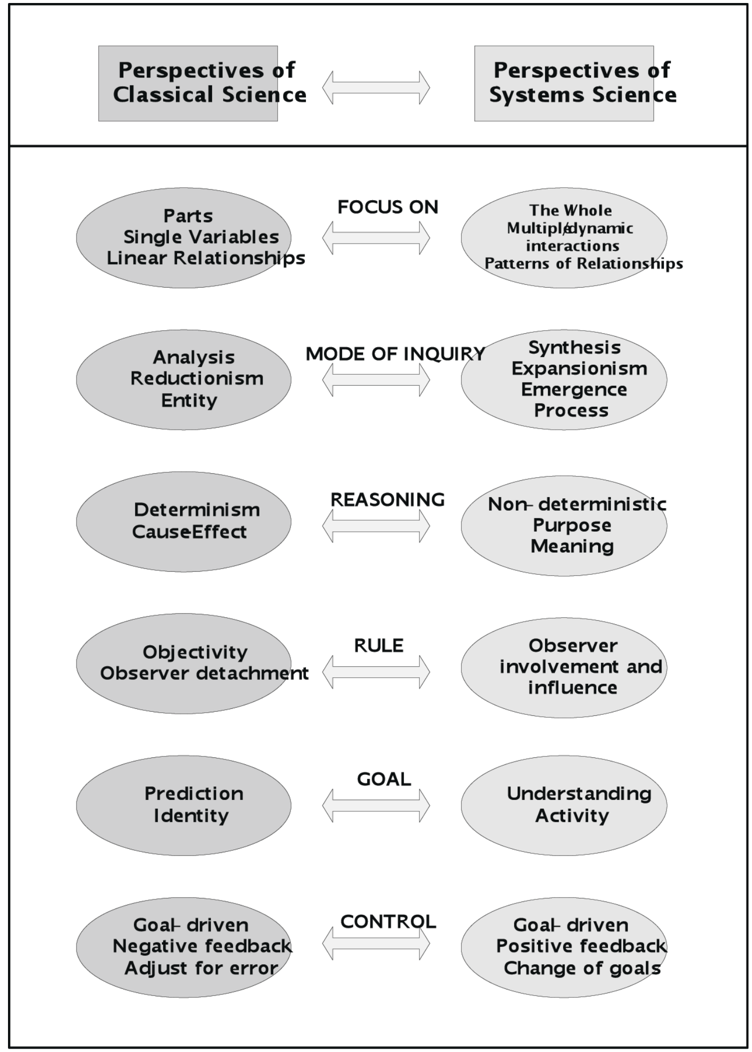


Figure 1: Key distinctions between classical and systemic orientations (Adapted from Banathy, 2000a)

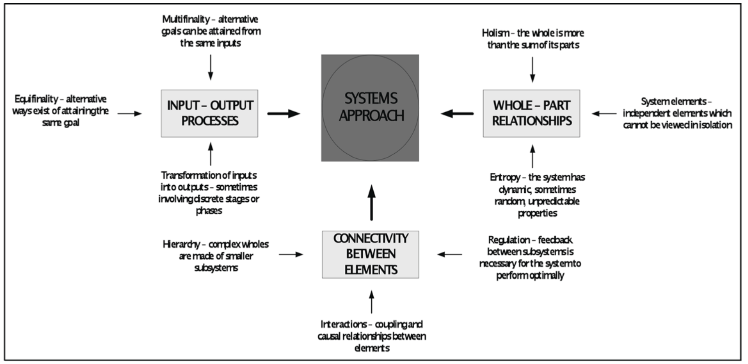
2.3 Components and Characteristics of Systems-based Approach

Based on the basic concepts of systems-based approach enunciated above and the works of researchers like Turner (1978), Capra (1996) and Blockley (1998), it is undoubtedly evident that the systems-based approach encapsulates many interrelated components, the properties of which are altered should the systems cloaked in any way (Waterson, 2009). These components are the main anchor of the systems-based approach. To this end, adopting a systems approach to solving the problem relating to HECCE in the context of this paper entails getting insights into the effects of interactions among different variables hypothesised to influence household energy consumption.

By drawing from the studies of Turner (1978) and Blockley (1998), Waterson (2009) was able to capture those components and their characteristics that are the central idea being communicated by the systems-based approach as shown in Figure 2. The characteristics are therefore similar to the problem of modelling HECCE. The three main components given by Waterson (2009) (Figure 2) are:

- Input-output processes – this aspect gives the relationships that exist between the systems inputs and their corresponding outputs containing elements like multifinality, equifinality, etc.
- Whole-part relationships – the main idea being communicated by this component is hinged on the fact that the working of the systems as a whole needs to be firstly analysed in parts as suggested by Gibson (1979). The component further suggests that the whole is quite more than just summing up the parts (Banathy, 2000a) as this kind of relationships existing between them are argued to be complex, dynamic, and chaotic in nature (Sinclair, 2007). Holism, entropy, and system elements are therefore expressed as the major elements of this component.
- Connectivity between elements – this component expresses the interrelationships among different elements within the systems in terms of hierarchy, interactions and regulation. The complexity of the systems here are hence elaborated based on causal relationships and feedback structure among these elements (Katz and Kahn, 1966).

Figure 2: Components and characteristics of the systems approach (Adapted from Waterson, 2009)



Additionally, Wilson et al. (2007) and Walker et al. (2008) offer the description of behaviour exhibited by the system in order to further capture its characteristics. They argue that a systems as a dynamic and complex whole containing an integrated interacting functional parts has energy, material, and information flowing through it. These energy, material, and information of the studied systems are placed within an environment that is surrounded by permeable boundaries, which is capable of exhibiting erratic behaviour while its elements seek equilibrium.

To this end, the study of Decleris (1986) classified systems into hard and soft systems. Hard systems, for example, are described as technical and physical systems that can be quantified while its behaviour can be fully controlled at the same time (Panagiotakopoulos, 2005). However, these cannot easily take unquantifiable variables into consideration. Different from the hard systems, soft systems are good at capturing and understanding unquantifiable variables like people's opinions, cultures, viewpoints and the likes. In short, it will address qualitative aspects of any problem situations. Therefore, the classification brought about the concept of STS as a systems-based approach capable of handling the complexity posed by the interaction of 'human' and 'machine', which is good at combining both the quantitative and qualitative research strategies together. And this appropriately fits into the problem of HECCE. The next section then discusses the STS theory.

3. THE SOCIO-TECHNICAL SYSTEMS THEORY

The STS theory has evolved over the years as a kind of coaction among the sociologists that specialised in a new area of academic endeavour termed the "sociologists of technology" (Dwyer, 2011). There was a general belief that engineers/technologists, for example, tend to ignore the importance of socio aspect of their work; while on the other hand, the social scientists tend not knowing much about the technology and therefore reluctant at considering the artificial reality of technical objects (Ropohl, 1999). The STS theory has then been used as the theory that combines the two divides together. Therefore, the STS theory serves as the theoretical basis for the problem in this paper. The rest of this section discusses the basic concepts of the STS theory and its domain of application.

3.1 Basic Concepts of Socio-Technical Systems Theory

The origin of the concepts of STS as a methodology for the systems-based approach of scientific inquiry could be traced to the studies undertaken by the Tavistock Institute, London especially during the post-war reconstruction of industry (Cartelli, 2007). Cartelli (2007) reports that the emergence of the concepts is highly necessary in pursuit of a fit between the work force and machine during the introduction of technological systems for work automation when it was found out that workers are resistant to technological innovation. Since then, the concept has come into luminance and serves as the theoretical framework underpinning many studies.

According to Walker et al. (2008), STS as a concept is founded on two main principles. The first one is the interaction between the social and technical sub-systems that set the conditions for successful (or unsuccessful) systems performance. They argued that the interactions are comprised partly of linear "cause and effect" relationships, the relationships that are normally "designed", and partly from "non-linear", complex, and even unpredictable relationships; which are those that are often unexpected. Soft, which is socio, does not necessarily behave like the hard, which is technical (Walker et al., 2008). Additionally, Walker et al. (2008) contends that the growth in complexity and interdependence makes the "technical" systems, for example to start to exhibit non-linear behaviours. And as such, the STS as a technique of the systems-based approach of scientific inquiry is used to handle this kind of complexity as both the methodology and tools. The second of the two main principles, is founded on "joint optimisation" of the two systems.

Interestingly, Dwyer (2011) illustrates the concept of STS by the use of a generic model as shown in Figure 3. According to her, STS is seen to contain components that are referred to as social structures and artifacts that are called technical elements, which contribute directly or through other components to a common system goal. It was shown that both the components and artifacts interact with each other. What is guiding the overall behaviour of the system is the system goal.

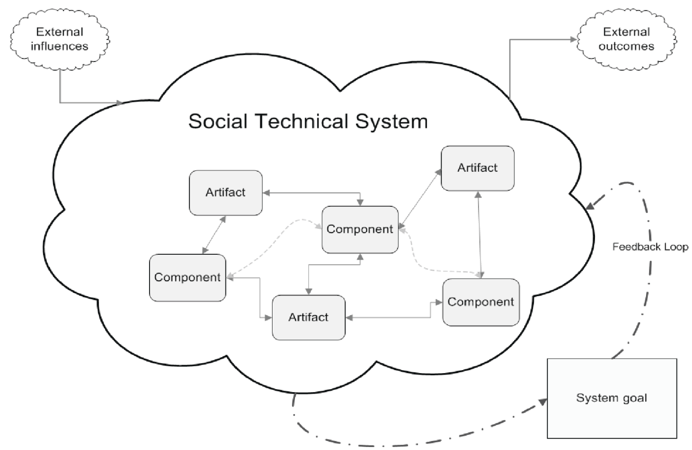


Figure 3: A model of a socio-technical system (Adapted from Dwyer, 2011)

The feedback loop enables the actual output of the system to be compared to the system goal. Hughes (2000) argues that it is only through the feedback loop that errors are detected and thereby corrected in order to have an improvement in system performance.

The central idea from the concepts of the STS can be applied to the issue of HECCE in order to put the discussion here in context. As presented under introduction of this paper, the household system consists of an interplay among the dwellings' system (in terms of dwellings' physical characteristics and technological systems put in place within it) refers to as technical systems (artifacts), occupants' system (in terms of behaviour towards energy consumption, for example) refers to as socio system (components), and external environment system (in terms of external temperature, energy prices, etc.) refers to as technical and/or socio system. These systems are then interrelate and appropriately influence household energy consumption and associated carbon emissions.

A detailed analysis of all the variables in the systems (not reported in this paper) suggests that they all depends on one another thereby making the systems to be complex. This is so mainly because the variables within each of the systems have multiple interdependencies with multi-causal feedback structure considering their effect on energy consumption and carbon emissions. Further, they are interconnected, chaotic in nature, and difficult to understand, predict and keep under control, thereby calling for a pragmatic approach like the STS approach to handle the situation under consideration. An appraisal of the problem suggests that the STS approach is adequate in capturing it. Hence, the STS theory serves as the theoretical background of the research reported in this paper.

3.2 Domain of Application of Socio-Technical Systems

A review of domain of application of STS by different researchers is undertaken by searching the library resource of the Heriot-Watt University entitled "Discovery". The resource brought together many databases including articles, dissertations, and theses indexed in Scopus, Science Direct, Emerald Library, British Library, Google Scholar, etc. These databases were searched using "socio-technical" and "model" as keywords. The query returned 83 articles. During the review of those articles, it was noted that the concept of STS means slightly different things to researchers in different fields of study, for example: in engineering, it means that organisational form follows technical function, while technical function too follows organisational form; in computer science, the technical system consists of hardware and software that make an information system, while the users of this system and the organisation in which it is embedded form the social system; etc. However, similarities in the use of this concept is stronger and more than the differences. Literature search was then conducted irrespective of the definition used for the STS by different researchers.

Based on the review, the STS has been successfully implemented in human-computer interaction studies, information technology, software engineering, engineering (general), business and management, medicine and the host of others. For example, de Greene (1988) used STS in the context of organisational design management. Likewise, Appelbaum (1997) used STS in the context of organisational development where it was argued that integration of organisational development with technological advancement into a total system could prove difficult, but the use of STS will make it possible. Also, STS was used in the context of innovation which predisposes systemic changes in any organisation (Geels & Kemp, 2007). Williams and Edge (1996), Rohracher (2003) and Geels (2004) used STS in the context of diffusion of technology in an organisation.

Further, the STS has been used in energy supply and demand, especially when it was necessary to study the socio-technical influences on energy use, e.g. Shipworth (2005), Shipworth (2006), and Motawa and Banfill (2010). The STS has been used in the computer/software engineering as well as communication and telecommunication engineering (Patnayakuni and Rupple, 2010). This concept of STS has also been found application in the domain of water management while considering irrigation project (Jayanesa and Selka, 2004) and in the domain of agriculture and food (Marques et al., 2010). The above then shows how research has transcended using the STS in solving real life problems.

The STS has, therefore, been previously used as methodology to model the complexity of real systems' elements and relationships as indicated above. The STS is difficult to model because of its complex nature. It is complex because its elements are with multiple interdependencies and have multi-causal correlation structure. Further, the STS exhibits a kind of non-linear behaviour where changes in input are neither proportional to changes in output, nor is the input to output relationship fixed over time (Motawa and Banfill, 2010). The ability of STS to integrate both "hard" and "soft" data together under the conditions described above makes it different from other complex systems. The modelling techniques for the STS are discussed in the next section.

4. MODELLING TECHNIQUES FOR THE SOCIO-TECHNICAL SYSTEMS

Based on the review conducted in Section 3.2 above, a detailed analysis of selected articles from the pool of articles reviewed was undertaken. Specifically, these articles were analysed for the modelling techniques utilised in the context of STS. The 83 articles, as mentioned in Section 3.2, were then analysed according to the STS domain, STS definition, whether or not modelling/simulation was performed, the modelling/simulation techniques that was utilised, whether or not the results produced are reproducible, whether or not the techniques presented are capable of being generalised to another domains of application, and whether or not the model can be easily extended and if it can be, to what extent can this be done? The main aim of this exercise is to identify the major techniques that have been used by different studies to conceptualise STS problems. To qualify for further analysis, the authors ensured that those articles with at least four of the above criteria were selected. The ones that were found suitable are 32 in number. Table 1 shows the results of this review. As shown in Table 1, the articles reviewed were assessed to indicate any presence of evidence to suggest within their body that there is a match or no match or unclear in STS application domain, STS definition, modelling/simulation, modelling/simulation technique, reproducible, generalizable, and extendable. The (+) sign indicates that there is a match, whereas a (-) sign shows that there is no match. The (?) sign signifies that evidence of those criteria is unclear.

Table 1: Review of modelling techniques for socio-technical systems

Article Authors	STS Application Domain	STS Definition	Modelling / Simulation	Modelling / Simulation Technique	Reproducable	Generalisable	Extendable
Bergman *et al.* (2008)	+	+	+	ABM	?	+	?
Carley (2002)	+	+	-	?	-	+	-
Iivari & Hirschheim (1996)	-	-	-	?	-	+	-
Jarman & Kouzmin (1990)	-	-	-	?	-	+	-
Shipworth (2005)	+	+	-	-	+	?	?
Sterman (1989)	+	-	+	SD	+	+	+
Olla et al. (2003)	+	-	+	ANT	-	?	-
Cai et al. (2009)	+	-	+	FL	+	?	-
Li et al. (2010)	+	-	+	FL	+	-	-
McNeese *et al.* (2000)	-	+	-	-	-	+	-
Ramanna *et al.* (2007)	-	-	-	-	-	?	-
Shah & Pritchett (2005)	-	+	+	ABM	-	+	+
Johnson (2008)	-	+	-	?	-	+	-
Shipworth (2006)	+	+	+	BBN	+	+	+
Smajgl et al. (2008)	?	?	-	-	-	-	-
Masys (2006)	+	?	-	?	-	+	-
Sterman (2000)	+	-	+	SD	+	+	+
Sutcliffe *et al.* (2007)	-	+	-	-	-	?	-
Thissen & Herder (2003)	+	+	-	-	-	+	-
Yahja & Carley (2005)	-	-	+	ABM	?	+	?
Lock (2005)	+	-	+	CM	-	?	-
Ritchey (2011)	+	-	+	MA	-	?	-
McIntosh *et al.* (2005)	+	+	-	?	-	+	-
Lock (2004)	+	-	+	CM	-	?	-
Wu & Xu (2013)	+	-	+	SD & FL	+	+	+
De Waal & Ritchey (2007)	+	-	+	MA	-	?	-
Jensen (2001)	+	-	+	BBN	+	+	+
Callon (1986)	+	-	+	ANT	-	?	-
Natarajan *et al.* (2011)	+	+	+	ABM	+	-	+
Feng *et al.* (2013)	+	-	+	SD	+	+	+
Carroll *et al.* (2010)	+	+	+	SNA	-	-	-
Carroll (2012)	+	+	+	ANT/SNA	+	+	-

ANT – Actor Network Theory, ABM – Agent-based Modelling, BBN – Bayesian Belief Network, CM – Configuration Modelling, FL – Fuzzy Logic, MA – Morphological Analysis, SNA – Social Network Analysis, SD – System Dynamics. '+' means there is a match, '-' means there is no match, '?' means unclear.

The result of the review conducted shows that most of the articles analysed explicitly indicate the STS as the domain of application for their studies. Also, about half of those articles claim that the STS method presented can be generalised. Furthermore, the analysis shows that just some of the STS approach presented can be reproduced and further extended to accommodate additional modules/sub-systems. It was also concluded from the review that out of 32 articles analysed, 20 of them provided the modelling/simulation techniques utilised for their different studies within the context of STS. Therefore, the output of the study shows some of the techniques that have served as decision support tools/platforms under which STS of real problems are modelled. To this extent, this study therefore identified the following as the techniques for modelling STS.

1. Actor Network Theory (ANT)
2. Agent-Based Modelling technique (ABM)
3. Bayesian Belief Network (BBN)
4. Configuration Modelling (CM)
5. Fuzzy Logic (FL)
6. Morphological Analysis (MA)
7. Social Network Analysis (SNA)
8. System Dynamics (SD)

The next section therefore critiques and discusses these modelling techniques.

5. CRITIQUE AND DISCUSSION OF THE MODELLING TECHNIQUES

For any of those techniques to be adequate in the context of this paper, there are some criteria they must fulfil based on the nature of the problem under investigation in this paper. For example, different researchers have criticised the energy models in the housing sector for the lack of transparency (Kavgic et al., 2010; Mhalas et al., 2013) as discussed in Oladokun (2014). Also, Hitchcock (1993), Kohler and Hassler (2002) and Shipworth (2005; 2006) established that the complex socio-technical systems are highly interdependent, chaotic, and non-linear, and problems involving these are better solved using a pluralistic approach.

Therefore, it is important to set the criteria upon which the STS modelling techniques will be compared. And as such, the modelling techniques are compared to one another based on (1) transparency, (2) multiple interdependencies (3) dynamic situations (4) feedback processes (5) non-linear relationships (6) hard and soft data (7) uncertainties of the variables involved, (8) chaotic assumptions and (9) the use of the model as learning laboratory. It is against this background the techniques were all assessed, compared, and critiqued in order to decide on which one of them or a combination of two or more will be able to capture the problem under investigation based on the above criteria. Table 2 summarises and compares all the STS modelling techniques. The tenets as well as strengths and weaknesses of each of the STS modelling techniques are therefore discussed accordingly in the following sub-sections. This exercise would, undoubtedly, help in identifying which of them is best for conceptualising the problem regarding modelling the complexity of HECCE.

Table 2: Comparative analysis of STS modelling techniques

Criteria	ANT	ABM	BBN	CM	FL	MA	SNA	SD
Transparency	√	√	√				√	√
Multiple interdependencies	√	√	√				√	√
Dynamic situations		√						√
Feedback processes								√
Non-linear relationships	√	√	√	√	√	√	√	√
Considering "hard" and "soft" data	√	√	√	√	√	√	√	√
Chaotic assumptions	√	√	√	√	√	√		√
Uncertainties		√	√	√	√	√		√*
Learning laboratory tool			√					√

** Limited capability in handling uncertainties.*

5.1 Actor Network Theory

Actor Network Theory (ANT) was first proposed by Michel Callon and Bruno Latour (Callon and Latour, 1981; Callon, 1986). Olla et al. (2003) argues that ANT provide a platform for understanding the creation of networks of aligned interests where, according to Olla et al. (2003), the world is full of hybrid entities containing both human and non-human elements. Carroll (2012) contends that the greatest strength of ANT lies in its ability to integrate both hard and soft data together (Table 2). Also, the approach is capable of modelling problems containing variables that have multiple interdependencies with non-linear relationships under chaotic assumptions. It, therefore, has some merit in modelling STS problems. However, the approach has been criticised for its inability to provide the means of differentiating between humans and non-humans elements within the model (Carroll, 2012).

5.2 Agent-Based Modelling

According to Jennings (2000), an agent is seen to be an entity or component that is autonomous, reactive, pro-active and capable of social interaction. Agent-Based Modelling (ABM) aims to model the global consequences of each of the entities/components of a system including their behaviour and interactions. This is then the main distinguishing element that sets agent-based models apart from other models (van Dam et al., 2009). In general, the ABM approach is applicable for modelling of complex systems if the following conditions are satisfied (van Dam and Lukszo 2006):

- The problem has a distributed character;
- The subsystems operate in a highly dynamic environment;
- The subsystems have to interact in a flexible way; and
- The subsystems are characterised by reactivity, pro-activeness, cooperativeness and social ability.

As shown in Table 2, ABM seems to be a suitable approach to create models of STS because of its capability to handle both hard and soft data with multiple interdependencies and treat non-linear behaviour of such data set under small uncertainties (Bergman et al, 2008; Natarajan et al., 2011). To this end, a number of studies have utilised the approach for modelling complex problems. For example, the study of Yahja and Carley (2005) used the approach to model improvement in multi-agent social-network systems. Also, Natarajan et al. (2011) found the approach useful in modelling energy consumption and carbon emissions of the UK housing stock. However, the approach has some drawbacks. For example, its weakness lies in its inability to handle multiple feedback processes and difficulty in being used as a learning laboratory.

5.3 Bayesian Belief Networks

Bayesian Belief Networks (BBN) was developed around late 1980's and its applicability didn't come into luminance until 1990s. According to Jensen (2001), BBNs emerged as an intuitive technique for reasoning under uncertainty. This technique combines different data types as well as learning from new observations as they become available. Advantages (Table 2) of using BBNs as opined by Gill (2002) are:

- The ability to learn as new information is received or population variables change
- The capacity to systematically integrate a wider variety of data types and any prior available knowledge
- Allow predictions about the likely future state of the system based on what is currently known about the system and assumptions about future data
- The capability to learn causal relationships and gain understanding of a problem domain and then predict the consequences of intervention
- Overt and clear model assumptions, and
- Straightforward sensitivity testing.

This approach has been successfully used in a number of applications. Application of BBN in the field of environmental management include: management of fisheries (Fernandez et al., 2002), land use change (Bacon et al., 2002), agricultural land management (Cain et al., 2003), and integrated water resource management (Bromley et al., 2004). This approach has also been applied to modelling the socio-technical influences on domestic energy consumption in one of the UK's Carbon Vision programme: Carbon Reduction in Buildings (CaRB) project (Shipworth, 2005; Shipworth, 2006). As argued by Shipworth (2005), however, BBN is used as decision support systems mainly because of their capability to integrate different array of data together, as well as synthesise relevant factors in social, economic, ecological and technical fields which then makes it particularly useful in the complex socio-economic/socio-technical environments of sustainable development. However, BBN approach is not without its own drawbacks. De Waal and Ritchey (2007) argue that using BBN may prove a little bit difficult during the initial problem formulation phase of the modelling process and difficult to deal with time dependent data set with feedback processes.

5.4 Configuration Modelling

Configuration Modelling (CM) is another technique and decision support tool recently proposed by Simon Lock (Lock, 2004; 2005) for modelling the STS. Lock (2005) acknowledges that managing the evolution of large systems is a complex and difficult task where the full social and technical implications of any proposed changes must be fully appreciated before a decision is made whether or not to proceed with their implementation. He contends that the task becomes challenging and difficult to manage since the interplay between the technical and non-technical components is often complex and the various human factor that are involved inject much variability and unpredictability into the system. It is against this backdrop that a new decision support tool that permits the investigation and exploration of different configurations of socio and technical components is needed in order to fully predict how changes made to the individual components or the overall configuration of a system will affect operational behaviour of that system during the real world operation (Lock, 2005). Lock (2004), however, argues that this modelling paradigm is a novel approach in the sense that it is easy and quick to construct and can as well help to promote understanding of different stakeholders. However, there is lack of evidence from the body of literature to suggest that this approach has the capability to capture multiple interdependencies of data set under dynamic situation. Furthermore, the domain of application of this approach has been limited to the area of software engineering as this has not gained a wider application, but has some merits in modelling STS.

5.5 Fuzzy Logic

The capability of Fuzzy Logic (FL) to model STS has been highlighted in literature. FL began with the 1965 proposal of fuzzy set theory by Lotfi Zadeh (Zadeh, 1979). It is a mathematical approach that is used to represent uncertain and imprecise information. Cai et al. (2009) argues that this method deals with reasoning that is approximate rather than fixed and exact, but effective in describing highly complex, ill-defined mathematical systems. Furthermore, the approach can effectively support linguistic imprecision and vagueness (Li et al., 2010). A number of studies have used this approach to model complex systems under different themes. For example, Cai et al. (2009) used the approach to identify optimal strategies within energy sector planning under multiple uncertainties of variables involved. Also, under the same theme as Cai et al. (2009), Li et al. (2010) combined the approach with stochastic programming to model energy and environmental planning systems. Further to this, Wu and Xu (2013) combined FL with SD to predict and optimise energy consumption of world heritage areas in the People's Republic of China. While the major strength of the approach lies in its ability to model systems under varying degrees of uncertainties, it does have some limitations that may debar it from being used within the context of this thesis. It lacks the ability to handle multiple interdependencies of variables under dynamic situations. Also, it does not support feedback processes and cannot be used as learning laboratory. As can be seen, the strengths and limitations of this technique are profound as succinctly summarised in Table 2.

5.6 Morphological Analysis

Morphological Analysis (MA) was developed by Zwicky – the Swiss-American astrophysicist and aerospace scientist – as a general method for structuring and investigating the total set of relationships contained in multi-dimensional, usually non-quantifiable, complex problems (Zwicky, 1969; Ritchey, 2011). The concept and application of MA as strategic decision support is closely related to BBNs. According to de Waal and Ritchey (2007), it allows small groups of subject specialists to define, link and internally evaluate the parameters of complex problem spaces easily, thus creating a solution space and flexible inference. They, however, argued that MA cannot easily treat hierarchal structure and causal relationships, but when combine with BBNs the benefits of both of these techniques can be optimised. This technique has previously applied to diverse fields based on the work of Zwicky. Among them are astrophysics, the development of propulsive power plants and propellants, the legal aspects of space travel and colonisation (de Wall and Ritchey, 2007). Suitability of this approach to the area of application of HECCE is limited, though it has some potential when combined with other suitable approaches as shown in the Table 2 above.

5.7 Social Network Analysis

Social Network Analysis (SNA) views social relationships in terms of network theory that consists of nodes and ties (also called edges, links, or connections). Nodes, according to (Freeman, 2006), are individual actors within the networks, and ties are the relationships between the actors. The resulting graph-based structures are often very complex. There can be many kinds of ties between the nodes. Research in a number of academic fields has shown that social networks operate on many levels, from families up to the level of nations, and play a critical role in determining the way problems are solved, organisations are run, and the degree to which individuals succeed in achieving their goals. Most importantly, SNA has the capability of modelling non-linear, multiple interdependent quantitative and qualitative variables (Carroll et al., 2010). Therefore, it has some merits in modelling STS, but its strength could be improved upon when combined with other approaches.

5.8 System Dynamics

System Dynamics (SD) emerged in the 1950s as introduced by Jay Forrester as multi-disciplinary field of study that has the capability to deal with complex systems. SD, as a systems-based approach, is seen as a methodological approach and set of analytical tools for modelling STS (Motawa and Banfill, 2010). Ogunlana, Lim and Saeed (1998) mention that the SD is an approach useful for managing processes with two major characteristics:

- They involve changes over time,
- They allow feedback, the transmission and receipt of information.

Interestingly, Coyle (1997) offers a robust definition of SD as a method "that deals with the time-dependent behaviour of managed systems with the aim of describing the system and understanding through a qualitative and quantitative model, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through simulation and optimisation".

Over the years, the approach has developed itself into a very powerful tool for modelling complex systems. To this extent, it has found a wider application in quite an array of different fields. For example, Ogunlana et al. (1998) used it in the field of project management, Feng et al. (2013) in the area of energy consumption and carbon emissions, and the host of other applications. The approach was able to garner use in different capacities based on its strength. Accordingly, Sterman (1992) justifies the application of SD to modelling complex problems in the sense that:

- SD models are well suited in capturing multiple interdependencies.
- SD was developed to deal with dynamics.
- SD is the modelling method of choice where there are significant feedback processes.
- SD, more than any other modelling technique, stresses the importance of non-linearities in model formulation, therefore, is able to capture any form of non-linear relationships.
- SD modelling permits both "hard" and "soft" data.

However, SD has limited capability of handling situations under uncertainties. This weakness has received due attention from the SD research circles and significant improvements have been made on this as some of the SD software now incorporate optimisation and sensitivity analysis of uncertain parameters.

5.9 Reflections on the STS Modelling Techniques for Household Energy

The above critique and discussion of different STS modelling techniques give the appropriateness of each of the techniques to conceptualise the problem of HECCE, which is the focus of this paper. Of the nine criteria used in appraising the techniques, the analysis done suggests that SD almost meets all the nine criteria, except for its inability to fully handle parameters under uncertainties, of which a full scale improvement on this aspect is underway. As argued in Section 5.8, SD was specifically introduced by Jay Forrester in order to handle complex problems that have multiple interdependencies and are dynamic in nature with many feedback structures. The tools for this technique have in-built functions to capture the non-linear relationships existing among different variables making up the model with the capability of accepting both the qualitative and quantitative data and convert same to simulation. The technique can also handle chaotic situations by invoking the delay functions in-built in the tools. It is necessary to mention that the technique is undergoing a constant review and over the years, the transparency aspect of it has been greatly enhanced and improved upon. This means that all the model variables including the algorithms can be assessed and scrutinised by third parties. Summing up all these characteristics of SD makes it more appropriate to conceptualise the problem under investigation in the context of this paper.

However, there are other techniques that meet substantial parts of the criteria of assessment of the techniques. For example, both ABM and BBN met seven each of those criteria. In ABM, the models developed using the technique can be easily scrutinised for its algorithms. The major drawback is in its inability to handle feedback processes which has been argued as germane to the dynamic characteristics of any of the techniques. Also, the approach cannot be used as learning laboratory where policies can be tested for results of implementation before being actually implemented in reality. In the case of BBN, the technique is transparent as well. Clearly, it is unsuitable for the problem in this paper because of its inability to handle dynamic situations involving feedback processes. However, they can complement the SD approach. Demonstration of the SD technique to model HECCE has been reported somewhere else. Interested readers are encouraged to check Oladokun and Odesola (2015), Motawa and Oladokun (2015a), and Motawa and Oladokun (2015b).

7. CONCLUSION

The study of Oladokun (2014) gives the shortcomings of current energy and carbon emissions modelling tools for the housing sector and recommends a paradigm shift in modelling techniques. This paper therefore discussed those shortcomings as the main strengths of the STS. Before the review of extant literature on modelling techniques for the STS, the paper first grounded the STS theoretically and philosophically by reviewing the systems-based approach of scientific inquiry. The following conclusions can be drawn from the study:

- The domain of application of STS is majorly in the areas of human-computer interaction studies, information technology, software engineering, engineering (general), business and management, medicine and the host of others.
- The modelling techniques for the STS include actor network theory, agent-based modelling technique, bayesian belief network, configuration modelling, fuzzy logic, morphological analysis, social network analysis, and system dynamics.
- A careful appraisal of all the techniques shows that the system dynamics approach is the most suitable technique in conceptualising the problem under investigation in the context of modelling the HECCE based on its ability to meet all the following set criteria: (1) transparency, (2) multiple interdependencies (3) dynamic situations (4) feedback processes (5) non-linear relationships (6) hard and soft data (7) uncertainties of the variables involved, (8) chaotic assumptions and (9) the use of the model as learning laboratory.
- The SD technique to model HECCE system has been demonstrated in Oladokun and Odesola (2015), Motawa and Oladokun (2015a), and Motawa and Oladokun (2015b).

The research in this paper has a number of implications for research practice, and/or society. The study identified novel approaches capable of exploring the complex intrinsic interrelationships existing among the STS of dwellings, occupants, and environment as relates to HECCE. This is in addition to the building physics, econometric, and regression-based approaches that have traditionally being in existence. Also, the approach can serve as a decision making tool for the policy makers upon which different scenarios regarding HECCE can be tested before implementation.

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