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From Air-conditioning to Clotheslines: Dynamic Conditions and the Nature of Energy Modeling for Code Compliance

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From Air-conditioning to Clotheslines: Dynamic Conditions and the Nature of Energy Modeling for Code Compliance

by

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Thesis

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Dedication

To my wife Catherine, whose quiet patience, love and support is my foundation without which I could not stand. And to my parents who have instilled confidence in me and provided the unwavering love and support needed for me to pursue not only this, but every endeavor in my life.

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Abstract

From Air-conditioning to Clotheslines: Dynamic Conditions and the Nature of Energy Modeling for Code Compliance

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This thesis, based on a methodology borrowed from Science and Technologies Studies (STS), studies the implications of using energy modeling software for code compliance in the architectural design process. Specifically, the careful study of the development and use the of the software itself, including the assumptions and frameworks of its developers and users, is required to accurately examine the implications and practical effectiveness of using energy modeling to aid in reducing the environmental consequences of the built environment. I argue that the value in studying energy modeling software is not primarily to improve the scientific accuracy of the software. Rather, the value is to demonstrate how the assumptions used in the software's calculation methodology can adversely influence the technological decisions made by building designers when using the software to demonstrate compliance with energy codes.

To develop this hypothesis I have employed both historical and empirical methods. In my historical analysis, I find that the origins of modern building energy modeling software date back to the beginning of the air conditioning industry at the start of the 20th century. One consequence of this history is that assumptions built into the software measure the relative efficiency of building components under static and assumed average conditions, but not the dynamic rates of consumption caused by inhabitation. This, in-turn, prescribes the problem-at-hand of energy code compliance as primarily technical.

However, as others have argued, dynamic social and circumstantial issues also influence energy consumption (Guy & Shove, 2000). Therefore as means to examine potential conflicts between the static and technical method of analysis employed by code compliance energy modeling software and the dynamic and circumstantial context in which buildings are designed, my empirical analysis is of a design process for a *net-zero energy* subdivision in Austin, Texas in which energy modeling was required and used extensively. The case study is designed to demonstrate how the problems-at-hand for each distinct group of stakeholders involved in the design process was varied and did not necessarily conform to the technical solution advocated by the energy modeling process.

A primary conclusion of my analysis is that all mature technologies come to us with embedded assumptions that may subvert our intentions. A secondary conclusion is that the competing assumptions and problem definitions of building scientists and building designers tend to frustrate the goal of sustainable development. My hope in studying energy modeling, in relation to practice and code compliance, is to discover ways to better use the analytical power of energy modeling that is more directly responsive to the dynamic and contextual conditions of architectural production and real world resource consumption.

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Chapter 1: Introduction

This thesis, based on a methodology borrowed from Science and Technologies Studies (STS), studies the implications of using energy modeling software for code compliance in the architectural design process. Specifically, the careful study of the development and use of the software itself, including the assumptions and frameworks of its developers and users, is required to accurately examine the implications and practical effectiveness of using energy modeling to aid in reducing the environmental consequences of the built environment. I argue that the value in studying energy modeling software is not primarily to improve the scientific accuracy of the software. Rather, the value is to examine how the assumptions used in the software's calculation methodology adversely influence the technological decisions made by building designers when using the software to demonstrate compliance with energy codes. The assumptions used for the calculation methodology of the software, I argue, can be traced to the software's legacy in the air-conditioning industry. One consequence of this history is that assumptions built into the software measure the relative efficiency of building components, but not the dynamic rates of consumption caused by inhabitation. My hope in studying energy modeling, in relation to practice and code compliance, is to discover ways to better use the analytical power of energy modeling that is more directly responsive to the dynamic and contextual conditions of architectural production and real world resource consumption.

1.1 The Current State of Energy Modeling

Measuring a building's operational consumption performance once it has been built and is occupied is fairly straightforward. One only has to gather the utility bills and sum the amount of water and energy used over a given time period. This data can be compared to other existing buildings of similar size and type to determine if the building is adequately efficient in relation to environmental policy goals. It is a much more uncertain proposition, though, to determine a building's performance prior to its construction. It is, I argue, actually impossible to determine a building's consumption prior to its construction. Yet regulating authorities, charged with implementing policy, need a standard by which to grant entitlements to build *before* actual performance can be determined. Tools, therefore, must be employed to insure that the *design* of buildings are copacetic to policy aims (not to mention aspiring to client's expectations and designer's intentions). An energy model is one such tool and is increasingly considered to be central to our attempts at more environmentally responsible design (Tupper et al., 2011).

Energy Modeling for Code Compliance

While energy modeling can serve many functions, including facilitating an analytic and iterative design process, the use of energy modeling as a tool to prove compliance with energy standards, and to assist in developing these standards, has become its primary use in the building industry ("An Architect's Guide to Integrating Energy Modeling In the Design Process," 2012). The two most prominent energy standards in the United States are the International Energy Conservation Code (IECC), published by the International Code Council (ICC), and ASHRAE 90.1, published by The American Society of Heating Refrigeration and Air Conditioning Engineers (ASHARE).

Both the IECC and ASHRAE 90.1 provide two methods of compliance: a prescriptive path and a simulated performance path ("2006 IECC Fundamentals ", 2006). Energy models are integral to both of these means of compliance. The prescriptive path requires certain building specifications that, if used in the design, would qualify the building as compliant. For instance, the code specifies mandatory thermal characteristics for building components; such as U-values for windows and R-values for roofs and walls. In order to determine the specifications for the prescriptive path, the code writers use energy modeling software to determine the relative benefit of each prescription (Morgan & Gilman, 2006).

If though, the designer wishes not to be limited by these precise specifications, the simulated performance path can be used. This path allows designers to use the same building energy modeling software, used to develop the code, to provide evidence that their custom design is at least as efficient as the prescribed method. Specifically, the code requires a comparative energy analysis. This entails that the software used to model the energy use of the proposed building also produces a baseline model that represents a similar building in size and use that conforms to the prescribed version of the code. When the energy model is run, both designs, the proposed custom design and baseline prescriptive design, are compared. Typically this entails an energy model practitioner (normally a mechanical engineer, although an architect will produce the model in the more straight forward cases) inputting the geometry, construction details and assumed operating schedules (as prescribed by the energy code) of the building design into the specialized computer program. Then, based on historical weather data published by the National Renewable Energy Laboratory (NREL), the model will simulate the thermodynamic response of the building and calculate the amount of energy required to run the mechanical and lighting equipment in order to maintain a minimum level of comfort (through prescribed temperature, humidity and lighting level set points). Most energy codes require that the calculations be made on an hourly basis over the course of a typical year and report the total amount of energy predicted to be used by the building under the assumed average conditions as specified by the code. If the proposed design is, as determined through simulation, to be *at least as efficient* as the baseline prescriptive model, then the custom design is deemed to comply ("2006 IECC Fundamentals ", 2006).

Both ASHRAE 90.1 and IECC are considered to be *model codes*. In the U.S., states and more often, local municipalities, have the right to regulate the built environment. The Federal government provides a few building and efficiency regulations, but for the most part, it is local municipalities that enforce building regulations (Moore & Wilson, 2013). The task to regulate the built environment is complicated and requires constant updating and managing. Writing and maintaining technical codes is generally beyond the capabilities and budgets of local authorities. Therefore *model codes*, written by professional and industry organizations (as I later will come to define as being part of the “technical community”), such as ICC and ASHRAE, have emerged to fill the need to write and maintain codes (Moore & Wilson, 2013). Consequently, as I will discuss in this thesis, energy codes, and the associated energy models used to develop and enforce the codes, do not necessarily propose neutral and unbiased solutions to energy consumption issues. Rather, the codes and software are influenced and biased by the operating assumptions of the technical community that has become responsible for writing and maintaining the codes. Since most regulation authorities and green building certification programs have adopted the IECC and ASHRAE 90.1 as their energy efficiency standards, the assumptions of how the technical community understands energy use and how these assumption are manifested in the tools used for code compliance, are important to examine.

Asset Energy Models

As such, I will primarily focus on the types of energy models used for code development and enforcement. The types of energy models used to demonstrate energy code compliance are generally referred to as 'asset' models (Ingle, Moezzi, Lutzenhiser, & Diamond, 2014; Polly, Kruis, & Roberts, 2011). An asset model is intended to predict the energy performance of buildings when the exact user and operational characteristics are unknown, as is the case for energy regulation across a varied building stock (Polly et al., 2011). Since it would be impossible to input all of the possible potential variables of how a building can be used across the entire population into an energy model, the asset model relies on averaged operating assumptions of a building in which the building can be reasonably expected to be operated. Therefore asset models measure the energy use of the building under standardized behavior and weather conditions with the intention of being able to compare results across an entire building stock (Polly et al., 2011).

While an asset model does provide results in terms of a building's expected annual energy consumption (normally in units of energy such as, kilo-watt hours (kWh) British Thermal Units (BTUs) or therms of natural gas), this type of analysis is better understood as an efficiency rating rather than a predictor of actual energy use. This is because the methodology of an asset model is to use the same (or similar) operating assumptions for every building. Therefore, since the operating conditions are held constant, the asset model effectively only measures the differences, and hence, efficiency, of a building's technical characteristics. Trying, then, to predict actual energy use of a specific building with an asset mode would be similar, for example, of trying to predict the actual fuel consumption of a car by only considering the car's miles-per-gallon (MPG) rating without knowing exactly how many miles a person will drive. For example, a person who drives a truck with a low MPG rating only a few miles per day will use less fuel than a person driving a hybrid car with a high MPG hundreds of miles per day. The hybrid car is still considered to be more efficient than the truck, it is just that consumption cannot be determined with an efficiency rating alone. Similarly, since an asset model uses standardized and average operating assumptions, actual energy consumption for a specific building, with specific operational characteristics, is difficult to ascertain. However, the relative efficiency of the building's technical characteristics can be compared to other buildings that were analyzed under similar operating conditions, which is the intention of the energy code.

1.2 A Problem of Consistency

The notion that that asset models are poor predictors of actual energy use for any one specific building is supported by various studies, such as an often-cited 2008 study prepared by the New Building Institute (NBI) (Turner & Frankel, 2008). This study analyzed the measured versus predicted energy consumption of 121 LEED certified buildings. The LEED standard requires that an asset energy model, as required in ASHRAE 90.1, be produce for each building to be rated. The model must demonstrate that the building design achieves a certain level of energy savings in order for the project to be rated under the LEED green building standards. This subject set provided the researchers a valuable source of data on the effectiveness of energy modeling, since each LEED rated building is required to produce a compliance energy model. Of the 552 rated buildings in existence at the time of the study, 121 responded to the researcher's request to provide actual measured consumption data.

The NBI study indicated that the *average measured* energy savings attributed to the buildings in the study, correlated with the *average predicted* savings by the energy model. This demonstrates the potential effectiveness of asset energy modeling in predicting the energy consumption of buildings from a system-wide perspective. For instance, the study found that, on *average*, the energy models predicted a 25% energy savings across all of the buildings studied (as compared to the modeled baseline code minimum as prescribed by ASHRAE 90.1). Measured consumption data of the buildings demonstrated that the buildings actually *averaged* 28% savings – slightly better than the aggregated predictions. However, the study also demonstrated that there was a great deal of scatter when comparing any *one particular* building's actual measured savings versus its corresponding modeled predicted savings. Results ranged from some buildings using only half the amount of energy as predicted to other buildings using nearly three-times more than predicted (Fig. 1). As the authors of study note,

> On an individual project basis, this suggests energy modeling is a poor predictor of project-specific energy performance. Measured EUIs [*energy use intensity*, kBtu/ft2/yr.] for over half the projects deviate by more than 25% from the design projections, with 30% significantly better and 25% significantly worse. (Turner & Frankel, 2008, pg. 23).

While perhaps showing evidence of system-wide effectiveness at a policy level, these results question the relevance of asset energy models as an effective and credible judge of performance for any one specific building.

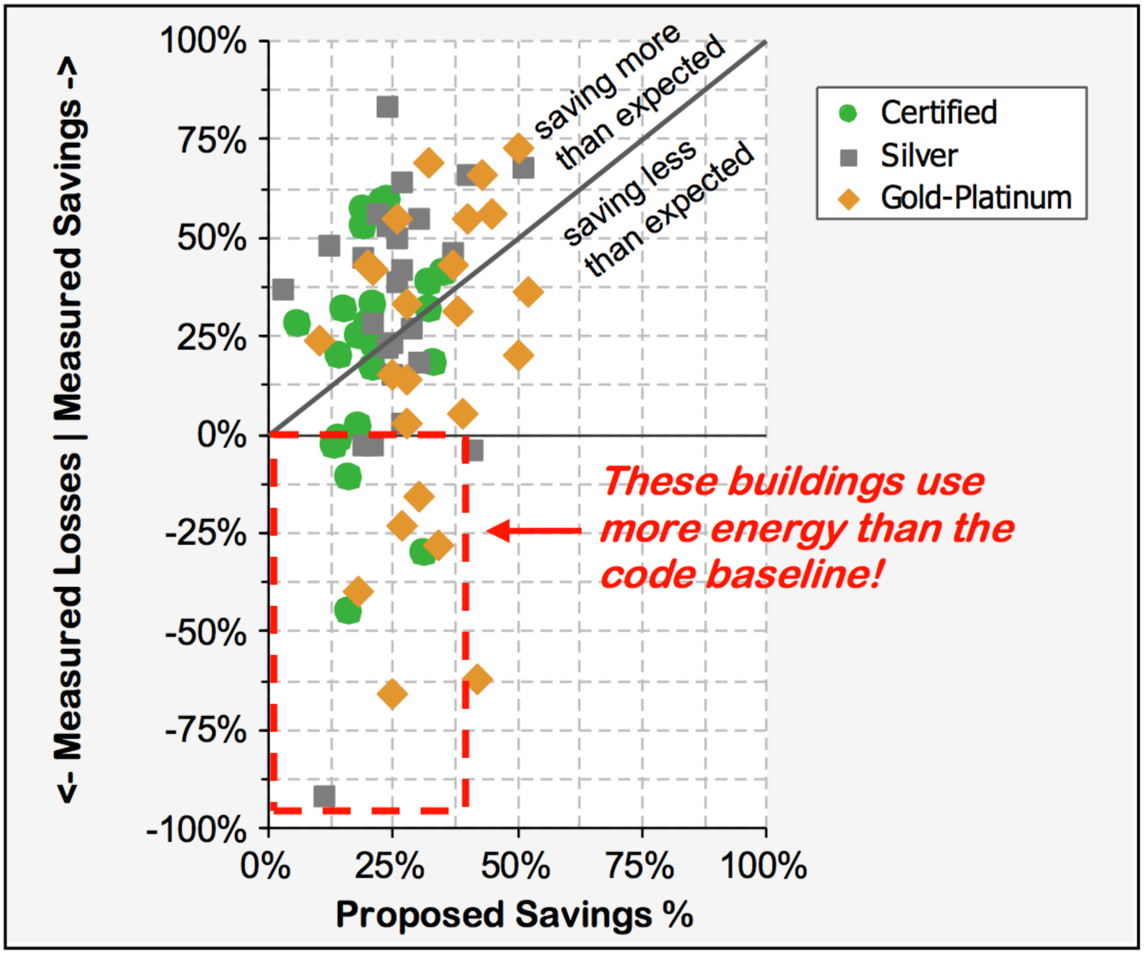


Fig. 1: Measured vs. Proposed Savings Percentages (Turner & Frankel, 2008)

Many other studies have found similar results; that while energy modeling might provide accurate predictions of *average* energy use across a set of buildings, results for individual building are very inconsistent (Ingle et al., 2014; Norton, Kiatreungwattana, & Kelly, 2013; Polly et al., 2011; Sullivan & Winkelmann, 1998). Most researchers agree, and as described above, that this is the case because asset energy models used for certification and code enforcement use average building operating conditions as a basis for analysis (Ingle et al., 2014; Norton et al., 2013; Polly et al., 2011). Therefore, an asset model will only accurately predict the energy use of buildings that are actually used in the same, average manner as assumed in the model ("Energy research at DOE, was it worth it?," 2001).

However, we cannot assume that average conditions will always accurately describe a building. So when buildings deviate from the assumed conditions in which they were modeled, as they often do, the models no longer will be an accurate measurement of its specific performance (Norford et al., 1994). Over a large enough sample size this might not register as a problem since some differences in conditions will result in reduced energy use, while other differences will result in increased consumption. This conclusion is supported by the result from the NBI study cited above where the averaged measured energy consumption aligns with the averaged predicted results, yet there is a great deal scatter of individual results *equally* both above and below the average. Therefore, as the data demonstrates, the models are only valid predictors of average energy use across a large sample of buildings and are poor at predicting individual building performance.

At a global or regional level, this might not be viewed as a significant problem. Even though any one specific building's predicted performance might be significantly over or understated, the results suggest that the average energy consumption of buildings designed to standards derived from the energy modeling process is decreasing. Therefore, one could argue, the use of modeling software to validate our energy related technological decisions on a system-wide scale contributes to our collective effort to reduce resource consumption even with the reported inconsistencies.

1.3 Problem Statement and Research Questions

Is there a problem, then, with relying on the current versions of energy modeling software to validate the environmental consequences of development as I propose in this thesis? The answer is yes, I hypothesize, because there is potential for the results to misstate the efficacy of certain purely technical measures on a project-specific basis when they are analyzed within an averaged and rationalized context. However it is not always apparent to the user of the software that there is such a technical bias. Therefore the model has the potential to mislead the user when making project-specific value decisions regarding where money should be spent, effort expended and compromises made, while pursuing the specific energy efficiency measures as dictated by the particular logic prescribed by the energy model.

In addition, and perhaps more critically, when energy model results are required to demonstrate energy code compliance or green building certification, the project team might be *forced* to choose from only a limited number technological solutions that happen to be able to be validated via the energy model. This has the consequence of precluding solutions that fall outside of the logic of the energy model and thereby tends to exclude the situated knowledge of the design team and project stakeholders in crafting appropriate energy efficiency strategies with respect to the specific context of the project. These more localized solutions tend to be more agreeable to the aspirations of the project stakeholders yet are difficult to employ because they cannot be validated (or deemed to comply with energy codes) with the current slate of analysis tools even though they may, in fact, be effective.

In other words, I hypothesize that current versions of energy models used for code compliance only account for half of the energy use equation. While the technical efficiency of the building's construction and equipment characteristics are important aspects of understanding energy consumption, equally important is how the building is operated and responds to *changing* conditions and circumstances. For a variety of reasons, a building's physical characteristics change over time. Lack of proper maintenance, the weathering of building materials, or discrepancies of how the building was actually constructed versus how it was intended to be; all are factors that influence how a building performs (Waltz, 2000). In addition, how buildings are operated is contingent on the price of energy, a person's political views, their socio-economic status and a variety of other social circumstances (Guy & Shove, 2000). As such, social and contextual factors are as much an influence in energy use as is a building's technical characteristics. By limiting energy analysis to only the static, technical qualities of a building, as I argue asset models do, a large part of the contingencies of how energy is actually used is not considered. Therefore, it becomes difficult to plan for these extra-technical contingencies, such as changing climate conditions, varying economic conditions or any other conditions not represented by the assumed average energy model inputs.

Techno-economic vs. Socio-techno Assumptions

While it is generally understood that the energy models used for code compliance do not account for changing conditions (Polly et al., 2011), why are they still used? Guy and Shove argue that the reason for this is that there are fundamental epistemological differences between the assumptions made about building performance by the technical community versus the everyday experience of building practice. Namely, Guy and Shove (2000) argue that the assumption made by the technical community, - that contextual issues are secondary to technical concerns - is a result of the technical community working almost exclusively in a *techno-economic paradigm*. A techno-economic paradigm assumes that consumers of information are rational economic actors and will, given sufficient knowledge and the absence of any market distortions, make rational, *and therefore similar*, choices with regards to efficient and proper use of technology. Accordingly, the assumption made by the technical community is that technical efficiency of a building is all that is needs to be considered since each person will use technology in similar ways.

Conversely, as I alluded to above, people use buildings circumstantially. Therefore building performance is understood in varied and contested ways depending on the situation and is contingent upon social and contextual factors. Guy and Shove (2000) suggest, then, that a *socio-techno* framework – one that considers contextual and social factors *equally* to technological factors and allows for multiples understandings of building performance - is a better framework to analyze building performance. Yet energy code compliance only considers technical solutions to the problem. Partly this is because the tools used for compliance only, as I argue, analyze technical solutions. If one believes, as I do, that social and contextual components of energy use are also needed, along-side technological solutions, to solve the energy problem, then this suggests that a new paradigm for our mode of energy analysis for code compliance is needed.

Research Questions and Agenda

It is, then, my intention in this thesis *to present a case for expanding the methods of energy analysis for code compliance to include contextual and social factors*. To do so, I ask two research questions: 1) How have energy models been developed and with what assumptions? And 2) How do these assumptions influence the technological decisions made in the name of energy conservation? Accordingly, I will present a historical analysis of the development of energy modeling, which demonstrates that the technical efficiency biased method of building performance analysis preferred by the technical community, is embedded in energy modeling software used for code development and compliance. Then, though a case study of the design of a subdivision that used asset energy modeling extensively, I will demonstrate how the technical efficiency bias in the energy model adversely influenced the technological decisions made by the design team.

A primary conclusion of this thesis supports the claim made by scholars of Science and Technology Studies (STS) that all mature technologies come to us with embedded assumptions that may subvert our intentions. A secondary conclusion is that the competing assumptions and problem definitions of building scientists and building designers tend to frustrate the goal of sustainable development (Moore, 2014). Accordingly, to begin this discourse, I will present in the next chapter a constructivist theory of technological change, namely the Social Construction of Technology (SCOT), which describes a methodology that provides a theoretical basis for these conclusions. Primarily, SCOT contends that the judgment of technologies are varied and contested and are not made solely on the merits of their technical characteristics alone. Rather, SCOT scholars claim, technologies need to be understood within their social context in addition to being judged on their technical merits.

Then, in Chapter 3, I will provide a literature review (albeit, limited) on the theories of architectural performance. Stemming from the discussion of SCOT, I will describe how the methodology used for code compliance energy modeling, is just one of many understanding of architectural performance.

In Chapter 4, to demonstrate how a technological bias has been integrated in the calculation methodology use code compliance energy modeling, I will present, an interpretive historical analysis of the development of energy modeling software. The historical analysis will trace the origins of modern building energy analysis software to the beginning of the air conditioning industry at the start of the 20th century. I conclude that the building scientists, who developed the air-conditioning industry and pioneered the thermal analysis methods for buildings, were mostly concerned with predicting the behavior of mechanical equipment under specific design conditions. Using the historical work of Gail Cooper (1998), I further conclude that mechanical engineers preferred this method of analysis because of the difficulty they experienced in guaranteeing the performance of their systems within the dynamic context of real world building operations and maintenance. This disposition developed by the earlier HVAC engineers has become standardized through the efforts of ASHRAE and has been incorporated into building energy modeling and codes.

Then, in Chapter 5, through a case study of the design of a subdivision that served as a pilot project to test practicality of a particular City of Austin policy initiative that mandates a level of residential building efficiency equivalent to net-zero energy use by the year 2015, I will demonstrate that the stakeholders involved with the design were persuaded by the energy modeling process to make design decisions that conflicted with their stated aspirations for the project. The case study demonstrates that contextual and situated knowledge is often dismissed when the dominant mode of analysis, as is the case with asset energy modeling, is limited to universal and context-free concerns.

A note regarding the 'technical community'

In this thesis, I present a general critique of the methodology used in the current versions of energy models used for code compliance. While these models have generally been developed and advocated by a diverse group of stakeholders, I refer to them collectively as the "technical community." I have borrowed this term from Guy and Shove (2000) who explain that the technical community can be identified as a group who share relatively similar approaches in thinking towards building performance – most notably, a bias towards technical solutions to the energy problem over social solutions (Guy & Shove, 2000, pg. 15). I consider professional engineering societies, such as ASHRAE, code writing organizations, such as ICC, building science researchers at universities and national laboratories, as well as individual architects and engineers who work with this same technical disposition, all part of the 'technical community'. It is not my intention to discredit the detailed and valuable work carried out by this community. Rather it is my intention to bring attention to additional factors that influence our understanding of energy use which are not always given equal attention by the technical community. These factors, namely social and contextual, I believe, are instrumental, in addition to technical concerns, to address the environmental issues we face.

Chapter 2: Methodology and Methods

2.1 Constructivism

For this thesis, I have chosen to adopt a constructivist ontological position. A constructivist framework takes the position that knowledge is not universal or objective. It is in fact constructed, explicit or not, through social agreements (Groat & Wang, 2001). This differs from a positivist frame of analysis, typically employed in the natural sciences, which assumes that an objective reality exists and that all observers of nature can and must eventually draw similar conclusions (Groat & Wang, 2001) no matter the circumstance. Conversely, an often-made argument by constructivists is to say that 'things might be different' than the official and seemingly final state they appear to us everyday (Latour, 2005). By this they mean that given a different arrangement of society or circumstance, epistemological truths might be perceived differently than as we accept them. Therefore, different social groups, working in different contexts, will produce and accept knowledge claims differently, and therefore each group might not draw similar conclusions to each other after all (Groat & Wang, 2001). Logically then, the context in which knowledge is presented has great influence on how we perceive truths and consequently - and importantly - how we choose to act. Within a constructivist framework then, careful study of context is crucial and simply 'looking at just the facts' will not reveal the complete story.

Often this framework is criticized for being relativistic. If everyone is able to profess the truth from their own vantage point, then how come we experience a common reality where the apple always falls on Newton's head? Or more importantly, how can we establish a common moral ground if everyone is free to choose his or her own truth? The point is not to establish a solipsistic social theory where every position is valid; it is just to admit that knowledge and artifacts do not come out of nowhere and are contestable. There is a story behind every fact that might not always be apparent when we first approach it.

This same criticism suggests that when something is deemed to be ‘constructed’, it is somehow inauthentic. Latour (2005) elegantly rebuts this criticism by saying that in most cases when we refer to something as constructed, we are acknowledging its reality. A building is, for example Latour (2005) continues, an assemblage of discrete parts that has been explicitly put together. By referring to it as constructed, we are not saying that it is inauthentic. Rather we are acknowledging its heterogeneous reality and the process in which it came into existence. This implies as well, that the building did not appear on its own, and given a different set of circumstances, it could have been built differently. A constructivist perspective uses the same logic to explain the creation and dissemination of knowledge and ideas, as well as the artifacts that embody them.

Further, as Latour (2005) explains: “Everywhere, in technology, engineering, architecture, and art, construction is so much a synonym for the real that the question shifts immediately to the next and really interesting one: Is it well or badly constructed?” (Latour, 2005, p. 89). Or more accurately, is it well or badly constructed for the circumstances for which it is intended? Latour (2005) continues that it is a fallacy, for example, to think that science experiments result in objective knowledge or facts about the world that would be discovered no matter the circumstance of the investigation. In reality, the experiments, the equipment and the labs themselves are literally and expressly constructed and routinely judged on the quality of their construction. In a sense, it is actually a compliment to tell scientists that their facts are well constructed, as it is a judgment of the quality of their scientific work (Latour, 2005). This is routinely done with peer reviews, a central tenant of the scientific method, where judgment is passed on the quality of experiment's construction not rather if it is simply right or wrong. Therefore the context in which the fact is constructed is paramount to its validity (and thus acceptance).

As such, for this study I take the position that we need to take a close look at the quality of knowledge constructed from energy models. I take a constructivist perspective both as a research methodology and as a hypothesis for improving the validity of energy models. As a methodology, constructivism compels me to look at the development of the energy model itself and the context in which is used in order gain insights for improvements. As a hypothesis, I contend that the problem with energy models is that they are developed largely with a positivist (or as Guy and Shove (2000) describe, a techno-economic, or determinist) perspective rather than a constructivist (or socio-techno) framework and consequently largely ignore the contextual and circumstantial components of energy use. Therefore an energy model, as I hypothesize, developed within constructivist framework might produce more meaningful results.

I am unable, though, within the limitations of this study, to test this hypothesis. Ideally to do so would require me to identify an energy modeling software developed with a constructivist framework as I propose. Then I would need to test its modeling results with respect to an actual project where I could gather real world consumption data and qualitative data from the stakeholders regarding the contextual issues of the project. Unfortunately I have yet to find such a software tool or project designed under these circumstances. And since my training is in architecture and not software engineering, I am unable to develop such a prototype software myself for testing. But there are abundant examples of projects designed with the currently accepted modeling technology that I am able to investigate. As such, I will use both historical and empirical analysis to present insights on how energy modeling software might be improved to better contribute to more responsible building practices. The historical analysis will focus on the history and development of energy modeling software. The empirical analysis focus on the contextual issues regarding the technical choices made for the design of an existing project where energy modeling was used extensively.

2.2 The Social Construction of Technology (SCOT)

More specifically, the version of constructivism that I will employ is generally referred to as the Social Construction of Technology (SCOT) theory. Generally, SCOT is an attempt at taking the social constructivist position and applying it to science and technology studies in order to form a theory of technological change (Bijker & Pinch, 2012). The position that SCOT scholars hold is that technologies are not neutral, or their development inevitable, but rather they are a product of the contingent social circumstances of their development.

Technological Determinism

The SCOT theory of technological change is a direct critique of the theory of technological change dominant in 19th and 20th centuries and which has coincided with the industrial revolution. SCOT identifies this dominant theory as *technological determinism* (MacKenzie & Wajcman, 1999) and is defined by Smith (Smith & Marx, 1994) as the belief that “changes in technology exert a greater influence on societies and their processes than any other factor.” In other words, technologies are the most influential factor in determining the ways in which we live and have strong influence in the structure and power relations of societies. For instance, a deterministic view of technology would assign strong agency to the automobile for the expansion of suburban development patterns. It would take the position that automobiles and the individualized mobility they provide, is a primary reason why suburban developments exist. Further, determinism implies that technology acts in one direction. That is, that while it has significant influence over society, its development is independent of social factors. In other words, its development is fueled based on its own internal logic and certain technologies are advanced over others based on their technical merits alone.

Smith (Smith & Marx, 1994) argues that there are actually two types of technological determinism. He assigns the particular view of determinism as stated above as, "hard," because it reduces the argument to an absolute assignment of agency. Conversely, a "soft" deterministic view holds that technology can influence social change, but at the same time, "responds discriminately to social pressures." While SCOT scholars agree with the determinist position that technologies do influence society, they disagree that the "hard" version of determinism is a complete explanation of technological change. They are more sympathetic to a "soft" determinism that acknowledges that change works in both directions – that society has just as great of influence on technology as technology has on society (Smith & Marx, 1994). So in the case of suburban development, a soft deterministic view would acknowledge the car as being important, but would also give strong, if not more, agency to economic, race relations and political considerations (for example, subsidy for gasoline development).

SCOT in Action

Pinch and Bijker (1995) present an empirical example of the development of the bicycle to explain SCOT and how social interests have influence on technological change. The bicycle we know today (while several variations exist, for example, the beach cruiser versus the racing bike), generally all take the same form: two equally sized wheels mounted to a diamond shaped tubular frame with a rear chain drive. But when, as Pinch and Bijker recount, the bicycle was first under development, much more radical variations were considered. The bicycle we know today was generally referred to as a "safety" bicycle in the late 1800s as it was considered a safer version to ride as opposed to the more common "ordinary" bicycle. An "ordinary" bicycle, today now commonly referred to as "penny-farthing", is the type with a large front wheel, high seat and direct pedal drive on the large front wheel (Fig. 2). These bikes were generally used by thrill seeking young men at the time and where primarily built for speed. To this group of users, the design of the bike was viewed as means to achieve faster speeds. But to other groups, such as women and the elderly, this design was considered to be dangerous, as the speed and height of bicycle could result in violent crashes. So, whereas to one group of users, the design of the high seated, large wheel bike represented a solution to their problem of speed seeking, to another group, the solution presented a problem of safety. Each *problem definition* resulted in different types of bicycles: the ordinary bike used for sport and the safety bike used for transportation. The point, is that the artifact itself cannot determine its own success or failure. It must be understood along side the social groups who view the artifact as solving or creating a problem relevant to them in order to understand why some technologies are advanced and others are not.

Fig. 2. Example of penny-farthing bicycles. Cunningham, A. (2011). *Penny Farthings*, [digital image]. Retrieved May 1, 2014 from Flickr: https://farm7.staticflickr.com/6142/5923141175_fae340c223_o_d.jpg.

Relevant Social Groups and Interpretive Flexibility

The abbreviated example above, introduces two important concepts: *relevant social groups* and *interpretive flexibility*. If artifacts are given meaning not solely on their technical qualities, but also by the social group who lobby for or against their development, then we must consider social groups relevant and influential to the development of the artifact or technology. In the example of the bicycle, both the young thrill seekers and those concerned with safety are both considered relevant social groups even though each group interprets the bicycle differently. What identifies them as a group is that each group has a common understanding (although different from each other) of the artifact (Cowan, 2012; Kline & Pinch, 1996).

What is important to consider regarding relevant social groups, is that understanding the assumptions that these groups hold can reveal to us important information regarding the technologies they favor and why they may or may not succeed. Today we currently use a bike that is most similar to the safety bike from the 1800's. But we cannot simply surmise that the safety bike's prominence is due to its technical superiority over the ordinary (Cowan, 2012). Rather, the relevant social group who favored a safer version of the bicycle proved to be more influential in its development. The common bike in use today solves the safety problem of speed by employing a gear mechanism that allows for the gear ratios necessary to achieve speed without having to use large over-sized wheels. But had there not been a social group lobbying for safety, there might not have been the impetus to incorporate safety features into the bicycle. Therefore, in the case of the bicycle, the version we use today has embedded in it the values of safety and therefore the bicycle takes a certain form. We cannot simply say that the safety bicycle was technically superior to the ordinary, just that the safety bike proved to solve a problem more relevant to a larger number of people, and hence there was motivation to design bikes with smaller front wheels (Bijker & Pinch, 1995).

The concept of relevant social groups and their ability to form their own definitions of the problems which technologies solve is explained by another concept: interpretive flexibility. Interpretive flexibility refers to an artifact's ability to not only be understood differently by different relevant social groups, in terms of their use and technical characteristics, but also in the criteria in which they are deemed successful or not (Bijker & Pinch, 2012; MacKenzie & Wajcman, 1999). So, for Pinch and Bijker's example of the development of the bicycle, for the relevant social group identified as the speed enthusiasts, the measure of success was the ability for the bike to go fast and the technical characteristic representing this success was the size of the front wheel. For the group identified as desiring safe transportation, the large wheel represented a problem and therefore a smaller wheel was the measure for success. The same technical characteristic, the size of the front wheel, was both a success and a failure metric depending on the values of the social groups' judgment. Again, this demonstrates how an artifact's technical characteristics are not neutral and cannot be judged without analyzing the social context in which they are developed and used.

Technological Momentum

While artifacts have the ability to be interpreted differently, as the concepts of relevant social groups and interpretive flexibility demonstrate, the concept of *technological momentum* suggests that there is usually the most discrepancy between interpretations during periods of the technology's development and less as the technology matures (Hughes, 1994). Hughes (Hughes, 1994) argues this concept adds another dimension to the discussion regarding soft versus hard determinism by adding the caveat of time to the debate. Hughes continues that, early on in a technology's development social forces play a more significant role. Once the technology, on the other hand, has a chance to mature, the influence tends to reverse and exhibits characteristics more in line with a hard deterministic perspective. In a sense, there is more of an open debate about the technology's proper use and the value of its different variances early on in its development as opposed to later in its development. A young technology tends not to have a large market share yet and many relevant social groups vie to define it in their own terms (Cowan, 2012). During this period, social forces shape the development of the technology as I have described above. But as technologies mature, they gain momentum through a process of "closure" and are less responsive to social pressures. Closure happens when the open debate surrounding the technologies quiets and the technology's development stabilizes on a particular path (Hughes, 1994). At this point, technologies appear to have more of a hard deterministic character in which they can exert a seemingly large amount influence on society and tend not to be seen as having the ability to be changed.

A way in which this transition occurs, Hughes argues, is that as "systems mature, a bureaucracy of managers… usually plays an increasingly prominent role in maintaining and expanding the system so that it becomes more social and less technical" (Hughes, 1994, pg. 105). By this, Hughes is making the point that as systems mature and close, a large contingent of people becomes invested in maintaining the technology's relevance. The technology's success then becomes less tied to its technical merits and more to the strength of the network of people supporting and invested in it. Where once the technology was shaped by social and contingent factors and could have very well taken various forms, the mature and closed system has catalyzed the creation of social groups intent on stabilizing the technology against change.

For example, there are countless organizations that rely of the success of the automobile. Obvious ones include oil companies, but also real estate agents who sell single family lots in suburban neighborhoods, or corporations who rely on cheap suburban land for their corporate campuses. These groups and many others rely on the automobile system to enable development patterns in which they are invested (Kline & Pinch, 1996). Even though public transportation technologies have proven to be more efficient and less expensive than the infrastructure and environmental costs needed to maintain the automobile, public transportation tends to only be viable in dense urban cores that tend to have higher land prices (Vuchic, 1981). So consequently, realtors, corporations who headquarter in the suburbs, and many groups who have financial stakes in suburban development, also have a vested interest in lobbying for funds to maintain the highway system enabling suburban development. It would be against their financial interest to advocate for public funds to support public transportation that might change development patterns. So while perhaps in postwar America, the automobile was one of a few possible transportation solutions considered, by the late 20th century and beyond, society had began to more strongly depend on the social and spatial system which the car had enabled (Kline & Pinch, 1996). Consequently, the discussion of which transportation technology we should invest in becomes less of a discussion regarding technical merits and one more of political, economic and social issues. When, as is mostly the case for the automobile in the United States, a majority of stakeholders (or the right stakeholders) have a vested interest in the success of a particular technology, the question of their development is closed and the technology then *appears* to be stabilized and resistant to change. This can be seen in the case of the automobile by the level of resistance public transportation initiatives receive by groups claiming that a radically different transportation system is just not possible. This was hardly case at the first half of the twentieth century when, for instance, streetcars seemingly had just as much of a chance of success as did the automobile (Kline & Pinch, 1996).

2.3 Actor-Network Theory

The notion of technological momentum and closure suggests that it is not always apparent to what extent the tools and technologies we use influence society since often they arrive to us in their mature and closed form. Latour (2005), Law (1992) and others have developed a theory called Actor-Network Theory that is interested in how technologies find closure and why they remain so. Central to their theory is the belief that studying the contingent arrangement of *people and artifacts* and the connections they form can help explain how our technological and social situation has come to be (Latour, 2005). Just as Hughes argues that technologies find closure with the help of social groups ("…a bureaucracy of managers…"), ANT, in addition, recognizes the influence that artifacts have in stabilizing society. Together social groups and technologies are both given equal agency (and hence both are referred to by ANT scholars with the same made-up term, *actants*) (Law, 1992).

For instance, ANT would dismiss an explanation of American car culture as being the result of the capitalistic *nature* of American society (i.e. Americans are a relevant social group which values individual freedom and therefore the automobile system was inevitably developed in to satisfy their inherent values). Instead, ANT would hypothesize that the availability of automobiles (an artifact), along with a middle class (a social group) who would benefit from their wide spread use, form a network in which car culture is the *result* (Kline & Pinch, 1996). If for instance, a car manufacturer was unable to produce an affordable car or there was no practical use for an affordable car, a car culture would not develop. Therefore there is no inherent societal explanation for car culture, but rather a circumstantial explanation where a technology and a group have found a common ground.

In other words, groups in conjunction with technologies create a circumstance in which a particular society emerges, not the other way around. Therefore different arrangements of groups and technologies will form different societies. This is a powerful notion. It implies that if we change the arrangement (network) of groups and technologies, we can affect social change. And further, the arrangement we experience today is not inevitable and formed by some mysterious social force. Rather there are real, tangible circumstances that we can study empirically that can help elucidate the reasons why our society has manifested in certain ways. In other words, things could be otherwise and we can empirically study the circumstances of why this is (Latour, 2005).

Black Boxes

Following an ANT methodology therefore requires careful empirical examination of all of the contingent arrangements of humans and artifacts connected through adjacencies and time in order to form a valid description of any particular action, event, object or situation. This is not always easy to do, as mentioned above, since once technologies have been stabilized and the discussions surrounding their development are no longer readily available, much of the contingencies of their creation are concealed and protected from scrutiny.

For this reason, mature technologies are sometimes referred to as *black boxes*. A black box is a term often used in science and engineering fields to identify a device, system or object in which only the inputs and outputs are required to be known for its proper use. The internal logic or assumptions embedded in a black box are either too complicated or unnecessary to understand by the user. Therefore black boxes conceal these complications in order to enable efficient operation. Similarly, when technologies achieve closure, ANT scholars consider them black boxes since the logic and assumptions of their development are no longer considered in their use. We tend to accept them as they are and use them unreflectively (Latour, 1987).

Generally, black boxes are useful to us on a daily basis and allow us to function efficiently. For instance, a desktop calculator is black box in that when we use it, we do not need to understand the circuitry involved that allows it to work. Otherwise the simple task of using the calculator could become overwhelming. In general, this does not present too much of an issue, as simple arithmetic is rarely controversial and we can accept the answers the calculator outputs without consequence. But when the black boxed technology is used to drive policy or affects how societies are structured, as I claim is the case for energy models, then the assumptions embedded in the back boxed technologies are critical to understand.

ANT scholars then take it as their mission to "open" the black boxes that we rely on to form societies as means to understand their implications. A technique that ANT scholars often use to open closed technologies is by studying *controversies*. Controversies are useful since they represent, often expressly, times in which a technology's development is not stabilized (Latour, 1987; Yaneva, 2012). It is in the discussions and arguments surrounding the development of a technology where researches can see evidence of the assumptions used to construct the technology. Further, this allows researchers to speculate how other possible operating assumptions might result in different versions of technologies and hence possibly different arrangement of societies (Latour, 1987).

Mapping Controversies

Following the lead of ANT scholars, Yaneva (2012), in her book, *Mapping Controversies in Architecture,* presents a method of how to investigate controversies, in her case for architecture, through a mapping process. Yaneva uses ANT to criticize the approach of architectural theory that only takes into account aesthetic, formal and static qualities of architecture. Architecture, she argues, acts in ways similar to black boxes in that the formal structures we experience everyday rarely reveal the assumptions and controversies involved in their design. She advocates, then, studying not just the formal structures of buildings themselves (as has been the tradition of the architectural history and theory disciplines), but all of the political, bureaucratic, technological and other ancillary circumstances surrounding the building's design. Inevitably, the final form the building takes can be traced back to decisions and arguments between stakeholders during the design process as wells as the materials, labor and skilled professionals which may or might not have been available at the time of construction. These contingencies might not be obvious in the final (or "closed") state the building appears to us after it has been constructed. Therefore Yaneva advocates mapping, through historical, document and qualitative analysis, to uncover all of contingencies, arguments and agreements during the design process.

Following her example for instance, simply analyzing the Sydney Opera House based on the formal meaning of its iconic domed sail-like roof misses the full understanding of the building. To understand the opera house one must look at the making of it - including the all of people, technologies, agreements and controversies surrounding its design and construction. Jorn Utzon is commonly credited for the design of the opera house. But by studying its making, we learn that Utzon himself did not have the capacity to realize the buildings on his own. As Yaneva relates the story, Utzon won the design competition to build the opera house based on concept sketches and not necessarily a fully worked out design. After winning the commission, Utzon and his limited staff found it difficult to execute the design as sketched. Nothing similar to the sail-like concrete shells had ever been constructed before on such a scale. The consulting engineering firm Arup was added to the design team to assist in devising a practical way to construct the shells. Because of the complexity of the form, Arup decided to employ their newly acquired computer analysis tools to help design the structure.

At first Utzon's firm and Arup developed a productive working relationship. Both parties appreciated the integrated process in developing the design for the shells and the computer proved useful in providing reliable analysis of the structural forces. But as the project progressed and the design proved difficult to resolve, tensions formed between the two offices. Arup became frustrated at the delays in receiving drawing from the architect and Utzon complained that Arup and the other consultants did not have the comprehensive vision to properly execute the design. This ultimately caused delays and budget problems for the project that resulted in public protests and political scrutiny. Eventually public pressure became such that the Australian Government forced Utzon to collaborate with a larger consulting architecture office to complete the project. Utzon refused and resigned from the project. Eventually, without Utzon involved, the project was completed and opened in 1973. Years later in 2003, with the controversy of the design process of the Opera house long closed, Utzon won the Pritzkger Prize for the design of the building.

Yaneva's point in recounting this story is that by explaining the *meaning* of the Sydney Opera house as an ode to the sail boats in the Sydney Harbor because of the form the building has taken, is only *partly* true. Neither can it be said that Utzon was *the* designer of the building, as the Pritzkger prize suggests. There is significantly more to the story than the completed formal structure can tell us. The form that the Opera house takes, rather, can also be attributed to the political will, public protest, computer technology, the physical properties of concrete, collaborating and disagreeing professionals *and* (and not just) a metaphor for the shape of a sail. Empirical research into the all of these "actants" (both human and non-human) is needed to understand why it is the opera house exists the way it does and where the agency for its creation lies.

For instance, had Arup not had access to computers to analyze the unique form, Utzon's design sketch might not have been able to be built as he intended. So while the computer did not have agency in the sense that it consciously influenced the design of the building, its presence made the conditions such that it enabled the design team to execute the project in a particular manner. Without the use of the computer, the shape of the shells almost certainly would have taken a different form or had even been built at all. By examining the physical artifact, we might understand that concrete is responsible for holding up the building. But nothing in the artifact tells us of the importance computer analysis had in its role of making sure the building stands up (not to mention the election year politics which forced Utzon to resign and other consultants to finish the design). As we will see in upcoming chapters, energy modeling has also been a technology "at hand" and has made conditions such, that we analyze the performance of building in a technically biased way. This might not be apparent by analyzing the formal aspects of buildings themselves.

In Yaneva's analysis we can see how mapping all of the actors (or actants) and controversies is necessary to gain a clear understanding of the contingencies involved in the building's development. In so doing, all of the possibilities of what the opera house could have been are illuminated and our understanding of it becomes richer, more accurate and can provide guidance on how we might build otherwise in the future. In this thesis, I plan to use the methods of mapping controversies to investigate both the making of energy modeling software and the implications of its use. Therefore a careful research into all of the arrangements associated with the development of energy modeling software is necessary to first, truly understand its nature and second, learn the options we have available to us to make changes. Similarly then, mapping the nature of energy modeling within the case studies presented helps us understand the software's influence in policy making and design and how we might develop alternate analysis technologies that better aspire to our goals.

2.4 Methods

To map the influence of energy modeling in architectural production, I will use both historical and empirical methods of analysis. The historical analysis will concentrate on the development of building energy modeling software while the empirical analysis will consist of a case study of the design process for a net-zero subdivision in Austin, Texas.

Case Study Selection

The 60 unit subdivision (both single family and multifamily), built on an 11 acre brown-field site in East Austin, is designed to be 100% affordable and *net-zero energy*. Net-zero energy buildings are designed to a standard in which, on an annual basis, the building consumes as much energy as it produces on-site. Primarily this is achieved by reducing the energy loads (or increasing energy efficiency) to the point in which it is economically and physically feasible to produce as much energy as the building consumes through on-site renewable sources (generally solar, wind and geo-thermal). Austin Energy, the municipality owned power provider, has agreed to subsidize the project by providing photovoltaic panels free of charge to the development. Austin Energy is proving their support in exchange for the right to study the project in order to test the implications of the City of Austin's policy initiative that will require that by 2015, all news homes constructed within the city must be net-zero energy capable. A task group was formed by the city council in 2007 to provide recommendations for how the city's code could be amended to achieve the net-zero capable goal. The task group concluded that net-zero capable homes would need to be at least 54% more efficient than homes being building under the 2006 version of the IECC. In order for the project developers to qualify for the subsidy for the solar panels, then, they agreed that the design of the buildings would be 54% more efficient than the 2006 IECC. The project designers agreed to demonstrate compliance of this requirement through the use of energy modeling. As such, this project provides a good opportunity to study the implications of energy modeling in the design process.

Historical Analysis Methods and Sources

Before I embarked on a qualitative interview process of the stakeholders involved in the project to develop the case study, I first began with the historical research of the development of building energy modeling software. Specifically I focused the research on the development of the DOE-2 calculation engine. DOE-2 is partly developed and distributed by the U.S. Department of Energy and is one of the most widely used software modeling engines and was used by the designers of the subdivision. To gain a general understanding of how DOE-2 was developed I began by looking at secondary histories written by academics interested in the improving the development of the various programing and physical modeling calculations of the software. Most significantly, the "Pre-read Report" (Tupper et al., 2011) from the Rocky Mountain Institute's *Building Energy Modeling Innovation Summit* conference provided me with a starting point. In addition, Haberl and Cho's history of the development of DOE-2 provided a good secondary source to begin (Haberl & Cho).

From the secondary sources I was able to identify a few key individuals involved in the early development of energy modeling. One individual, Tamami Kusuda, was a researcher for the National Bureau of Standards (NBS) and has written many of the foundational scientific papers used in the development of energy modeling software. His papers provide insight on the intentions of the early software research projects. In addition, his personal history of the early development of energy modeling as he recounted as a keynote address at the 2001 International Building Simulation Association Conference provides an inside perspective of the circumstances surrounding the development of the software methodologies (Kusuda, 2001).

In 1970, Kusuda, while working at the NBS organized the first conference on the subject of computerized energy analysis methods. Fifty-nine papers were given at the conference with topics ranging from computer graphics for energy analysis to algorithms describing the physical phenomenon of heat transfer. In addition, several papers were given which described the development process and methodologies for many of the first computer energy software programs. This primary source proved to be very useful for the historical analysis (Kusuda, 1971; Lokmanhekim, 1971; Romancheck, 1971; Tull, 1971).

An interesting finding from the general historical research is that the Association of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) has played a significant role in developing energy modeling software. Their efforts were primarily in support of the development of building energy use standards that they publish. Histories of ASHRAE and in particular the history of ASHRAE 90-75, the first comprehensive energy code published in the United States, provide useful information on how energy modeling has been incorporated and instrumental to energy codes (Kirkwood, 2010).

The strong connection of ASHARE to the development of the software reveals that there is also a strong connection between the air conditioning industry and the methodology used in the software. As such, I have used Gail Coopers comprehensive history of the American air-conditioning industry to demonstrate how the early air-conditioning engineers developed a method of efficiency analysis that is still used in contemporary energy modeling software (Cooper, 1998).

As mentioned above, part of the intention of the subdivision, at least from Austin Energy's perspective, was to test the practically of the city's plan to require that all new homes built after 2015 are net-zero capable. Therefore, since my research objective is to analyze how, or how not, the energy modeling process is copacetic to the intentions of the stakeholders, I must establish what the City of Austin's intentions are in requiring this level of performance. To do so, I have gathered public records regarding the development of the city's policy including notes from a the task force convened to advise city council on the code changes the city should adopt in order to achieve its goal.

Qualitative Empirical Research Methods

To establish the intentions of the project stakeholders and determine how the energy modeling process influenced the technological decisions of the design team, I conducted semi-structured interviews with some of the key figures involved with the project. The people interviewed included:

- the owner of a local homebuilding company and a development partner for the project;
- the executive director of a community housing development organization and the other development partner;
- one of the architects responsible for the first set home to be built;
- a code official from Austin Energy who served as an code and energy modeling advisor for the subdivision design and;
- the executive director from the community design center who acted as the project manager for the subdivision and who was contracted to perform the energy modeling.

I audio recorded all of the interviews with the permission of the interviewees and have omitted their names for their privacy. The interviews were conducted between October 2013 and November 2013 and the protocol for the interviews is listed in Appendix A. Important to note, that while I was conducting the interview, the first eight housing units were just finished and occupied. Consequently, none of the interviewees were able to comment on issues regarding the inhabited units. In December of 2013, I re-listened to the interviews and transcribed pertinent portions of the conversations that directly involved information about how the technological decisions were made for the project. Finally, in full disclosure, I was employed by the community design center from July of 2009 until August of 2012 and was directly involved with some the energy modeling work. While this experience, undoubtedly influenced my impressions of the project and energy modeling process, I tried to only present information acquired from the interview process to form the conclusions of this thesis.

Analysis Methods

As a means to interpret the findings of both the historical and qualitative analysis, I prepared mappings which, following Yaneva's ANT methodology, graphically presents and organizes all of the actants involved in the study which I found to be important. This includes not only people, but artifacts as well. Controversies between actants, which I believed to be telling, are arranged graphically and their points of conflict are marked with red connecting lines. These mappings, as developed with a constructivist perspective, should not be taken as hard causal facts. Rather, these mapping represent my interpretations of the circumstances that I believe tell a story about the influence of energy modeling. Another person, with different sets of values most likely could arrange the maps differently. The mappings can be found in Appendix B.

The theory of technological change I presented in this chapter, I believe, is relevant to the study of energy modeling. As I will demonstrate in the forthcoming chapters, energy modeling for code compliance as it is practiced today, follows a particular logic favored by the technical community. But there are many other modes of analysis favored by other groups that considers different measures of success than do the ones reported from the current form of code compliance energy models. SCOT and its related theories begin to give us a model that can explain how one particular technology, such as the current slate of energy modeling software, has come to dominate and shape its field. What makes energy modeling software so relevant to study, is that not only is it a socially constructed technology itself, but it is also a tool which stabilizes the social agreements about building technology and influences to a great extent the technological make-up of the built environment. So if we believe, as many do, that the built environment contributes to environmental problems and therefore needs to be reconsidered, examining the tools in which we use to design and make decisions is just as important at looking at the physical structures themselves.

Chapter 3: Literature Review

In the previous chapter I drew upon the literature of the Social Construction of Technology (SCOT) theories to explain a theory of technological change that accounts for why some technologies advance and are deemed to be successful and why others fail. Central to the theory is that the reason for the success or failure of technologies cannot be ascertained by simply looking at their technical characteristics alone. To do so would assume that technologies fail or succeed based on their technical merits and are neutral to social pressures. SCOT scholars argue against this deterministic position mainly through the concepts of "relevant social groups" and "interpretive flexibility" (Cowan, 2012; Hughes, 1994). Relevant social groups judge and advocate for technologies in relation to the group's unique and particular understanding of a problem that they believe the technology can solve. Insomuch as different groups can construct different problem definitions, technologies can therefore be flexibly interpreted as solving or failing to solve the problem in relation to the group's values. This idea refutes the notion that a particular technological development path is inevitable or is simply an instance of applied objective science. As Moore and Wilson explain:

> Although most of us assume that, for example, the steam engine naturally and logically precedes the gasoline engine, and the gasoline engine necessarily precedes the atomic reactor, SCOT advocates argue that there is no internal logic within artifacts that was not put there by their makers.

And hence,

> There is, then, no neutral and natural evolution of technologies or buildings that precede human interests, there is only the social and political process of deciding how we want to live together and with nature…. Technologies (including buildings) emerge, then, not from the application of pure science, but from the negotiated agreements, codes, and standards that regulate relations between producers, governments, and consumers (Moore & Wilson, 2013, pg. 37).

As I briefly introduced in the first chapter, energy modeling, a new technology, both in its use to demonstrate energy code compliance and as a tool to develop prescriptive energy codes, has become an important technology through which we judge the environmental performance of buildings. With respect to the discussion of SCOT from the previous chapter, I will argue in this chapter, that first, architecture, or buildings, are themselves technologies and therefore should be analyzed as such. And second, because they can be considered technologies, they can be, as previously discussed, flexibly interpreted. In other words, their performance, environmental or otherwise, can be varied and contested. As such, the type of building performance that is measured by energy modeling software is just one of many types building performance – a technical based performance, I argue. And in light of Moore and Wilson's argument above, its incorporation into energy codes, constitutes a socially constructed, opposed to a purely scientific and neutral mode of analysis.

3.1 Technologies

Up to this point, I have referred to technologies in a general common sense way without giving an explicit definition of the term. In order to demonstrate how architecture can be analyzed as a technology, it is important to provide a working definition of the term since the contemporary common understanding of "technologies" is generally limited to electronic devices, software or engineered equipment (for instance, smart phones, web pages or automobiles). A casual browsing of the Technology section of the New York Times online edition or any other of the technology blogs that proliferate on the Internet demonstrates this undoubtedly. But as MacKenzie and Wajcman, as well as Moore and Wilson, explain, technologies are better understood not just as artifacts, but also as the knowledge and practices associated with their use and development (MacKenzie & Wajcman, 1999; Moore & Wilson, 2013).

To this end, Hughes (Hughes, 1994) makes a useful distinction between the term "technical," which he refers to as a physical artifact or characteristics of an artifact, and the term "technology," which he refers to as a system that includes both technical and social aspects (people, institutions, values, economics, politics, etc.). In other words, technology is a "socio-technical" system. A Library, for instance, is generally not referred to as a technology, but rather as a building or a place. But from Hughes' definition, we can understand it as a technology. For instance, the walls, roof and columns as well as the bookshelves and electronic catalogs are the physical components that we associate with a library and is how we recognize it as a place - its technical characteristics. But the library also includes the conceptual organizational strategy of the reading materials, values of knowledge preservation, the civic and democratic services the library provides, as well as our collective agreement that we are expected to return borrowed items. While it might be obvious that a library could not exist without a roof to protect the books from the weather, it is not always in our conscious understanding of a library that without its social aspects, such as the democratic values of equal access to knowledge, the library would not have a reason to exist in first place. A library is not simply a building full of books, but rather a socio-technical system, or in terms of STS scholars, a technology. An interesting conclusion from this definition of a technology is that the library's social characteristics tend to define its nature more strongly than does its technical characteristics. For instance, a library can exist without walls, roofs and bookshelves, as is demonstrated by the trend of universities making their materials available electronically through the Internet. It could not, however, exist in any form without democratic values.

Analyzing a library as technology, however, is not to deny that buildings also have aesthetic or cultural value. Rather, it is to keep discussions of aesthetics from masking other values, such as their role as agents of social values. Moore and Wilson (Moore & Wilson, 2013) continue the argument that since technologies are both technical artifacts and reifications of social values, technologies are intended to be action-oriented. In other words, technologies provide us the means to change or create conditions in response to our values. To demonstrate that architecture can be understood in similar terms, Moore and Wilson performed a comprehensive content analysis of the Journal Architectural Education (JAE) to ascertain what the contemporary discourse of which architecture consists. Their hypothesis is that professionals, historians, critics and theorists do not only write about architecture in terms of art objects, or what a building *means* (as has been the case for centuries prior to the modern era). Rather, the current discourse of architecture is quite varied and is often written about in terms of what they *do*. This, Moore and Wilson claim, is consistent with their understanding of technologies as being action-oriented. In other words, technologies are a means at solving problems, whether that problem is democratic ways of preserving knowledge as in the case of a library or communicating over long distances as in the case of a cell phone. We expect buildings to be action-oriented, as Moore and Wilson's research demonstrates, and therefore we must account for them as being also sociotechnical systems as well as aesthetic ones.

3.2 Performance

If buildings are technologies that are action-oriented and reflect our values, how then do we judge if buildings are successful in this respect? Since building are expensive to construct and are generally designed to last at the very minimum of 20 years, the concept of a building failing is usually reserved for either catastrophes or for such poor construction that they need to be demolished. Therefore we generally, speak of buildings, not in terms of absolute success or failure, but in terms of degrees of good or poor performance. But as the discussion from Chapter 2 suggests, how we measure performance and what we believe to be important performance measures depends on the values and assumptions of the groups responsible for their development.

To this end, Kolarevic and his co-editor Malkawi, in their edited book, *Performative Architecture*, seek to gather various positions on the concept of architectural performance in an attempt to argue that "the meanings of performance in architecture are indeed multiple and intertwined and are irreducible to a simple, succinct definition" (Kolarevic & Malkawi, 2005, pg. 3). Through a collection of essays, Kolarevic and Malkawi assemble ideas of performance that span cultural, social, spatial and technical aspects. Their main intent is to examine how the increasing and varied role of performance considerations is influencing design. But even as the building industry is becoming more concerned with performance, or as Kolarevic says, what buildings *do* instead of what they *are*, he has found that

> As we engaged the theme in its broader dimensions, we discovered that little has been written about performance in architecture. Yet this term — performance — has been widely used by owners, designers, engineers, cultural theorists, etc.

> Performance in architecture increasingly matters; however, it means different things to different people (Kolarevic & Malkawi, 2005, pg. 3)

Therefore, since different measures of success will dictate different solutions to a problem, it is important to understand and be critical of how groups, or in terms of SCOT, relevant social groups, decide to measure performance.

In the following sections, I will present some various concepts of building performance in order to be able to evaluate in which ways the type of performance measured by energy models compare with other types of performance concepts. While I could perhaps identify a multitude of relevant social groups which each measure building performance differently, I will limit the discussion to what I think are three main categories of people directly involved in the design process: owners, occupants and the technical community. For the first two, I will co-opt terms usually used in economics, "supply-side" and "demand-side". I will use these terms to describe how performance measures are viewed from the perspective of either, the owner (the supplier), of buildings and the occupants (the demand users) of buildings. Then, in contrast, I will describe how technical performance measures, in the form of regulations and standards, originate not from the values owners or users, but rather from the economic interests of the technical community.

Supply-Side Performance

The general idea that performance in architecture can hold different meanings to different people is not that radical of a position in everyday practice. Buildings are normally commissioned by owners who have a specific problem that needs solving. Buildings are expensive endeavors and owners will carefully prescribe a building program that attempts to solve that problem (Heymann, 2006). Hence, it is typical that buildings are judged from the owner's perspective, or in other words, the supply-side, using different metrics depending on the type, budget and purpose of their development.

Since architects are normally argents of owners, architects are bound contractually to provide services in line with the owner's performance intentions. The American Institute of Architects (AIA), a professional organization representing the business interests of architects, very carefully writes contracts that stipulate what services that an architect should provide. Commonly in these contracts, the architect is expected to uphold professional standards of care (as generally regulated by their peers) and is expected to research appropriate design criteria for the project type and scope as *specified by the owner* (AIA, 1995). Therefore each project's performance criteria is set privately by an agreement between the owner and the architect. Outside of code requirements and the architect's duty to uphold a professional standard of care (usually the legally minimum standards to protect the health, safety, and welfare of the general public), each building's performance criteria, from a supply side perspective, is project specific and dictated by the owner (AIA, 1995).

For instance, the measure for success for a speculative office building is far different from that of a museum. The speculative office building might be judged whether the rental price per square foot and construction budget matched its pro-forma. A museum, on the other hand, is typically judged on the how successfully it fulfills the cultural mission of its patrons and often if the museum building is received favorably in the popular media. Design accolades might be seen as critical to the success of a museum, while, they might be completely irrelevant to the speculative office building. And at the same time, a generous patron might tolerate budget overruns for the museum, while for the speculative office building, overruns might result in bankruptcy for the developer. Either way, performance measures, at least in relation to programmatic and contractual aspects of a building, are often expected to be project specific, varied and judged by the satisfaction of the owner.

Demand-Side Performance

From the building inhabitants' perspective, or demand-side, performance is judged in a slightly different manner. Whereas the owner might be concerned with the economic or institutional performance of the building, an office worker or building user is usually more concerned with personal comfort or usability. To judge the comfort performance of a building, the most common metric used is derived from a model of whole body comfort, developed by Fanger, called the Predicted Mean Value (PMV) (Djongyang, Tchinda, & Njomo, 2010). Essentially, the PMV method attempts to predict the comfort satisfaction of building occupants through the results of laboratory studies testing human respiration and physiology in response to varying atmospheric conditions. The goal of the methodology is to prescribe temperature, humidity, and air-speed values that at least 80% of people will find comfortable depending on specific anticipated activities and clothing levels. Various standards used by the technical community are based on Fanger's methodology. These standards form the basis of how a building is judged in terms of occupant comfort. Buildings that do not meet these standards are usually deemed as poor performing from the occupant's perspective.

While Fanger's model is generally accepted as a measure of comfort, it is primarily only a design standard. The methodology provides metrics that the design team attempts to achieve. Whether or not these standards are actually met in the constructed building and whether the occupants will actually feel comfortable are judged via a *post-occupancy evaluation* (POE). A POE is usually both a quantitative and qualitative assessment of a building after is has been constructed and occupied. Quantitatively, a POE will examine to what degree the technical systems of the building are working as compared to the building's design intent as prescribed by comfort standards (such as Fanger's model). Measurements of the physical qualities (for instance, lighting levels or air infiltration levels) area taken and compared to the basis of design established during design.

While the technical measurements are helpful in determining if the building was built to its specifications, usually POEs are more valuable in determining the perceptions of comfort and usability from the building occupant's perspective (Preiser & Vischer, 2005). The qualitative component of a POE is normally conducted through a comprehensive survey and interview process of occupants after the building has been open for some time. Occupants are asked if they experience any discomfort in using the building and if the building is sufficient in meeting their expectations. Preiser, a proponent of POEs and academic who has developed a comprehensive method for conducting POEs, which he refers to as a Building Performance Evaluation (BPE), asserts that the greatest value in a POE comes from the knowledge gained from measuring the gap between the stated functional design intent of the design to the perceived performance of the building by the occupants (Preiser & Vischer, 2005). In this way, the performance is not strictly judged based on technical metrics alone. But rather, it is based on the effectiveness that the metrics provide in relation to the building occupants. Once determined, the knowledge gained from POE process can be archived and used to inform future designs. In this way, Preiser recommends a continuous feedback method for informing the design process. Therefore a POE process develops a demand-side concept of building performance that reflects, or at least is influenced, by the building occupants' satisfaction.

The concepts of supply- and demand-side performance measures is rich enough to deserve a thesis topic of their own and much more could be written about regarding the implications of basing performance from each perspective. My intention is to assert that different groups can influence performance measures and each group brings *specific* intentions to a project. In terms of supply-side, owners essentially develop performance measures that facilitate their project-specific needs, primarily programmatic and economic. Demand-side measures, take into account perceptions of performance by those who are not usually involved with the design process. However, specific issues of usability and comfort can be judged empirically based on the occupant's sets of values. Therefore, in both supply- and demand-side performance measures, metrics tend to be project-specific, value-based, and varied.

Standardized Technical Performance

This expectation, though, that performance measures can be project-specific, does not always extend to the building's physical technical performance, at least not in how building are regulated. Buildings are generally expected to physically perform, that is, to resist gravity, keep indoor conditions pollutant-free and keep water out as intended throughout the expected useful life of the building no matter its type. We tend to use quantitative metrics to describe and calculate a building's physical performance in this sense. We calculate and measure, for instance, pounds per square inch of bearing capacity of the foundations or air changes per hour for infiltration performance of the envelope. Performance then of this type is defined as a static property of the building's technical characteristics and is generally universal in nature from building to building. These functions are not expected, nor are they designed, to change. However, as I will argue in this section, technical performance measure are value-based as well and are not as neutral as they appear (Moore & Wilson, 2013).

Technical performance metrics are mostly used by prescriptive building codes that regulate the built environment. These standards provide quantitative means to precisely measure and assist in gauging the soundness of construction. Technical standards are commonly understood as means to protect the health, safety, and welfare of people in the built environment (such as fire protection for buildings or structural provisions for earthquakes) (AIA, 1995). Hence, they are assumed to be scientifically based and neutral to social values (other than those of safety). Energy models, which have been developed as a tool to assist in developing technical standards for energy consumption in buildings, tend to be viewed in a similarly neutral manner. However, Moore and Wilson claim that technical standards (and the methodology used to develop them) also are a means to provide economic certainty to the marketplace. These measurable standards provide protection to building designers from litigation against claims of negligence and thereby protect not only the public, but also the economic interests of building designers and product manufacturers (Moore & Wilson, 2013).

Moore and Wilson trace the historical precedent for these types of technical codes, or as they refer them as, economic codes, to constitutional debates regarding local versus federal jurisdiction rights. In short, the debate over the extent of states' rights versus a strong centralized federal control, extended to the debate over who should be able to regulate the built environment. The debate, which is still healthy today, remained unsettled throughout most of US history and, as a result, the federal government has only provided a limited amount of building regulation. In response, the building industry, realizing the need for standardization for economic purposes and as a means to exert control over regulation, took it upon themselves to write their own standards (Moore & Wilson, 2013).

As such, industry and professional organizations were formed, such as ASHRAE, as a means to self-regulate (Heldenbrand, 2001; Kirkwood, 2010). They did so through issuing standard guidelines and model codes which states and local municipalities could adopt through reference. This is the same process in which ASHRAE 90.1 (and IECC) has become the legally accepted measure for energy use in buildings. These standards specify exact, scientifically derived, and measurable metrics that building components must achieve as means to demonstrate sufficient performance ("Building Energy Codes 101," 2010). However, in light of the discussion above, even these seemingly neutral and scientifically derived standards are socially constructed as well.

For example, while ASHRAE 90.1 and other similar standards do provide a sound logical basis that has helped considerably in reducing the consumption of energy in buildings; they do so with prescriptions that fall within the limited expertise of technical community. These prescriptions, laudably, have guided the building community to more closely examine the types of mechanical equipment we use (Little, 1976). For instance, we no longer use electric resistance heating, an extremely inefficient means to heat buildings, as our primary heating source. In addition, we have greatly improved the thermal characteristic of various building components, such as windows, that further help reduce energy consumption in buildings. However, as I argue in this thesis, the standards do not address equally important components to energy use – the changing physical and social circumstances that affect how people use buildings. Further, as I will argue in the next chapter, these operational circumstances of buildings usually fall outside the expertise of the technical community. Since the standards are written with the technical community's self-interest in mind (Heldenbrand, 2001), the standards assume a static, average condition of the building under particular operating scenarios (Cooper, 1998). This rationalization of the circumstances pertaining to building operations, not coincidently, allows the technical characteristics of a building to become the focus of regulation and, hence, be wholly within the range of expertise of the technical community.

3.3 Inconsistent Energy Modeling Results

This insight, that the methodology behind engineering design standards (and as I shall demonstrate in Chapter 4, also used for energy models) does not necessarily guarantee energy performance for individual buildings, is supported by various studies that conclude that the results of energy modeling analysis for individual buildings often do not match the actual measured energy consumption of the building. I briefly mentioned one such study in Chapter 1, conducted by the New Buildings Institute (Turner & Frankel, 2008), which studied the actual measured energy performance of 121 LEED rated buildings. As previously mentioned, this study found that the energy use of nearly 50% of the buildings studied deviated at least 25% from their modeled projections. There have been other such studies that have found similar results.

Norford et. al. (1994), recognizing this inconsistency, conducted a study to try to determine the factors that cause such discrepancy in energy modeling. In particular, the authors studied factors that had led a DOE-2 energy model of a particular office building to underestimate the actual energy consumption of the building by more than half. Amongst other finding that identified issues with the calculation algorithms of some the physical phenomenon in building, the overwhelming conclusion was that the discrepancy could be attributed to the wrong assumptions the modelers made regarding how the building was to be actually used.

For instance, the building was designed to provide natural day lighting to the open office areas form the perimeter windows. As such, the modelers used a lighting electrical load assumption of 1.0 W/ft2 as specified by the ASHRAE standards at time. In actual use though, the researchers measured that the lighting loads were 1.5 W/ft2, 50% higher than anticipated. Further inquiry to why the lighting loads were so poorly assumed revealed that the open office spaces, originally intended to be mostly day lit, where not being used as such. Head height cubical partitions filled most of the space and thus required supplemental lighting for the office workers. In addition, blinds on the perimeter offices were mostly kept drawn for privacy reasons. These contingencies were not accounted for in the model and consequently the lighting electrical consumption of the building was severely underestimated.

The researchers document other similarly poor assumptions about the building's actual use including HVAC set point assumptions, nightly operation schedules and the estimated amount of office equipment in use. An interesting finding in particular was that part of the energy saving estimated in the model was attributed to a detailed HVAC operation schedule controlled by an automatic control system. The control system was scheduled to turn down the air-conditioning system at night (referred to as a "setback" schedule) and then turn the system back on a few hours before the building was scheduled to be re-opened. However, the building operators found that the system was too complicated to control and consequently the HVAC system was set run at all hours instead of on its setback schedule. As such, the researchers concluded that:

> The story of this building is not a failure to meet informed energy expectations. Rather, those making the energy prediction assumed what might be considered the very best energy behavior on the part of the tenant and building operators and ruled out any specific concern for the tenant's office lifestyle and how the building operators served the tenants. [And further,] One legacy of this work should be considerable caution about what constitutes a low-energy building. Such a label, based on expected or even measured energy consumption, encompasses the building envelope, the HVAC system, how the systems are operated, and how the occupants use energy. Our work has shown that the nature of the occupants' business, including energy intensive facilities, the choices occupants make about how to use lights and office equipment, and the manner in which the conditioning equipment is operated have enormous impact. (Norford et al., 1994, p. 128)

Norford et al.'s study demonstrates that specifying the technical characteristic of a building through assumed performance metrics is not a sufficient means to guarantee low energy performance of buildings. As the study demonstrates, the circumstantial ways the building is used, for instance, the height of the cubical partitions used in open office spaces or the complexity of the HVAC control system, have just as great of an influence on energy use as does the building's technical characteristics.

Even so, using more informed assumptions of how buildings are actually used in order to make better energy consumption predictions, as the study above suggests, I argue, is not necessarily the answer to better energy models. The reason I believe this to be the case, is because even with detailed, credible information about how a building is specifically expected to be used, conditions continually change. Importantly, we never know, for sure, the nature of these changes.

For instance, Waltz (2000), a working engineer and energy efficiency consultant for many years, provides some anecdotal evidence that demonstrates that even when the users of buildings are surveyed in order to improve the quality of the operating assumptions used for modeling, the information they provide cannot be trusted. In a book Waltz wrote as a primer for energy efficiency retrofit modeling, he conveys stories detailing the surprises he has encountered when surveying actual buildings for energy audits. Waltz, as part of his energy retrofit analysis method prepares energy models to analyze the effectiveness of potential efficiency upgrades. Part of this process is to gather information about how a building is operated in order to prepare a meaningful energy model that will analyze the effectiveness of the proposed efficiency measures. Notably, he writes about the importance of surveying a building at night. He suggests this because, over the course of his long career, he has learned to be skeptical of owner's assertions about how their buildings are actually operated. For example, a building's operating schedules are often related to him that reflects the normal daytime business hours of the company. But often, his night surveys reveal that janitorial crews might leave the lights on in the building until 2 a.m. While in another situation, an owner of a company with a significant amount of over-seas business assumed that his employees work late into the night. However, his night survey suggested that this rarely was the case. Waltz's anecdotes reveal that buildings are not used in static or rational ways even if we assume that they are.

3.4 Performativity rather than performance

In the previous section, I described three general understandings of building performance. An owner influenced measure that accounts for programmatic performance; a user measure that accounts for comfort and usability; and finally a technical measure, which, while considering the health safety and welfare of the general public, primarily responds to the economic interests of the private industry and professional organizations that write technical performance standards. The consequence of this last performance concept in terms of energy policy, is that technical standards alone cannot be relied upon to guarantee energy performance. This brief survey of building performance concepts, in agreement with SCOT as well as Kolarevic, demonstrates that there are no neutral, value-free measures building performance.

Accordingly, the idea that technical measures are not the result of, as in the words of Moore and Wilson, "pure science", but rather are influenced by the values of the group responsible for their development, is fundamental to my hypothesis. If, in fact, building performance could be described by science alone, then the technically focused methodology used in energy models would be a reasonably accurate method to predict energy consumption. But since there are various ways in which buildings are actually used, technically focused energy models only represent a narrow understanding of performance. In this next section, I will present a more comprehensive concept of building performance that acknowledges the dynamic, and at times, unpredictable, ways buildings and users of buildings, perform.

A Theory of Performativity

Leatherbarrow, in his essay contribution to *Performative Architecture*, titled, "Architecture's Unscripted Performance," (Leatherbarrow, 2005) argues, that the static conception of performance assumed by technical standards does not account for what buildings actually *do*. He argues that buildings continually adjusts, resists and accepts the ever-changing conditions in which it is a part. The manner, and managers, of its performance changes over time and in response to changing conditions. This is true, he argues, for program, as sometimes warehouses are, for instance, turned into residences.

It is true is for physical performance, such as resistance to gravity, as cracks and settlements demonstrate. And further this is true for aesthetics, as sunlight changes the appearance of materials and the ambience of a space over the course of the day and from season to season.

For these and similar reasons, Leatherbarrow contends performance is better described as an active rather than a static metric. For example, Leatherbarrow speaks of performance in the sense of how we describe what a stage actor does. While the actor follows a script, he or she is always adjusting to the other actors, the audience, the stage props and so on such that the exact nature of the performance can never be fully anticipated, planned or described before the actual event happens. Architecture performs dynamically in this same way – it interacts with changing natural conditions and human expectations of it. It does not have a performance, it performs. So to reduce this performance description to a reductive metric, such as a bearing capacity, an infiltration rate or EUI, does not describe what architecture actually does and how it responds to changing conditions.

The point is not to diminish the importance of the rationalized metrics that are used to design and judge buildings. Parameters are needed in order to make decisions and have some certainty in our actions. The point is that we should not confuse these rationalized metrics for a description of building performance; as performance is much less rationalized and predictable than these metrics imply. In addition, using these metrics as a measure of certitude, as they are used in regulation and are presented to us in energy modeling results, conceals the dynamic character in which buildings actually perform. As Leatherbarrow concludes:

> At the outset I distinguished between two kinds of understanding in the theory of architectural performance: the kind that can be exact and unfailing in its

> prediction of outcomes, and the kind that anticipates what is likely, given the circumstantial contingencies of built work. The first sort is technical and productive, the second contextual and projective. There is no need to rank these two in a theory of architectural performance; important instead is grasping their reciprocity and their joint necessity. If acceptance of an uncertain foundation for performance seems to plunge practice into irrationalism, we need only remember that most of the decisions we make in our daily lives rest on a foundation that is just as uncertain. …For a theory of ***performativity*** we should seek nothing more and nothing less: instrumental reason and the rationality on which it depends, *plus* situated understanding that discovers in the particulars of a place, people and purpose the unfounded conditions that actually prompt, animate and conclude a building's performances (Leatherbarrow, 2005, pg. 18, emphasis added).

Here, Leatherbarrow concludes by providing two broad concepts of architectural performance: "the kind that can be exact and unfailing" and "the kind that anticipates what is likely." Considering the focus of this thesis, importantly, what then is concept of performance used by energy modeling? And further, if energy models are central in our efforts to reduce consumption in the name of sustainability and the models, as I argue this chapter, do not seem to capture the nature of how buildings are actually used and consume energy, why do we use them? As I discussed earlier, Moore and Wilson present a hypothesis that the seemingly neutral technical standards in which we use to regulate the built environment, are actually infused with the values of the professional organizations that develop those standards. Consequently the values of these groups might not strictly align with concepts of performance that we assume the standards represent. In the next chapter, then, through a historical analysis of the development of energy modeling, I will attempt to demonstrate how this disconnect between operating assumptions of energy models and our perceptions of what we expect from them developed.

Chapter 4: History of Energy Modeling

To this point I have described a theory of technological change that proposes that technologies are socially constructed and different social groups can interpret their success differently. Further, buildings can, and should, be analyzed as technologies and therefore, how we measure their success, or performance, is socially constructed as well. In other words, performance measures are not neutral. Accordingly, in the previous chapter I outlined various way in which building are judged and that energy modeling represents just one of the ways in which we measure the performance of a building. At the same time I identified that there are fundamental flaws in the operating assumptions of the current slate of energy modeling software programs used for code compliance. Namely, these assumptions presuppose that buildings can be described in a rationalized, somewhat predicable manner. Rather, I argue that buildings are used more circumstantially than we assume and, further, agree with Leatherbarrow's contention that buildings are constantly adjusting and reacting to changing conditions. This implies that a building's performance, especially in terms of it energy consumption, requires more than just an accounting of its technical characteristics.

Yet energy models tend to use averaged and rationalized operating assumptions to in order to perform its calculations. This has the consequence of biasing the effects of the technical characteristics of a building on its energy performance and is perhaps the reason why energy modeling results have been shown not to align with real world consumption. Why, nevertheless, are the tools we use to gauge energy performance so heavily focused on the technical characteristics of buildings only? A historical analysis of the development of energy modeling will help in understanding why and how energy modeling software are so heavily technically focused.

4.1 The Basics Principals of Energy Modeling

As commonly understood in the building industry, an energy model is a computer software tool that is used to analyze the probable energy consumption of a building over the course of a typical year ("An Architect’s Guide to Integrating Energy Modeling In the Design Process," 2012). There are many end-uses for energy in buildings, including lighting, heating, cooling, ventilation, appliances and anything that a person might plug into a wall socket. Accordingly, a model will perform various specialized calculations (called *sub-routines*) for each of the energy end-uses based on the information about the use and configuration of the building as inputted by the user. The model will total the results from all of the sub-routine calculations and report a total energy use to the user, typically reported in terms of a standard energy unit such as British Thermal Units (BTU), kilowatts-hours (kWh), or Therms of natural gas. While today we typically associate energy models as a tool to determine whole building energy use in relation to our sustainability goals (typically for LEED and other similar regulation compliance) ("An Architect’s Guide to Integrating Energy Modeling In the Design Process," 2012), this was not necessarily the main purpose for which computer energy analysis models were originally developed. Such “certification tools,” and the social conditions that produced them, did not yet exist.

However, energy use was a concern to the heating, ventilation and air-conditioning (HVAC) industry. Of all the energy end-uses in a building, heating and cooling account for roughly 50% of the total energy used ("2003 Commercial Buildings Energy Consumption Survey", 2005). As such, energy consumed by air conditioning equipment must be carefully managed and is a major operating cost consideration. Accordingly, the air-conditioning industry, as well as energy utility companies, have a considerable stake in managing the energy that conditioning equipment consumes. Understandably then, the first attempts at using computers to predict building energy use were developed by the air conditioning industry and utility companies and primarily focused on the behavior of air conditioning equipment.

Since the invention of artificial heating and cooling methods for buildings in the late 19th and early 20th centuries, engineers have struggled with effectively analyzing the heating and cooling loads of buildings (Cooper, 1998). Air conditioning design was more of an "art than a science" (Tull, 1971). Accordingly, the unpredictability of such a large energy end-use created a significant amount of uncertainty for both the emergent HVAC industry and as well as the utility companies (Lokmanhekim, 1971). The air conditioning industry (including engineers and manufacturers) needed to be able to deliver a service that their customers could afford to use (Cooper, 1998) and the utility companies needed to be able to make fair estimates of power consumption so that they may plan for reliable energy distribution (Romancheck, 1971). The HVAC industry and utility companies share a common need to be able to rationally understand how air-conditioning equipment uses energy. We can understand the HVAC industry and utility companies, then, as a relevant social group that shares a common need for a rational method to analyze the effects of air conditioning. Collectively they developed computer analysis methods to do just this.

Thermodynamics, Loads, and the Difficulty of Calculations

Considering the intentions of this group, a large part of the early energy models (as well as today's versions as we will see) were dedicated to calculating the thermodynamic performance of a building. In theory, by understanding the thermodynamic properties of a building, an engineer can design a predictable, properly sized and hence, economical HVAC system. But this is a very wicked and complex problem. The thermodynamic performance of buildings is the result of a highly complex set of interacting phenomenon. The constantly changing position of the sun, the thermal storage properties of building materials and complexities of air movement, just to name a few of the numerous relevant physical parameter, all need to be considered simultaneously in order confidently predict indoor environmental conditions. Its own branch of the natural sciences, such as thermodynamics and fluid mechanics, explains each phenomenon and each of which is each governed by highly complex equations (Kusuda, 1977).

Consequently, manual calculations used to predict indoor conditions are tedious and requires a great deal of mathematical skill to preform (Kusuda, 1977). The typical working engineer does not have the skill or time to perform such tedious calculations, so simplification methods were developed in order for the engineer to reasonably design systems (Cooper, 1998). These simplification methods, though, were not always accurate and could create a liability problem for the engineer if the systems they designed did not sufficiently condition the building (Tull, 1971). To compensate, many engineers would over-size equipment to account for this uncertainty (Romancheck, 1971). But as computers became more accessible in the 1960s, engineers recognized the value in using computers to assist in the complicated thermodynamic analysis of buildings. The first computer programs to analyze the thermal performance of buildings, were not so much concerned, then, with energy use, but rather the heating and cooling loads of the building in order to assist engineers in designing properly sized equipment so as to provide adequate comfort at a reasonable cost.

These computer models were referred to as load calculation models as opposed to energy models. A load, although related to energy use, is not an equivalent metric to energy use. A load is defined as the instantaneous amount of work that a piece of equipment needs to perform in order to achieve a pre-set goal (Kusuda, 1977). Loads are influenced by various factors including the thermodynamic qualities of the building envelope, the amount of people and equipment in each room, as well as the thermostat settings. For instance, a cooling load is the *rate* of work an air conditioner must do to in order to extract the proper amount of heat to make sure that the indoor air temperature remains at a constant, comfortable level. Energy, on the other hand, is the total *amount* of power the equipment uses over *time* and requires knowledge of how the building will be operated in order to calculate. While total energy use is a concern when designing systems, the engineer must first be able to specify equipment that will properly keep conditions comfortable for occupants. To do so, the engineer must determine the maximum load the system will need to handle. If the equipment is undersized, it might not be able to properly remove or add enough heat to or from the space during the most extreme weather conditions. Inhabitants in a building with an undersized system will be uncomfortable during the hottest and coldest days of the year. This might lead to complaints, and even possibly law suites.

In addition, from the utility's perspective, loads are important to predict. The energy grid is a dynamic and complex system. One of the main sources of complexity is that the grid has no ability to store energy; it is only a means of distribution. To do this efficiently, and with least amount of losses, the utility must match the supply of power at any given one time with the current load. If the grid experiences unexpected spikes in loads, expensive on-demand auxiliary power generation equipment must be started in order to meet the demand. When air conditioning equipment first starts up, it produces a high electrical demand. The larger capacity of the equipment is, the higher the spike. Therefore, the utility companies want to make sure that air conditioning equipment is not over-sized and produce unnecessary spikes in demand (DOE, 2014).

Therefore, engineers perform load calculations in order to size mechanical equipment properly. The laws of thermodynamics govern load calculations. Thermodynamics is the science of how energy creates work in a system. The science is based on two fundamental laws, the 1st and 2nd Laws of Thermodynamics, which state, that first, both energy and mass are always conserved and that, second, energy (in the form of heat) always flows form high temperatures to low temperatures (or otherwise known as entropy). So, by the 1st law of thermodynamics, the air conditioner must remove an equivalent amount of heat from the room as is being added to it in order to maintain a constant temperature. The task for the engineer is to predict over the course of a year, the times in which the building will experience the highest loads (or highest rate of heat gain or loss) and then specify equipment that can handle that rate. In order to do this, the engineer needs to account for all of the possible heat gains or losses a building will experience (Kusuda, 1977).

Heat enters (or leaves) a building though windows, roofs and walls. People, lights and equipment also generate heat from the inside of the building. To measure the total heat gain or loss a space will experience, mechanical engineers will first calculate the heat resistance of the envelope, generally referred to as the “u-value”. The lower the u-value (hence greater resistance to heat loss or gain), the less work the mechanical equipment needs to do in order to compensate for unwanted heat loss or gain through the envelope as the result of higher or lower outdoor temperature as compared to the desired indoor temperature. In addition, the engineer must account for the number or people, lights and equipment that will be in the building that release heat inside the space (Kusuda, 1977).

Before the use of computers to manage these complex sets of conditions, the engineer would assume, based on historical high and low outdoor temperatures, the expected extreme weather conditions that the building might experience when making this calculation (Cooper, 1998). This was a reasonable methodology, given the complexity of the problem, since if the equipment can handle the most extreme conditions, then it would be probable that it will also be to handle less extreme conditions. But even still, the method was at best an approximation *since it only considered a static condition* - the one or limited time when the building would expect the most extreme weather condition (Lokmanhekim, 1971). There was no practical way to analyze conditions in between the extremes. With the concerns for managing loads and the high capital cost of equipment, engineers sought more robust ways to predict the performance of the equipment under more realistic dynamic weather conditions and occupation schedules so that they would not feel compelled to oversize equipment (Lokmanhekim, 1971). The computer, along with hourly weather data, afforded them this opportunity because it allowed the engineer to account for not just the single expected extreme condition, but allowed the engineer to analyze the dynamic thermal conditions of a building year round.

4.2 The History of Energy Modeling

The Introduction of Computers

One of the first engineers to recognize the possibilities for dynamic thermal analysis using computers was Kusuda. In the 1960s, the Cold War was ramping up and the threat of nuclear war between the USSR and the US was at its highest point than any other time in history. As such, fallout shelters were constructed by both private citizens and the US government to temporarily house people in case of a nuclear attack. People would need to shelter underground for a minimum of two weeks to allow the nuclear fallout to settle and the surface conditions to be safe enough to evacuate the area. Underground shelters would need to be able to accommodate many people in a small area for long periods of time. Therefore the comfort of people in these confined conditions was important to consider when designing these shelters. Would conditions be bearable underground for such long periods? The Department of Defense contracted the National Bureau of Standards (NBS) to study the comfort conditions of fallout shelter to answer this question. Kusuda, a mechanical engineer working at the NBS at the time who specialized in air conditioning design, was tasked to analyze the thermodynamic performance of these underground shelters (Kusuda, 2001).

Prior to working at the NBS, Kusuda worked for an air conditioning manufacturer, Worthington, designing air conditioning coils. At Westinghouse, Kusuda was first exposed to computer analysis. Worthington pioneered the use of computer analysis to design air conditioning coils and published a paper on the subject in a journal published by ASHARE (Soumerai, Kusuda, & Ditfach, 1959). The programs Kusuda used at Worthington were fairly basic since the company only had access to consumer level computers. Nonetheless, the experience was influential in teaching him the value of computer analysis. When Kusuda arrived at NBS, he then had access to the powerful state of the art computers which only large institutions, such as the US Government, had access. Even so, Kusuda had to convince his managers to allow him to use the computer to perform his analysis of the fallout shelters. The older mangers did not see the value or necessarily trust the methodology computer analysis employed (Kusuda, 2001).

As I mentioned above, the thermodynamic equations needed to accurately predict indoor air conditions are complex and require a great deal of skill to solve. The older managers at NBS were skilled at these manual calculations and trusted them. They did not, however, trust the computer simulations mainly because of the "brute force" method the computer uses to solve the simultaneous equations needed for the analysis. The great advantage computers have over humans is the speed and volume at which they can perform calculations. While mathematical, calculus based, methodologies might theoretically solve the equations more precisely, hand calculations require much time and effort to solve (Kusuda, 2001).

Because of the complexity of the mathematical thermodynamic solutions, manual methods are limited to the capacity of a human to perform them. The computer, on the hand, can use, at great volume, arithmetic and algebraic approximations of the more precise calculus methods to arrive at a similar results more quickly (normally referred to as "numerical methods"). This allows a more complex analysis to be performed that *takes into account the more dynamic dimensions of the phenomenon.*

For example, the manual calculus methods normally used for less dynamic situations is a reasonable methodology if the test subject is relatively straightforward and uniform. For instance, take the example of an analysis of the heat loss of a pipe buried deep underground where the inside temperature of the fluid running through it and ground temperature surrounding it is relatively constant. A representative section though the pipe can be analyzed with the precise calculus methods and the results can be reasonably extrapolated over the length of the pipe since the pipe's conditions remain fairly constant along its length. But in the case of the fallout shelter, the ground temperatures vary greatly at different depths of the structure. This is because the shelters are designed to be constructed relatively close to the ground surface. The temperature of the ground varies more dramatically closer to the surface as opposed to deeper conditions where the ground is more insulated from the fluctuating temperatures above. Kusuda understood this to be a problem for analyzing the fairly shallow shelters and knew that the traditional manual methods of analysis would be too complex to solve in this situation. So, given his experience with computer analysis, he suggested that NBS use their powerful computers to successfully perform the analysis (Kusuda, 2001).

Eventually Kusuda was allowed to use the computers for his analysis. This proved to be successful and Kusuda's calculations were eventually verified empirically by NBS. This led to NBS funding Kusuda's work to continue the development of computer thermal models. While Kusuda's program to analyze fallout shelters proved to be successful, the computer time needed to run the program was not practical. It took over 10 hours to complete the simulation for a study period of 14 days for the shelters. At the time, there were several other researches also exploring ways to use computers for thermal simulations. Two of whom, Stephensen and Mitalas, working for the National Research Council of Canada, developed more efficient routines to calculate heating and cooling loads which dramatically reduced the time needed to run the programs. The methodology Stephensen and Mitalas developed formed the basis for the majority of modern energy model programs, including the first program developed for the private consulting sector. The program, Heating and Cooling Calculations (HCC), developed by a consulting engineering group of engineers committed to advancing the use of computer analysis in everyday engineering practice, Automated Procedures for Engineering Consultants (APEC), was designed to run on small affordable computers available to the private sector. Stephensen's and Mitalas' routines made it possible for simulations to be carried out on modest equipment. As a result, many engineering firms and utility companies began to invest in computer systems to run these heating and cooling calculations (Kusuda, 2001).

ASHRAE Standards and the Post-Office Program

By the late 1960s many organizations were fully committed to computer analysis of thermal and energy loads and several national laboratories, (most notably, NBS), consulting firms and utility companies had robust software projects under development. ASHARE (and their various previous incarnations) had up until this point provided the industry standards for the manual calculation methods for heating and cooling loads. Realizing that their methods were becoming outdated by use of the computer, ASHRAE set an agenda to update their standards for use with computer simulations (Tull, 1971). ASHRAE formed a working group named, the Task Group Energy Requirements (TGER), to standardize computer calculation methods to determine heating and cooling loads in commercial buildings. The group developed procedural calculation standards, largely based on Stephensen's and Miltalas' as wells as Kusuda's earlier work, which other organizations could use to develop their own software packages (Tull, 1971).

The United States Postal Service (USPS) was one of the first organizations to develop one of these software packages based on ASHRAE's procedures. Cleverly named, the Post Office Program, its primary purpose was to help assist in life-cycle cost assessments of the office's building projects. In the mid-1960s this was the most sophisticated program in development. Since the program was intended to help USPS to assess potential capital equipment investments in future facilities, the program was designed to not only analyze the thermal loads of the building design, but also simulate *the operational energy consumption of various HVAC systems* (Lokmanhekim, 1971).

Being able to simulate systems, as well as loads, is crucial when trying to estimate energy consumption of buildings. Conditioning equipment, as explained above, adds or removes heat from the inside air of buildings in order to maintain a constant indoor temperature set point. Following the 1st Law of Thermodynamics, the equipment must add or remove the same amount of heat as is gained or lost by the building in order to maintain constant indoor temperatures. But because of the clever nature of HVAC equipment designs, engineers are able to use the laws of thermodynamics to leverage input energy use so that the equipment can use less energy to operate than it adds or removes from the building. For instance, a heat pump type air conditioning system only requires about a third as much energy to operate as it removes from a space. HVAC equipment are chosen, then, based on their efficiency of how much energy they use to operate as compared to how much they can add or remove. So, the Post Office Program was able to incorporate the efficiency characteristics of various equipment types in order to determine how much energy the system will use based on the cooling or heating loads the program calculates over the course of a year. Finally, the program was sophisticated enough to take the energy consumption calculated and apply an economic analysis to the results to assist in a life-cycle cost assessment of the design (Lokmanhekim, 1971).

These three components of the Post Office Program - loads, systems and economics - would prove to form the basic methodology that all modern energy models would employ and provide the user with a comprehensive process to isolate various components of a building to determine its effect on energy consumption. Iterative studies could be performed to test, for instance, the effects of different window types, building orientations or wall materials on the heating and cooling loads and over all energy use of the HVAC system. Many permutations of building configurations could be analyzed to help the designer choose the optimal building configuration in terms of HVAC energy use. This proved to be a valuable tool for building designers and engineers in assisting with technical decisions. The thermal performance of buildings is, as already discussed, a complex issue. The model allows designers to better understand how the building works as an integrated system and how one seemingly unimportant aspect of the building design might actually affect energy performance. Only by testing variations, can the designer learn how different building systems interact.

For instance, the usefulness of the Post Office Tool was recognized early on in its use (Tull, 1971). Engineers were able to recommend smaller capacity HVAC systems for the USPS buildings because they discovered, through the hourly energy simulation, that the peak loading condition the buildings experience would occur after the post office facilities would be closed. This is a condition, which without the use of an hourly simulation program, would be difficult to discern since usually the hottest part of the day is 3pm or 4pm in the afternoon, before closing hours. But because of the effects of the thermal mass of the building design under consideration, this peak loading condition was shifted to after closing hours. This phenomenon, sometimes referred to as thermal lag, is caused by the excess afternoon heat getting absorbed by the mass of the building before it has a chance to heat up the air inside, thereby delaying the peak cooling loads on the building. Therefore, the designers did not have to specify a system that satisfied the peak cooling condition since the building would be unoccupied at this later time. Using a calculation method that only accounted for the peak design conditions or a less sophisticated model that did not account for thermal lag (such as Stephensen's and Mitalas' equations provide for), the designers would not have a had a good way of discovering this phenomenon before the building was to be built. As a result the designers of the post office buildings were able to specify smaller capacity systems with more confidence (Tull, 1971).

Dynamic Calculations, But of What?

With the Post Office Program and the other similar computer programs, the relevant social group represented by the technical community, seemed to have developed a technology that adequately addressed their desire for more rational ways to analyze the behavior of mechanical equipment. The software gave engineers the ability to analyze the thermal behavior of buildings as weather conditions change over the course of a year and how the technical characteristics of building affect its thermal loads. For instance, the tool makes it easy to determine if in fact increasing the R-value of walls in buildings will lower the cooling load and to what degree. Then, by taking into account equipment efficiencies, a better approximation can be made of how energy will be consumed by the system. Paramount to this ability, was the inclusion of dynamic weather data. The models correctly account for how a building responds to the ever changing and somewhat random weather conditions. This was an important improvement to the previous methods that only accounted for peak weather conditions.

In addition, as the success story of the Post Office Program as described above demonstrates, consideration of how a building is expected to be used in relation to its hourly thermal profile, can help designers make more prudent technical decisions. The designers knew the proposed operating schedule of the USPS buildings and using the knowledge of the thermal behavior of the building, were able to make a sound choice with regards to the size of the mechanical equipment. The energy model allows this type of analysis because it can accommodate operating schedules within its calculations.

However, as Waltz's research reveals, as discussed in the previous chapter, buildings are not always operated in the manner we expect. So while the designers of USPS projects were given specific operations schedules to base their calculations on, there is nothing to say that the building will not be used in a different way than what was inputted into the model. What if USPS, for example, decides to add a night shift to their working schedule a few years down the line? This might significantly alter the loading patterns of the building and might affect the efficiency of the building (if, for example, the smaller sized system could not keep up with the later peak load).

The designers, of course, could easily account for different operation schedules through an iterative process testing different schedules just as they could test the effects of different wall types. The problem is, that while the model can dynamically account for the *building's* ability to respond to dynamic thermal conditions (through the systems' responses to varying loads), it does not examine, on the other hand, how *people* both create and respond to dynamic thermal conditions.

Energy models, as designed by the technical community, have very sophisticated routines for calculating dynamic heat flow and how systems respond accordingly. The operating schedules, on the other hand, are treated as fixed schedules independent of the changing conditions (York & Cappiello, 1982). For example, when the outdoor temperature rises, the model will calculate how much of that heat penetrates the building and will simulate how the HVAC system responds according to the set point of the modeled thermostat. The HVAC systems operate on a fairly basic logic. If the indoor temperature does not match the set point, the air conditioning system will respond in pre-determined, predicable manner – either add or remove heat from the room.

This is true even in more sophisticated models where "economizers" are considered. An economizer is a control device that senses varying environmental conditions and alters the response mechanism of a system. For instance, an outdoor air economizer will sense the outdoor air temperature and switch off the compressor (the cooling mechanism of a HVAC system) if the outdoor air is cooler than the temperature for which the thermostat calls and will draw in outside air to cool the space. In these situations, drawing in cooler outside air is less energy intensive than using the compressor. Economizers can be set up to respond to a multitude of environmental conditions and can be programed into a model to simulate various responses. This represents a very sophisticated control scheme and the models can very effectively analyze the expected saving of using these types of controls (York & Cappiello, 1982).

In this understanding of HVAC control systems, though, human responses are left out of the equation. The model assumes that the equipment will adjust the indoor environmental conditions based on pre-set operation schedules that do not dynamically vary after they have been programed. It assumes that people will always defer to these systems to control the indoor environment.

However, as I discussed in relation to the concept of interpretive flexibility, people do not always respond to technological solution in similar ways. For instance, it is a common experience for one person to feel comfortable in a space where another person in the same room is uncomfortable. It is difficult, if not impossible, to predict how the uncomfortable person might respond. If the person is too cold, they could override the pre-set thermostat (thereby annoying everyone else is already comfortable). They could simply put on warmer clothes. Or, as we sometimes see in open offices, the person could plug in a portable space heater under their desk. How the person responds is difficult to anticipate. The person's response probably has something to do with whether on not they are paying the utility bills, their positions on conservation or their relationship with rest of the people in the room. The point is, though, that people respond to varying conditions differently in contrast to the purely technical and pre-programed responses of the HVAC control systems that get modeled in the software. These human responses to environmental conditions have just as much of an effect on energy use as does how the mechanical systems respond. *Humans are half of the system*.

Methodology Consensus

The accommodation for unpredictable human responses, though, is largely left out of the energy modeling methodology developed by the technical community, nor was is it a significant topic of inquiry during the early days of the software's development. Evidence of this is demonstrated in the papers submitted to the first international conference on the topic of computer simulation of building performance (Kusuda, 1971). The conference held in 1970, titled*, International Symposium on the Use of Computers for*

Environmental Engineering Related to Buildings, was organized by the NBS in association with ASHRAE and APEC under the leadership of Kusuda. Over 400 engineers and architects attended the conference that was organized, with the realization that computers were becoming the standard method of thermal and energy analysis, to facilitate the exchange of ideas between practitioners active in the emerging field. Fifty-nine papers were submitted at the conference and a book of the proceedings, edited by Kusuda, was published in 1971 (Kusuda, 1971). The submitted papers covered a wide range of issues connected to computer simulation in the building industry, including graphical presentation methods, building physics research, algorithm development, and varying examples of the application and development of particular pieces of software. While some papers acknowledged accuracy limits of computer simulation due to the unpredictability of how buildings actually get used, there was no apparent research agenda presented that dealt specifically with this issue. In Kusuda's preface to the published proceedings, he summarizes that further needs are:

> recognized for advanced techniques or new procedures—such as the calculation of accurate room temperature change under realistic climate conditions, simulation of air conditioning system dynamics, optimization of the system and component selection based on relatively advanced mathematical concepts, and effective use of graphical displays or data structuring (Kusuda, 1971, pg. IV))

Absent from this recommendation is the need to research how to incorporate into computerized energy simulation the contextual issues of how buildings are actually operated. The focus, rather, is on how the mechanical equipment responds to variations of the environment and not how inhabitants respond to variations of context or even how overall conditions might change. Further, in the descriptions of most of the software programs, building operation inputs are discussed along side weather inputs as if they a were, similar to the weather, given and unaffected by the conditions of the building (Graham, 1971; Lokmanhekim, 1971; Tull, 1971).

One paper, though, titled: “Energy Estimating – How Accurate?” by Romancheck (1971), an engineer working for the utility, Pennsylvania Power and Light, cautions that the “building unit is a dynamic living entity not a static box” (Romancheck, 1971, pg. 220). He questions the accuracy we should expect from energy models results when the input data is not only approximated, but also when deciding which type of data to use, “[w]ho will decide what is significant and what isn’t” (Romancheck, 1971, pg. 220). He continues, “[w]hat exact value is in computing the sun’s exact angle relative to a new building when someone comes along and builds a structure adjacent to it” (Romancheck, 1971, pg. 220). So while dynamically changing contextual conditions seemed to be at least acknowledged at the conference, suggestion of how this might be address in future software programs was not considered.

But why is this technical bias generally the disposition that engineers hold? Why was there was great concern to model how mechanical systems adapt to changing conditions, even to the degree of developing sophisticated algorithms to model economizers, but not that much concern for taking into consideration of how people adapt to changing conditions or even how the conditions themselves could change? After all, although engineers are responsible for designing systems, they still are in service of people and are concerned with how buildings are actually used. Cooper’s work in the history of the development of air conditioning in American sheds some insight.

4.3 Air Conditioning and the Development of Analysis Methods

The following section recounts the history of the early development of the air-conditioning industry in America from Gail Coopers seminal book, *Air-Conditioning America: Engineers and the Controlled Environment*, 1900-1960 (Cooper, 1998). In her words, the book is about the struggle between two choices:

> The choice of design professionals, engineers and architects, who favor a controlled rational system, a building that is so integrated with its mechanical services that it becomes a machine itself and is controlled by technical authority. A second is the choice of some users, who want an interior that is more comfortable but not necessarily ideal and favor a technology that is above all flexible and responsive to the consumer's needs (Cooper, 1998, p. 3).

Cooper explores this choice through the different historical circumstances between the developments of fully engineered commercial air conditioning installations versus the residential appliance window air conditioner. Important for my discussion, is Cooper's hypothesis regarding the early development of the air conditioning industry where she contends that: "[e]arly air-conditioning systems required that buildings - and, consequently people's activities - be organized around technical requirements." Through her narrative I will demonstrate that this assumption, that engineers designed systems with the expectations that buildings and people should conform to the technical requirements of air-conditioning, is the same logic which compelled the early developers of energy modeling software to concentrate on the technical behavior of the mechanical equipment and discount the effects that people have in the performance of a system. The following recounts her narrative.

The Problem of Manufacturing

Cooper tells the story of the history of air conditioning beginning with the issues industrial manufacturing experienced with contending with varying climatic conditions in the late 19th century. Prior to the means of artificially conditioning factories, the locations of where factories could be built and the efficiency in which they were able to produce goods, was dependent on climatic conditions. The workability of raw materials used for textile production, for example, were highly susceptible to changes in humidity. When the yarn used to weave textiles was too dry from lack of moisture in the air, the motorized looms used in the manufacturing process would snap the strands of yarn. Therefore the factory foremen and workers operating the looms were highly attuned to slight changes of humidity on the factory floor. The idea that factory workers were unskilled labor was unfounded during this time. Part of the skill that workers needed was the ability to judge the climate conditions and adjust the machinery or the indoor climate accordingly in order to maintain production schedules. At the time, though, the only means to adjust the indoor air conditions was to operate the windows to try to control the humidity. However, this only provided for a small range of control. Therefore factories tended to be built in locations that had climatic conditions agreeable to the particular manufacturing process of the factory. For instance, the climate conditions of the northeast United States proved to be favorable for textile production. This posed problems for the factory owners, though, since by being limited to only certain locations, the labor pool available was limited and manufacturing had to be seasonally based. Further because of the "art" needed to control the climate conditions and understand the response of the raw materials to humidity, the labor force possessed a certain amount of leverage since ultimately they could increase (or decrease) production efficiency based on their skills of adjusting to the climate conditions.

Further, since factory floors could be quite large and there were no automated controls for opening and closing windows, the factory workers themselves, being near to the windows, controlled the openings. This set up a conflict between the factory workers and the owners. Often times the factory conditions, either because of the weather outside or because of the certain humidity levels needed for manufacturing, could be unbearable. Factory workers naturally would open and close windows not only to control the manufacturing process, but also to keep themselves comfortable.

So, there was a considerable desire, then, for owners to be able to artificially control the indoor air conditions of factories themselves from a distance. Firstly, this would allow factories not to be location dependent and they could be moved to areas with lower labor costs. Secondly, manufacturing would be able to conducted year round. And thirdly, the control of the indoor environment would be out the control of the workers thereby assuring more consistent conditions and would remove the amount of skill a worker would need to operate the equipment.

Humidity Control

Solutions were sought at first to control humidity, since it was the moisture content in the air that was the most critical indoor condition for most manufacturing processes. Engineers devised equipment that would use fans to blow air over falling water or ice. This would lower the temperature of the air and since cooler air has less capacity to hold moisture, water would condense out of the cool air, thereby lowering the humidity. The comfort provided to workers by the cooled air was only a pleasant by-product of the dehumidification process.

But soon the value of being able to provide more comfortable conditions for people was recognized. A telling anecdote is the story of the graduation ceremonies for Cornell Medical School at the turn of the 20th century. An air conditioning system had been installed in a medical school lab used for dissection of cadavers. The humidity control was needed to help preserve the cadavers. But because of the cool conditions in the room, groups began to gather in the space on warm days. Soon, graduation ceremonies were held in the cadaver room since a gathering of large crowds in other rooms was generally unbearable.

But while the demand for conditioned air began to increase in the early 20th century, the means at which engineers had to predict how their systems would affect indoor conditions was rudimentary at best. The physics of how heat flows in building was poorly understood and so, systems were sized based on rough room volumetric calculations and not explicitly the principals of thermodynamics (it was not until the mid 19th century that the laws of thermodynamics were even considered by scientists). Without this knowledge, engineers could only guarantee that their systems could provide "less" or "more" humidity, not the exacting control modern air conditioning equipment can provide.

Wolff's Rational Method

Without design standards or accepted methods of calculation there was an economic premium available to engineers, who through skill and experience, could specify systems to meet desired conditions. Alfred Wolff, an engineer from New York, was one of the first engineers to begin to rationally analyze the cooling and heating requirements of buildings instead of the common rule-of-thumb based approach. Wolff's innovation took a precedent from German methods at sizing radiator coils, called the "heat-unit" method. The novel innovation of the heat-unit method was that it not only took into consideration the cubic size of the room, but also both the amount of windows and the materials that the walls were made. *For the first time, a link was made between the architectural features of a building and the performance of conditioning equipment.* In addition, Wolff was a meticulous record keeper. He would take measurements of the outdoor air temperatures, the indoor conditions and the amount of people and lights inside the buildings that contained his installations. Soon he began to make correlations to the amount of tons of ice his systems would require to keep temperature at comfortable levels on the inside. In doing so, Wolff also came to realize that people seemed to be most comfortable not only at around 75 degrees in temperature but also around 55% relative humidity.

Wolff was able to rationalize the design methods used to size his equipment around these metrics and consequently became the most successful air condition engineer of his day. Wolff installed some of the first comfort systems in homes for wealthy clients such the Vanderbilts and the Carnegies. Most successfully, Wolff installed a comfort conditioning system in the New York Stock Exchange in 1901. This system used a brine solution piped through cooling coils instead of ice to cool the passing air. Using his past experience, Wolff successfully sized the system (still referred to as the amount of "tons" of cooling, even though ice was not used). Together with the cooling coils, a heating system was integrated into the ventilation system. With outside air passing cheesecloth filters, the system at the New York Stock Exchange could be considered the first fully operable air conditioning system, similar as we know them today.

Carrier and the Desire for Precision

While Wolff could anticipate what the cooling loads should be and design systems to specific capacities, the technology was not yet available to dynamically control the cooling equipment based on exact conditions. It was Willis Carrier who was able to solve the problem of precise humidity control. Carrier, after graduating Cornell University with a degree in mechanical engineering, took a job at a ventilation equipment manufacturer in their research and development department. The company took a commission to install a ventilation system in a multicolor printing press room. Humidity was a crucial to multicolor printing since the paper needed to be passed through the press multiple times for each color. As the humidity changed in the room, the paper would swell or shrink making it difficult to match the alignment of the previous pass. While the company that Carrier worked for was primarily involved with installing ventilation systems, Carrier took it upon himself to try to control the humidity through conditioning the air. Carrier ultimately settled on a fan coil system similar to Wolff's installation at the New York Stock Exchange. His first attempt though was not as successful as he hoped since he severely underestimated the volume of airflow needed to bring the humidity down.

Eventually, Carrier would refine his system by switching from fan coils to fine mist spray chambers to condition the air. By doing so, Carrier was able to create airflow with 100% humidity. Then by either warming or mixing it with cooler air, he could control the relative humidity of the air before sending it to the room. This process proved to be very successful. Noting the success, Carrier would become obsessed with learning how to further control humidity to exact levels. This led to him publishing a paper on what he called, "rational psychromrtric formulae." Psychrometrics is the study of how heat and moisture behave in the atmosphere and relates air properties in terms of humidity and temperature. By developing exact relationships between air temperature and moisture content, Carrier knew precisely how to control the humidity levels in a space and how much energy was needed to do so. Psychrometrics is the basis, to this day, of how engineers design air conditioning systems. As such, Carrier, and the company named for him, have become synonymous with air conditioning equipment.

Guarantees and Conflicts

With the ability to control precisely the humidity of a space, Carrier and the air-conditioning industry could now guarantee precise atmospheric conditions inside of buildings. If a factory owner needed the conditions inside the factory to be precisely 70 degrees Fahrenheit and 40 percent relative humidity, Carrier and Wolff's methods of calculations could prescribe a system that would deliver these conditions. But, in addition to the more sophisticated modes of analysis that the Wolff and Carrier introduced to the engineering discipline, they also introduced a new conflict in *who* controls the environmental performance of a building.

As I described above, prior to mechanically conditioning of factories, a conflict existed between the owners and the workers as to who controls the environmental conditions inside the factory. Workers, quite rationally, tended to keep conditions comfortable for themselves, while owners, with equally rationality, favored conditions best for the raw materials. Since workers normally had direct control of conditions through windows, a conflict was set up between management and labor. The artificial control of the indoor environment had promise to settle the conflict on the side of management, as management could control the thermostat. But since air-conditioning systems were a large capital investment, owners wanted assurance that, in fact, the conditions they specified would be met. In a competitive marketplace for engineering services, engineers then had motivation to provide guarantees for their installations. The problem for engineers, as Wolff's heat-unit method establishes, the architectural conditions, as well as the activities that take place inside the building, have great influence on the effectiveness of the mechanical system. In other words, in order to be able achieve exact conditions, engineers have to make assumptions regarding the construction and the level of activity inside the building and design a system accordingly. If, in actuality, conditions turn out to be different or owners decide to use the building in a different manner, the engineer's calculations will be off and the system will not perform as specified.

So now, engineers had an interest in prescribing not just the mechanical equipment, but also the architectural features and the activity that occurs inside the building. This set up a conflict between owners and engineers in the warranty of air-conditioning installations. As a result, engineers would not offer general warranties. Rather they would place conditions on the warranties that assumed certain conditions. As Cooper explains, "One consequence of this more sophisticated view [that air-conditioning systems are influenced both by the architecture and activities within] was that engineers attempted to freeze both the building and processes [of the factory's production] within the original design parameters" (pg. 29). Cooper goes on to quote a warranty document from an engineer of the time expressing that "*General* guarantees covering cooling, which may be covered by different types of Webster Apparatus cannot be made in satisfactory manner. Installations so equipped are usually designed to meet *specific conditions* and suitable guarantees will be furnished in each case upon request" (pg. 32, emphasis added). In other words, engineers would only guarantee their installations based on the conditions presented to them *at the time of design*. No guarantee is implied if conditions change. Cooper continues by conveying stories of engineers, who being called back to a building by owners' complaints of underperforming systems, would nail windows closed in order to make sure that no source of unexpected humidity would enter the space. So, while a conflict once existed between owners and workers of how the indoor environment would be controlled, owners were now in conflict with engineers over the conditions of performance guarantees.

Expertise

Part of dilemma of this conflict between factory owners and engineers was who possessed superior knowledge and expertise over the proper factory processes. Cooper tells another story of one of Carrier's employees who, while investigating why a gun power factory was experiencing higher levels of humidity than expected, noticed that the factory was running the drying equipment as a continuous dryer instead of a batch dryer. Carrier had designed the equipment to only handle the moisture of certain size batches of powder at a time and not a continuous feed. As a result extra, moisture was building up inside the factory. When asked why the owner was running the dryer as in a continuous manner, the owner replied that he could process more powder in this way and would make more profit. As this story illustrates, the engineer is now in a position where he is arguing with factory owner about the best way for the owner run the factory, an expertise the engineer is not trained to do. But engineers had reason to want to standardize the activities inside buildings. Standardized, and therefore predicable, processes would be easier to design for instead of having to engineer, from scratch, systems to meet individual and changing needs.

But the engineer, negotiating from a position of less knowledge than the factory owner about manufacturing processes, was at a disadvantage in attempting to control the activities inside the factory. Therefore engineers sought, through the quantification of the performance measures governing air conditions as well as scientific reasoning of building physics, to produce operating and building standards that would place the knowledge and expertise of these standards in the realm of the engineer.

For instance, by standardizing the assumed amount of heat that one horsepower produces in an electric motor, engineers could make guarantees based on the excepted design intent and not necessarily on the actual conditions of the factory (if for example, the factory decided to use other than standard motors). As such, professional organizations such ASHRAE began, *in the interests of engineers*, producing standards in which engineers could rely and base their warranty claims on. It is not so much that these standards were not based on sound reasoning, just as the air standards based on Carrier's pyschrometrics were based on empirical and sound evidence. It is just that the standards were techno-centric and of the type that could be controlled by the mechanical equipment the engineers were designing. In other words, the engineers could make a better claim of expertise, and be duly rewarded for it, with the support of technical standards, than they could trying to regulate manufacturing processes (or behavior). If owners wanted guaranteed performance of their HVAC systems, they would need to build factories that meet the industry standards, such as limiting the amount of air infiltration into the building. In this way, the owners were now arguing with engineers about windows instead arguing with their employees.

So, to return to the question of why the engineers involved with development of energy modeling software perhaps only accounted for the mechanical response to dynamic weather conditions, and not how occupants might respond to changing conditions, Cooper's characterization of the early history of air conditions and the methods analysis that were developed, sheds some light. In short, engineers wanted to keep the problem a predictable thermodynamic one - a realm of expertise over which they held control - and not one where they had to predict or account for use patterns or other unforeseen contingencies which were beyond their abilities to control.

4.4 Energy Conservation and Regulation

Up until the 1970s, and the symposium on computer simulation hosted by NBS, the utility of energy modeling software and the air conditioning load analysis methods which the software was based, was to provide credible data on how to size mechanical equipment in relation to life-cycle capital costs of building projects. It was not until the oil embargo in 1973 that the focus of energy modeling turned towards conservation. The Organization of the Petroleum Exporting Countries (OPEC) is a coalition of nations from the Middle East, North Africa, Asia and South America, who collectively control the world market for petroleum. In 1973, for political and economic reasons, OPEC limited the supply oil and raised its price per barrel. This resulted in a worldwide energy crisis as energy supplies became tight in non-OPEC countries (which the United States in not a member). This crisis highlighted the vulnerability of the world energy supply and raised security concerns for nations who relied on foreign energy supplies (Kirkwood, 2010).

This caused the world to more closely examine the manner in which it consumes energy. As a result, the United States acknowledged that buildings account for roughly a third of the total national energy consumption. In response, the National Conference of States on Building Codes and Standards (NCSBCS), an organization formed to address the problem of non-uniformity of state building codes, requested the NBS to develop building conservation guidelines which states could use to better coordinate the national response to the energy crisis (Kirkwood, 2010). The NBS, based on its experience with the thermal building analysis research by Kusuda and others, was in position to best provide the research necessary to write an energy conservation standard. By this time, Kusuda had developed a robust energy analysis program, called the National Bureau of Standards Load Determination Program (NBSLD). In addition, NBS had constructed a 70,000 cubic foot environmental chamber in which test structures could be built and building components could be tested under varying environmental conditions. The chamber could be set to specific atmospheric conditions and the energy use of the conditioning equipment in the test structures could be measured and compared to the modeled predictions. NBSLD program was validated using the test chamber and proved to be a good predictor of the energy use of the test structures. The results were published and the computerized analysis of energy use gained the credibility needed in order to form basis energy code standards (Kirkwood, 2010).

In 1974, based on their computer simulation analysis methods (which included Kusuda's NBSLD program), NBS published a document titled, *Design and Evaluation Criteria for Energy Conservation in New Buildings*. This document was not intended to be an enforceable code. Rather, the document was intended to provide guidance to states in crafting their own energy codes on their own terms. However, in 1975, the US Government passed the Energy Policy and Conservation Act, which required states to adopt energy codes regulating the use of energy in buildings in relation to national standards. With this new law, there was a need to develop enforceable standards at the national level. At NBS' recommendation, NCSBCS engaged ASHRAE to transform the NBS document to an enforceable consensuses based standard. ASHRAE, realizing the importance of this task, not only for the country, but also as a means for ASHRAE as an organization to influence energy policy, agreed to write the standard. The result was ASHRAE 90-75 and it represented the first codified national energy standard (Kirkwood, 2010). ASHRAE 90.1 (a later, and continually revised version of 90-75), as discussed in early chapters, would be become the basis for most energy codes and well as the standard for green building programs.

With ASHRAE 90-75, states had enforceable language to regulate energy use as required by federal law. As a means of enforcement, the federal law provided sources of funding to be made available to states that enacted compliant energy codes. As a result, states created energy offices in charge of developing and evaluating proper codes and distributing federal funds associated with the law. California was one of first states to pursue compliance with the new federal law and took advantage of the available federal funds. With the assistance of the federal Energy Research and Development Administration (ERDA, which would eventually be renamed The Department of Energy (DOE)), the newly formed California Energy Commission (CEC) enhanced the USPS's Post-Office Program (the most advanced software of the time) to provide a tool to assist California in developing energy codes based on ASHRAE 90-75 (Haberl & Cho).

This tool, named Cal-EDRA, was not only used to help evaluate the prescriptions of the code, but was made publically available to practitioners and municipalities to use to demonstrate and evaluate compliance with the code. Eventually, with additional support of the Lawrence Livermore Labs at the University of California, Cal-EDRA would be updated and rolled into a DOE sponsored research project to develop a software tool specifically for code development. Eventually renamed, DOE-2, the software would be become the preeminent energy modeling calculation engine and is still in use today (Haberl & Cho). DOE-2 is also the main component of EnergyGauge USA, the software that was used to model the energy performance in the forthcoming case study.

Discussion

It is hard to over-state the significance of the influence of energy modeling software in the development of energy codes (which primary purpose is to address energy consumption in the building sector). From the first instance of energy code regulation in the United States, energy modeling software was inextricably linked. However, as demonstrated by the history presented in this chapter, the research used to develop the algorithms of the software was based on the science of predicting heating and cooling loads for mechanical equipment. Accordingly, *the intention of the foundational software used for code compliance was not energy conservation*. Rather the software was derived from the interests of the technical community to predict and control the use of mechanical equipment *under specific conditions* as understood at the time of design. Therefore, when the technical community organized to develop energy codes, it was quite rational for them to develop a methodology, centered on asset modeling, that only considered average and standardized operating conditions.

Yet, as Leatherbarrow and others have noted, buildings are not static artifacts and it cannot be assumed that they will maintain the same conditions as was presumed at the time of their design. This includes the physical condition and soundness of construction, as well as how different people, in different circumstances, understand the proper ways the building should be used. While predicting, in a rational manner, how mechanical equipment will behave given a certain design parameters is important to understanding how energy is consumed in a building – it is just half of the equation.

Even so, as the software has been adopted from a tool to assist in HVAC design to a tool to analyze energy consumption for conservation purposes, the focus of software revisions has still been on how the software can better simulate the mechanical components of a building under varying climatic conditions and not necessarily how operational or other contextual conditions might change. Sullivan and Winkelmann (Sullivan & Winkelmann, 1998), in a study for Lawrence Livermore Berkeley National Laboratory, list the revision history and major software improvements of DOE-2 over the course of its development history. Nearly every update is concerned with improving the simulation accuracy of the technical aspects of a building. The revision history log demonstrates how little effort has been invested to include simulations of how energy is consumed under dynamic contextual operating conditions, including providing how use patterns might change or vary from design assumptions. Again, the historical basis for this bias can be traced back to how the thermal building analysis methods developed in the early days of the HVAC industry were only concerned with the given design parameters. Due to the nature of mechanical engineering and HVAC industry at the time, there was no reason to account for the possibility of other operational conditions (see Appendix B for graphical mapping of findings).

A report from the National Research Council examining the benefits of the research and development initiatives of DOE, demonstrates the consequence of this bias. The report indicates that, while DOE-2 did accurately predict the energy consumption of building that adhered to the operating assumptions used to model buildings, “DOE-2 substantially overestimated the energy savings (i.e., by as much as 100 percent) in monitored buildings that were not operated as initially assumed in the DOE-2 simulations” ("Energy research at DOE, was it worth it?," 2001). The report continues that:

> While it is clear that software programs and information technology can play an important role in building design, it is very difficult to precisely estimate how much energy can be “saved” by DOE-2 or any other analytical tool. At best, DOE-2 allows predictions of how much energy *might* be saved over a period if certain building components are assembled in specified sets and only under certain specific assumptions. ("Energy research at DOE, was it worth it?," 2001, pg. 100)

However, by its compulsory nature, energy codes do expect that the technical energy efficiency measures prescribed the energy model will, in fact, result in lower consumption. But as the above study indicates, as well as the many other studies cited in this thesis, the technical decisions enabled by energy models do not necessarily result in lowered energy consumption, at least not on a project-specific basis.

The NRC report continues, “nevertheless, DOE-2 did demonstrate that software tools can facilitate energy efficiency improvements, and it helped redefine the *mode of thinking* in the energy efficiency industry” ("Energy research at DOE, was it worth it?," 2001, pg.101, emphasis added). However, if the energy model represents a certain, technically biased, *mode of thinking*, how has this mode of thinking manifested itself in the architectural design processes and to what effect? In the following chapter, I will present a case study of a project that was significantly influenced by the use of energy modeling. The project, a sub-division in East Austin, aspired to provide housing that was not only extremely energy efficient, but also extremely affordable. Given the circumstances of the project, the project team was required to demonstrate, through energy modeling simulation that the units will perform to a certain level of energy efficiency. The use of energy modeling represented a new analysis method for most of the people involved in the design decisions. Therefore, how the model, and its technical bias, influenced and compelled the team to make certain technical decisions can be examined.

Chapter 5: Case Study

In the previous chapter, I argued that besides the consequence of not consistently achieving the stated goal of energy use reduction, the use of energy models, because of their technically biased methodology, might preclude designers from exploring other beneficial energy conservation strategies which are more socially and contextually based yet might not be able to be analyzed with the current versions of energy models available. The following case study was designed to understand the consequences of the technical bias embedded in energy modeling on the architectural design process and if it does preclude solutions outside of its logic. In the following sections, I will, based on interviews with project stakeholders and using Yaneva's mapping methodology of describing in detail the circumstances of the project, analyze the design process for a 60 unit, single family housing subdivision in East Austin.

5.1 Project Overview

The sub-division is a joint development venture between a local homebuilder ('the builder'), with strong ties to the East Austin neighborhood in which the project is built, and a local community housing development organization ('the CHDO' (pronounced: chode-o) whose mission is to provide affordable housing to residents within the same neighborhood. In addition to the affordability and community development aspirations of the project, Austin Energy (AE), the city-owned electric utility, has agreed to provide solar panels at no cost to the project. In return for the panels, AE required that project be designed to be *net-zero capable*. Net-zero energy buildings are designed to a standard in which, on an annual basis, the building consumes as much energy as it produces on-site. To review, as previously mentioned, this is achieved by reducing the energy loads (or increasing energy efficiency) to the point in which it is economically and physically feasible to produce as much energy as the building consumes through on-site renewable sources (generally solar, wind and geo-thermal). AE has agreed to provide the solar panels in exchange to be able to use project as a pilot study to test the feasibility of the city's recently passed Climate Protection Plan which requires that by 2015, all new homes built within the city must be net-zero capable. To qualify for the solar panels, AE required that the project team develop energy models of the home designs that demonstrate the expected annual energy use of the designs.

The project team also included a community design center ('the design center') to assist with project management as well as four architectural design offices ('the architects') to design the actual homes. In order to fulfill the requirements for the pilot study, the architects were contractually required, as stipulated by AE, to produce designs, as demonstrated by the energy model, that were 54% more efficient than the current energy code at the time of design, the 2006 International Conservation Code (IECC). AE recommended that the project team use the DOE-2 based, EnergyGauge, as the code compliant energy modeling software. Since the architects did not have the capacity to build the energy models themselves, the design center was tasked with managing and building the energy models for the architects. In addition, the homes were limited to a tight $125 per square foot construction budget to meet the affordability goals.

In the following section I will describe the circumstances of the design process and the corresponding relevant social groups to hopefully gain a meaningful understanding of how the required energy modeling process influenced the design.

5.2 The Relevant Social Groups

The Climate Protection Plan (The City of Austin and Austin Energy)

The City of Austin has had a long history of being on the forefront of environmental policy and helped lead the way in developing regulations to address climate change issues in the United States. In 1990, Austin Energy created the first green building program in the nation, named Austin Energy Green Building Program (AEGBP) ("White Paper on Sustainability," 2003). In general, green rating programs, such as AEGBP, are voluntary incentive programs that encourage the design of sustainable building projects through recognition and certification. According to Austin Energy:

> Developing and maintaining our own Austin specific rating systems allows us the flexibility to carry out Austin's aggressive climate protection goals. We use these ratings to pave the way for energy and building code changes that will reduce building energy use. This continuous improvement cycle benefits everyone in our community ("Austin Energy Green Building Program Homepage ", 2014).

As noted in Austin Energy's description above, the city uses the green building program as means to test and advance aggressive code changes to achieve their climate protection goals. Accordingly, the measures that are promoted in the program are designed in such a way so that they could be enforceable in future code revisions. Following this logic, AEGBP has adopted ASHRAE Standard 90.1 (for commercial buildings) and the International Energy Conservation Code (IECC, for residential buildings, which references ASHRAE 90.1 as an energy standard) to set energy efficiency goals within the rating program. For instance, projects earn points towards a rating by demonstrating above code (i.e. ASHRAE 90.1 or IECC) energy savings through an energy model simulation of the proposed design.

The success of AEGBP led to other cities creating green rating programs for themselves and in 2000, with AEGB as a precedent, USGBC created the nationally focused LEED rating system. Austin, wanting to remain a leader in the climate change regulation and in recognition of the greater extent of climate concerns, in 2007 passed aggressive legislation to further reduce the carbon pollution associated with the city. The plan, called the Climate Protection Plan (CPP), contains sub-plans to address specific measures to reduce the greenhouse gas emissions that the city produces. One such sub-plan is the Housing and Building Plan. Its stated goal is to "make Austin building codes for both residential and commercial properties the most energy efficient in the nation" (*Austin Energy Resource, Generation, and Climate Protection Plan to 2020*, 2007). One of the sub-plan's strategies to accomplish this goal is to revise the city's building energy code to require that by 2015 all new homes constructed will be net-zero energy capable (*Austin Energy Resource, Generation, and Climate Protection Plan to 2020*, 2007).

Logically, to determine if in fact a house is net-zero, one has to only gather the annual energy bills of the home and compare the results to the amount of energy the home produced over the course of that same year. But as a matter of policy and code compliance, the definition is much more contested. It is difficult to provide regulatory approval for a net-zero home before it is built since it is impossible to know that a building is truly energy neutral before it is occupied. Therefore as a matter of policy, specifications and *design performance* standards need to be created in order to judge whether or not a building is considered net-zero *before* it is built.

To devise these standards, the city council commissioned a taskforce to study the ways the current energy code at the time could be modified to achieve this elusive goal. Named the Zero-Energy Capable Home (ZECH) taskforce, the volunteer citizen group was assembled with members from the building, design and construction fields, environmentalist, concerned citizen, building scientists and city staff. Their findings concluded that in order for a home in Austin Texas to be net-zero capable, it would need to be 54% more efficient than the 2006 IECC. The taskforce then recommended that energy code amendments be passes in order to achieve this citywide goal ("Final Report to Council," 2007).

By using code amendments as a mechanism to pursue policy, the ZECH necessarily needed a way to use the provisions in the code to define the parameters of a net-zero energy house. The ZECH task force was able to do this through the energy modeling procedures as specified by the IECC. The ZECH taskforce used this comparative energy analysis method, as specified in the code, to determine the above code energy saving rate needed to achieve to net-zero capable designs (ones that could physically accommodate and with reasonable cost, sufficient on-site renewable energy). They then designed and analyzed, through this same modeling procedure, prescriptive measure code amendments which resulted in raising the efficiency of the prescriptive code requirements. For instance, the 2006 IECC specifies that wall insulation for homes should be R-13. But the task force, through the use of energy modeling, determined that greater savings cold be achieved at a reasonable cost by mandating that, in addition to R-13 wall cavity insulation, a layer of continuous R-2 rigid insulation be added to the outside of the wall studs. This measure reduces the amount of heat flow through the normally un-insulated wood studs, sometimes referred to as thermal bridging. To implement this and many other prescriptive measures, the city of Austin would pass ordinances amending the IECC model code.

Realizing that substantial changes to the building code, though, would not be economically or politically feasible, the task force recommended that incremental changes be adopted in parallel to the normal three-year code revision cycle that the city already follows. The first change would start in 2007 by proposing amendments to the then forthcoming 2006 IECC to raise its efficiency by 11% (such as by requiring continuous insulation). In 2009 amendments would be proposed to bring efficiency up to 30%, then 48% by 2012 and finally 54% in 2015. Effectively then, with the city council's approval of the plan, the definition of a net-zero capable home in Austin would be a home that is 54% more efficient than the 2006 IECC ("Final Report to Council," 2007).

This represented an aggressive policy on the part of the City of Austin. While the ZECH taskforce provided thorough analysis of the feasibility of this aggressive code, the definition adopted by the task force was based only on energy modeling results. Therefore, empirical evidence was needed to confirm that the progressive (and potentially controversial) code amendments would indeed produce net-zero homes within reasonable costs. So in 2007, Austin Energy, appropriately through the supervision of AEGBP, sought out a pilot project that they could use to demonstrate the feasibility and effectiveness of the code.

AEGBP identified a project that could serve as pilot. The project, a sub-division in the low-income Montopolis neighborhood in southeast Austin, was being developed on city-owned land by the city's affordable housing department, Austin Housing Finance Corporation (AHFC). The city council approved money for Austin Energy to provide solar panels to the project and an agreement was reached with the AHFC to partner with AEGBP to design the homes. Staff architects within Austin Energy designed a few model homes using energy modeling analysis methods as provided for in IECC. Unfortunately, due to financial issues, the project was shelved before it was built.

The Developers

Meanwhile, another sub-division of similar size was being planned in East Austin on the site of a former informal dump. The homebuilder partner of the development team originally purchased the land for the project. The homebuilder's intention was to develop the land for profit, although they also saw the project as an opportunity to develop affordable housing as a means to serve and improve their community. Traditionally, they have been a homebuilder and not necessarily a developer. They wanted to develop the land in a manner that would best benefit the community and so, lacking development experience, especially in affordable housing, partnered with the CHDO.

The CHDO brought to the project experience and the knowledge of how to secure city and private subsidy to make the affordability goals feasible. The CHDO has a history of over 30 years of working in the neighborhood and are skilled at combining various funding sources together in order to get projects built. They currently manage over 140 units in East Austin and primarily serve a population that earns less than 60% of the regional median family income (MFI). The successful track record of the CHDO has resulted in a positive reputation of the CHDO in the community. Together, the homebuilder and the CHDO, would co-develop the project and ensure that all 60 planed units would be affordable to families who earn no more than 60% MFI.

The Consultants: Architects

The CHDO is a small, community non-profit controlled by a board of directors consisting of residents within the Central East Austin neighborhood area. The board is tasked with not only maintaining the financial health of the CHDO, but also representing the community's strong desire to maintain the character of the neighborhood in the face of strong gentrification pressures. An early important decision made by the board was to hire four different architecture firms to design the homes as a means to diversify the architectural character of the large subdivision so keeping with the board's strong desire to preserve the neighborhood character.

All of the architects chosen were locally based small firms each of who had prior experience working with the development team. At the time of writing this thesis, only a set of four duplexes has been funded and built (out of the 60 total single-family and multifamily units planned). Hence, I have focused my research on the architect who designed these first 8 units. A sole practitioner, the architect, has built a business and reputation for high design single-family homes. He came to the project, though, from a sense of community service. Often the architect provides pro-bono services for community focused projects and while he provided services for a fee on this project, his involvement is as much do with his desire for community service, as it is a business venture.

The Consultants: The Design Center (project manager)

Even though only 8 units have been built to date, all 60 units, the brownfield restoration, which was required, and the site infrastructure plans were all designed at a single time. Being a small organization though, the CHDO, had to hire a consultant to assist with this large development and design process. The CHDO hired the design center to help with project management services. A non-profit itself, the design center's mission is to "improve the quality of life for all by providing sustainable design, planning and development services to low- and moderate- income individuals, families and neighborhoods." Primarily, the design center works for other non-profit affordable housing providers, such as the CHDO, and brings strong environmental and social justice values to the projects in which they are involved.

The director of the design center is an architect himself, and had previously been involved with AE in helping to design the net-zero homes for their original and defunct Montopolis pilot project. When hired on for this subdivision, with knowledge of the shelved AE pilot project, he informed the development team that AE had funds available to provide solar panels on a project of similar size. The director then made the connections and helped broker a deal between the development team and AE to use the sub-division as pilot project to test the feasibility of the 2015 net-zero capable homes policy.

5.3 The Design Process

The design process for the homes proved to be a unique experience for all the members of the project team (the homebuilder, CHDO, the architects and the design center). The primary goal for the project's developers was to create affordable housing for the residents of East Austin. This part of Austin had traditionally been a poor and underserved community with mostly minority residents. However, with a location only a few miles from downtown, East Austin, for the past decade has faced strong gentrification pressures. Many long-time residents have either been forced to move out because of escalating property taxes or compelled to do so because of the high price for which they can sell their property. Both the homebuilder and the CHDO wanted to ensure, then, that this project would attract either residents who had previously moved from the neighborhood or current residents who needed a means to be able to stay. It was important that project serve the needs for the local residents and did not, similar to the growth trends in the area, turn into a symbol of the rapid development impacting the neighborhood.

Therefore the designs of the homes were critical and much effort was expended to vet the designs with the community and its representatives. Two public community design charettes, facilitated by the design center, were held to solicit feed back from the community. These meetings influenced the site planning and unit mix of the project. In addition, final approval of the home designs would be provided by the volunteer, neighborhood based board of directors of the CHDO. Most importantly, from the perspective of the board of directors, was that the designs needed to "feel like the homes" the people in the neighborhood were accustomed to and, most importantly, were affordable. While energy efficiency is an important component to affordability aspects of the development, from the perspective of the developers, the high-performance net-zero goal was not their primary concern. Rather, it was an opportunity that was presented to them and they saw value in the prospect.

On the other hand, AE was primarily concerned with the energy performance of the subdivision. The affordability component, while a general civic concern for the utility company, was more important to them in order to demonstrate that net-zero homes could be regulated and built at reasonable cost. In terms of the energy performance of the designs, then, AE would be the group to give final approval. Funding approval was based, as mentioned above, primarily on the modeling results.

The design center would provide the modeling services for all of the architects. The process would work by the architects first submitting schematic designs to the design center. The design center would model the designs based on guidance from AE. Again, since AE's primary objective was to determine if the net-zero capable homes were possible to be regulated through the building code, the modeling process very closely aligned with the provisions in the code. The IECC (as well as ASHRAE 90.1) prescribes very specific operating conditions that must be used for the energy model. For instance, the code prescribes that temperature set points used for the model must set at a constant 78 degrees for cooling and 68 degrees for heating. Other aspects, such as building size and assumed occupancy numbers amongst others assumptions, are also prescribed as part of the protocol in the code. AE closely reviewed the models to ensure that they were produced with the appropriate protocol similar to what is called for in the energy code. Once approved, the design center would return the results to the architects and recommend adjustments to their designs in order to meet the energy modeling goals.

Each architect participated in the process in different ways. For instance, the architect for the first 8 units was the most proactive of the team. He learned how to perform the modeling himself and would use the energy model with his own internal design process. The reasons he gave to take on the modeling responsibilities himself, was to gain a better understanding of how the technical decisions were made. Since he, as a licensed professional, is liable for the designs, he wanted a measure of control in the process. In addition, he found it time consuming to transfer the information needed to model the designs to the design center. This was a frustration he expressed in general regarding energy modeling, in that the models did not “play well” with the other software he uses for his own production workflow.

In contrast, another architect, one who had worked with the CHDO previously on other projects, approached the design process as he had in other projects he had completed with the CHDO. This architect designed the homes as he normally would and allowed the design center to critique the design based on the modeling results. For instance, the architect would adjust the amount and locations of windows in the normal design based on the energy performance as related to him by the design center.

When the design process was first on its way, the CHDO was a bit skeptical of the process. The director of the CHDO's first impression was that they could probably achieve a net-zero design by following the design prescriptions for a 3-star (out of 5) rating under the Austin Energy Green Building Program. Three-star was the normal standard to which the CHDO builds their other properties and the director had been pleased with the resulting energy use of those properties and was not sure what additional information the energy model would contribute. Although, most of their other properties do not have solar panels, he admitted that he could not be sure that they would be net-zero if panels were added. So, the director, over time, did come to see the model as a means to validate his already held assumptions.

However, as the design team realized through the process, using the currently available standard high efficiency building specifications (such as those prescribed by AEGB), while close to hitting the target, still produced a result that was off by about 5% or more from the goal. Further, due to the requirements of another private funding source, the units were required to be mechanically ventilated with a certain amount of outside air rather than allowing residents to ventilate by opening windows using their own judgment. This, from a purely energy minded standpoint is problematic. Great effort was expended to design buildings that were very airtight. Allowing conditioned air to escape the building or un-conditioned air to leak in causes the air-conditioning equipment to expend more energy. So, in response, many green building guidelines suggest constructing tight building envelopes to prevent any un-wanted air from infiltrating.

Airtight buildings however, as subsequently discovered, have caused an indoor air quality problem in new buildings. While, older, leaky buildings, lose a lot of energy through the envelope, the fresh outside air prevents contaminants from accumulating inside the building. The accepted strategy to combat this problem is to mechanically introduce, in a controlled manner, as opposed to uncontrolled through leaks in the envelope, a specified amount air into the building based on how many occupants are expected to be using the building. However as the architects struggled to meet the efficiency goals as prescribed by the energy model, any excess energy use from mechanical ventilation was unwelcome.

The most energy efficient way to mechanically ventilate a building is to use an *energy-recovery ventilator* (ERV). An ERV is a fan unit with a built in heat exchanger that has the ability to exchange heat and moisture with the corresponding exhaust air in order to minimize the amount of extra heat or cooling the air-conditioning needs to apply to the fresh incoming air. This type of equipment is not normally used in housing construction and is an expensive addition to the project.

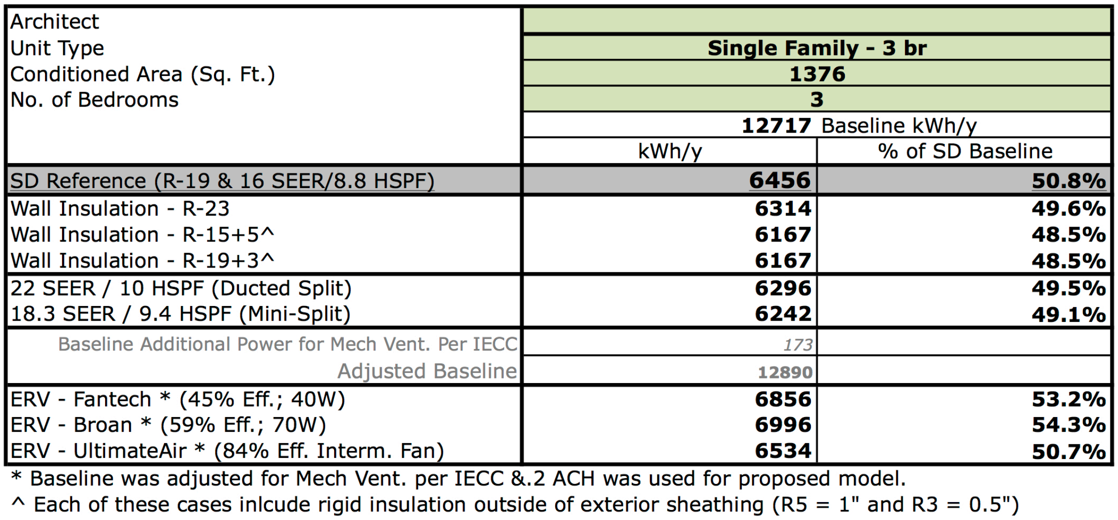
The addition of the ERV highlighted a trend in the project up to this point where, in order to achieve the last few percentage points to meet the efficiency goal, more expensive technology was needed. For instance, in order to meet the cost budget, the designs were originally specified with conventional (although high performing) direct-expansion air-conditioning systems. To meet the last few percentage points an even more efficient system would need to be used. These included either variable speed inverter air-conditioning systems (know as 'mini-splits') or geothermal heat pumps that exchange heat with the ground through deep bore holes underneath the house. Both of these options are expensive and needed to be examined with great care if they were going to be used. In addition, the architects, who contractually were obligated to produce designs that both met the efficiency requirement and the tight $125 per square foot budget, were nervous that the costs were getting out of hand. In response, the design center organized a brainstorming session with the architects and Austin Energy to strategize ways in which the team could meet the goals in the most economically responsible way.

The meeting proved to be fruitful and many ideas were considered. A main topic of discussion at the meeting was the accuracy of the energy modeling results. Team members asserted that they believed that the designs would actually perform better than the models were predicting. Further, there was skepticism that the model actually represented the occupancy patterns that the inhabitants would exhibit. In particular the models predicted that roughly 25% of the energy consumption was attributed *miscellaneous electric loads* (MEL). A MEL, or as it is sometimes referred to, a plug-load, are all of the energy end uses from household or electronic devices that are used intermediately by the occupant (such as televisions or hairdryers). Built into the energy models are algorithms, which, based on empirical usage studies in relation to air-conditioned floor area, will predict the amount of MELs for the design. These algorithms are normally "back-boxed" and are not directly controlled by the modeling practitioner and therefore there are no energy efficiency measures that can be applied to the model that could reduce the value of MELs that the model calculates.

Even so, ideas were suggested at the meeting that measures, such as energy monitoring systems, can and have been shown to reduce the amount of plug-loads in buildings by giving occupants feed-back information on their energy use. As such, the design team inquired if Austin Energy would allow a reduction in the miscellaneous load automatically reported by the energy model if they included an energy monitoring system. AE ultimately decided not to allow any reductions since model could not predict how and what type of electronic devices people would ultimately use in the buildings. There was more confidence in the algorithms representing average use conditions already included in the model. Therefore it was decided not to reduce the results as given.

However, the model does report, separately from the miscellaneous loads, the amount of energy used by the clothes dryer. The CHDO director suggested, then, that based on experiences with his other properties, their tenants use clotheslines to dry their clothes quite often. The model on the other hand, assumed that an electric dryer would always be used to dry clothes. As such, the amount of energy that the model reported attributed to clothes drying was quite high in their opinion. This observation did seem quite reasonable to all at the meeting and the project team then negotiated with Austin Energy to allow the clothes drying energy expenditure reported in the model to be cut in half if the design team designed a clothesline into the project.

As a follow up from the meeting, the design center prepared a sensitivity study, which systematically analyzed the effectiveness of successive design alternatives, to examine the options that were discussed (Fig. 3). A 1,376 square foot, 3-bedroom home design, was used for this particular study. The measures studied included different wall insulation schemes (R-23; R-15 + R-5 continuous; R-19 + R-3 continuous;), different HVAC technologies (22 SEER direct expansion; 18 SEER mini-split), as well as three types of ERVs (45%, 59% and 84% recovery efficiencies). In addition, the sensitivity study included the assumed 50% energy saving from including clotheslines in the design. From the analysis, the “best-case” scenario included the 18 SEER mini-split, R19 +R-3 insulation scheme and the 84% efficiency ERV. In total these measures account for about 3% additional savings in the modeled energy use. In comparison, the assumption that the use of clotheslines would reduce the dryer energy expenditure by 50%, showed a 5% overall energy reduction for the home.



Architect		
Unit Type	**Single Family - 3 br**	
Conditioned Area (Sq. Ft.)	**1376**	
No. of Bedrooms	**3**	
	12717 Baseline kWh/y	
	kWh/y	% of SD Baseline
SD Reference (R-19 & 16 SEER/8.8 HSPF)	**6456**	**50.8%**
Wall Insulation - R-23	**6314**	**49.6%**
Wall Insulation - R-15+5^	**6167**	**48.5%**
Wall Insulation - R-19+3^	**6167**	**48.5%**
22 SEER / 10 HSPF (Ducted Split)	**6296**	**49.5%**
18.3 SEER / 9.4 HSPF (Mini-Split)	**6242**	**49.1%**
Baseline Additional Power for Mech Vent. Per IECC	*173*	
Adjusted Baseline	**12890**	
ERV - Fantech * (45% Eff.; 40W)	**6856**	**53.2%**
ERV - Broan * (59% Eff.; 70W)	**6996**	**54.3%**
ERV - UltimateAir * (84% Eff. Interm. Fan)	**6534**	**50.7%**

* Baseline was adjusted for Mech Vent. per IECC &.2 ACH was used for proposed model.

^ Each of these cases inlcude rigid insulation outside of exterior sheathing (R5 = 1" and R3 = 0.5")

Fig. 3. Sensitivity study prepared by the design center. Pyrek, A. [Courtesy of the design center].

Depending on the particular home design, the measures suggested by the sensitivity study, as well the reduction in clothes drying energy, brought the designs to either meet the prescribed 54% efficiency rating or at least within 3%. The design center, acting as project mangers, gave instruction to the architects to complete the designs based on the information from the sensitivity study and prepare a set of drawings for preliminary pricing. They further instructed the architects to include bid alternatives for the various measures from the study so that they could, based on cost/benefit analysis, choose the final design specification.

As mentioned earlier, only 8 units (4 two-unit, stacked duplexes) have been built to date. The units ended up being built with measures suggested by the energy modeling sensitivity study and were built to budget. In addition, the architect was able to, probably because of his proactive stance towards the modeling process, fine tune the design such that is cost effective to use a geo-thermal heat pump HVAC system. As a result, the modeling demonstrated an efficiency rating 2% higher than the 54% target.

5.4 Findings

The units have been occupied since October of 2013 and preliminary consumption data has been collected by the design center and made available for use in this thesis. Surprisingly, the data is similar to the NBI report cited earlier, that while on average across the 8 units, the total cumulative consumption average matches the modeled predictions. Based on the limited 3 months of consumption data, the model predicted that all 8 units would consume 4,638 kWh during this time. The actual consumption data showed that units cumulatively used 4,405 kWh, 5% lower than predicted. On an individual unit basis, though, the results show a great deal scatter. For instance, 5 of the 8 units demonstrate discrepancies between the modeled resulted and measured consumption by at least 15% with two units showing a discrepancy of 25%. Although data is limited, the scatter in the results does demonstrate, even with the careful consideration of the technical characteristics of the proposed designs, that the prediction of how building will be used based primarily on its technical characteristics does not always tell the full story. A more interesting finding from this case study is not the consistency of the actual energy consumption versus the modeling results, but rather how the process affected the technological decisions for the project.

From the detailed description of the intentions and the nature of the design process as described above, we can begin to see the definitions of relevant social groups with respect to the energy model. To summarize, I identified four relevant social groups involved in the design process: 1) the City of Austin; 2) The Developers; 3) The Architects; and 4) The Design Center. Each had unique intentions and relationship with respect to the energy model. The City of Austin's main concern was to determine if the Climate Protection Plan and its enforcement though the energy code could be achieved within reason. AE viewed the model from the standpoint of code enforcement and viewed the results in a regulatory manner – either the designs complied with the model and the specified protocol or they did not.

The Developer's main intentions were to develop a project that serves their community and is affordable. The environmental aspects of the project, while a concern of the developers, were pursued opportunistically and only after the affordability goals were met. The energy model was seen as a technical issue best handled by the design professionals. As such, they held some skepticism in the use of the model, and for the most part, they deferred to the design professionals regarding the model. The exception being the case of the clothes dryer when they felt it necessary to question the validity of the model's assumptions.

The Architects, while perhaps amiable to the community service and environmental aspects of the project, were first concerned with fulfilling their contracts. They either, as in the case of the architect of the first 8 units, were engaged with the energy model themselves as means to understand how decisions were made. Or, the architects took the position in which they wanted clear directions on how to proceed. In both cases the model was a contractual gateway that needed to be addressed in an efficient manner with respect to their workflow.

And finally, The Design Center, took a facilitator's and environmentalist perspective to the project. The director of the design center originally initiated the net-zero aspect to the project by connecting AE to the developers as part of fulfilling one of the design center's core missions – sustainable design. Their oversight of the modeling process, while on one hand was necessarily needed in order to manage the compliance aspect of the project, they also found ways in which to contextualize the modeling for the specific goals of the project. This intention was best carried out through the organization of the brainstorming session. They were the group primarily responsible for researching the different ways to comply with both AE goals and the developers. For instance, researching the ERV systems options as well researching energy monitoring systems to help the residents save money (and as a means to receive credit in the energy model for the MELs). Their relationship with the model was an iterative and interpretive process.

As the above summary illustrates, the concept of the energy model had different meanings to each group (see Appendix B for graphical mapping of findings). Each group had different expectations for the model and interacted with it differently. However, even though each group carried deferent goals for the project, the technical choices that the design team had to make were primarily influenced, and some cases mandated (as in the case of the ERV), by the results of the energy model. The preliminary results suggest that the buildings are generally performing as expected on average. Examining only the final kilowatt-hour results of the model, though, can be a misleading measure of performance. While perhaps prescribing technological measures that appear to have satisfied the efficiency goals, what was not always obvious to the group was the how the assumptions of the model's methodology compelled certain technological choices which might have other consequences which affect the success of the project in their own terms. In other words, the energy model was not a neutral scientific tool to measure the performance of the building, but rather carries with it certain assumptions about performance and which variable are important to consider. In the next section I will highlight some of these consequences as means to identify insights on how the methodology can be improved in include a broader range of variables.

Clothesline

While it is certainly possible to add a clothes dryer schedule to the energy model that assumes that the tenants would use the clothesline for half of their drying needs, the assumption would be just an educated guess to the actual usage of the dryer. The assumption's accuracy would be just as relevant as would be the assumption that the electric dryer will be used 100% of the time. However, AE granted the design team credit for half of the modeled energy use of the dryer for simply adding a clothesline into the design. But how do we know that the tenants will actually use the clothesline? The answer, candidly, is that we do not know, for sure, if the tenant will use the clothesline or not. So while the energy model did allow for the possibility of analyzing various ways the building could be used (dryer or clothesline), it provided no practical way to analyze the likelihood of how it might be used. And so, based on an educated guess, AE credited half of the energy use for simply including the clothesline in the design because the model could not provide a means to more intelligently analyze the situation. However, does this mean that we cannot ever determine the *likelihood* of how the clothesline will be used?

The architect, in his interview, presented an interesting insight to potential success of the clothesline. The first set of duplexes that have been constructed are stacked; meaning that one unit is built on top of the other. One of the features the developers wanted incorporated into the designs was a front porch. For the lower unit it was possible to design a front porch on the ground level outside their door, but for the top unit, this would not be possible. An upstairs balcony, as well, was not included because of the added expense. To compensate, the top unit was given a designated area on the ground floor to serve as their porch and outdoor living area. The architect, then, in response to the clothesline request, designed space for the clotheslines in each of the unit's outdoor spaces on the ground floor. This satisfied the requirement to modify the modeling results and no further analysis was taken.

But there are factors that can be examined which might give clues, or at least probabilities, of how the clothesline might be used. For instance, the clothesline for the unit on the ground floor is fairly accessible; it is just outside the front door. However, for the upstairs unit, their clothesline is down the stairs. Is it fair to assume that both units will use the clothesline with the same frequency? If we assume that the tenants are perfect economic actors and that energy and cost savings alone will dictate their behavior, then maybe we can assume that both units will be used the same way. If we factor the specific circumstances of the configuration of the design, though, we might conclude that it is more inconvenient to use the clothesline from the upstairs unit. It is probably a safe assumption, then, to presume that the tenants on the ground floor might use the clothesline more often than the tenant on the top floor and hence will affect how much energy is used in each unit.

These circumstantial considerations of how the building might be used, though, is not accounted for in the model. Yet, the assumption that simply adding a clothesline will result in reducing the electric clothes dryer usage in half accounts for, significantly, 5% of the total savings in the model. When compared to the suite of other expensive measures analyzed in the sensitivity study (extra insulation, high performance HVAC and

ERV) that accounted for only 3% savings, an error of 5% or more can significantly skew the cost benefit analysis.

The potential inaccuracy of the educated guess about the effects of including a clothesline into the design is not a fault of the energy model per se. But the absence of any means to properly evaluate the very real energy savings a clothesline, or other occupant behavioral issues, highlights a shortcoming of the technically biased methodology. Since, the model does provide a means evaluate the efficacy of other technical components, such as the ERV, the saving assumed from the inclusion of such technical measures is deemed to be a requirement in order meet the regulation standards. However, the provision of a clothesline might result in same energy savings at much lower cost and with less complication. But because the model does not appear to analyze the impact of the clothesline as accurately as an ERV, it is difficult to incorporate the clothesline as a strategy. So depending on the assumed efficacy of the clothesline, perhaps it was not necessary to use the geothermal HVAC system? Or maybe a more efficient system is needed if the clothesline turns out to not be as effective? But in order to determine how effective the clothesline will be, the manner in which it is included in the project and the circumstances for energy saving which it provides is needed, and I argued, can be analyzed to the same degree that the ERV can. The point is, that the circumstances of the building design, *in addition* to the technical characteristics affects energy use. When both are not considered the true efficacy of individual measures are hard to ascertain.

Affordability

The CHDO director related a benefit of receiving an estimated energy use prediction from the modeling process that he had not expected at the beginning of the project. The city's affordable housing guidelines prescribe a definition of affordability based on a tenant's income. In order to be considered affordable, the tenant cannot pay more than 30% of their income for housing costs. For example, if a person earns $12,000 a year, then they would be expected to pay $3,600 a year, or $300 a month for housing costs. This number, though, also includes utility costs. So the CHDO has to subtract from the $300, a pre-determined estimate of the utility costs based on historical data provided by the city for the type of unit that is rented. So hypothetically, if the city data suggests that a one-bedroom apartment normally has about $50 a month in utility costs, the CHDO would have to subtract that amount form the rent. The tenant would pay $250 in rent and $50 in utility costs.

If, on the other hand though, the CHDO pays for the utility costs as part of the rental agreement, then they can charge the full $300 to the tenant for rent. The tenant still pays the same total monthly amount, $300, but now the CHDO can collect the entire amount themselves. This is an easy decision to make for the CHDO if the energy model predicts the total monthly energy use will be less than the city's pre-determined allowance. If so, it will be better financially for the CHDO to include the utilities as part of the rental agreement. Therefore the credibility of the model is important for the CHDO's decision whether or not to include utilities in the rental agreements. If the model over-estimates the amount of energy savings, the CHDO will be obligated to pay the higher utility costs.

This introduces a liability to the CHDO. Since, from the tenant's perspective, if the cost of utilities is included in the rent, the tenant does not have a price motivator to limit energy consumption. For instance, with respect to the issues of the clothesline from above, if the tenants are not being charged for energy use, and it is more convenient to use the clothes dryer inside the unit than to walk downstairs to use the clothesline on the ground floor, chances are they will use the inside electric dyer more often than clothesline. Yet since these contextual factors are not entered into the model for consideration, the cost benefit analysis cannot be made based on the modeled results alone. If the CHDO takes the energy modeling results without understanding the nature of its assumptions, they might be persuaded to make a decision based on incomplete information, which could have severe financial consequences.

Importantly then, the manner in which the energy model reports results is significant to understanding the limitations of the modeling process. As described throughout this thesis, the energy modeling results of asset models are more reliable across a large building stock as opposed to any single building. Yet the results of asset models used for code compliance report absolute consumption predictions (in either energy units or as, sometimes required by code, cost units). So when presented to a stakeholder not directly involved with modeling process, as was the case for CHDO director, the energy model results appear to be an accurate prediction of the *specific* project. This misunderstanding can have the consequence of persuading imprudent decisions by the owner or decision maker, if the confidence of the results is overstated.

Slab Edge Insulation

One of the issues the builder raised was the use of slab edge insulation. Adding slab edge insulation is an energy saving technique for buildings with a slab-on-grade foundation, as is the case for this project. Normally, a slab-on-grade foundation is a monolithic slab of concrete roughly 4 to 12 inches thick that is poured directly on the ground. Insulation is placed vertically around the perimeter of the slab in between the slab edge and the adjacent ground and is use is to prevent heat from escaping (or entering) the building from the perimeter of the slab. Intuitively, it might seem more logical to place insulation in between the bottom of the slab and on the top of the ground to prevent heat transfer between the two large surfaces. However, since buildings are usually conditioned and remain at narrow temperature ranges (68 to 78 degrees normally), and because of the high heat storage capacity of the ground, the temperature of the ground directly beneath the building will remain within the same temperature range as the house. Essentially, because the house remains at constant temperatures, the house and the ground will reach temperature equilibrium. Therefore because there is no temperature differential, there is no need for insulation between the two.

Ground temperatures immediately adjacent to the house, however, can vary greatly. Since there is no structure insulating the ground adjacent to the building, the ground temperature fluctuates with the outdoor air temperature. This creates a situation were there is a temperature differential between the ground directly beneath the slab and the ground adjacent to the slab. This temperature differential will open a pathway for heat to transfer from inside the house and through the slab edge to the adjacent colder (or warmer) ground and represents a liability to the thermal envelope of the building. This potential for heat loss is mostly a problem at the slab edge as opposed to the center of the slab since heat transfer is a function of not only temperature differential but also distance. Therefore by installing vertical slab edge insulation the building will perform better in terms of its thermodynamic response.

Adding slab edge insulation is a rational measure to pursue, and the model can calculate the thermodynamics that govern this behavior in buildings and can demonstrate the energy saving from its use. However, as the builder recounts, the addition of the insulation measure posed problem for the construction process. At first, concerned with added cost and the fact that the homebuilder, not being accustomed to including slab edge insulation, did not properly prepare for the inclusion of the insulation. Slab edge insulation is something that is usually not installed in Austin. It is used more commonly in colder climates where the ground freezes for longer periods of time. There might be various reasons why it is not used in Austin. Although, I did not research the reasons for its limited use in Austin, I can reasonably speculate the since Austin is primarily considered a cooling dominate climate, slab edge insulation probably does represent that effective of a measure as opposed to when it is used in colder climates. Consequently, as the builder explains, he did not properly prepare, out of lack of experience with the building technique, for how the insulation gets installed. Because the insulation is simply a 1-inch sheet of foam placed on the outside of the slab, when it is exposed above the grade, it is vulnerable to damage and difficult to repair. The builder had difficulties installing the insulation and protecting it throughout the construction process.

Further the builder related that he was not sure of the utility that insulation provided. Had he known, he said, or been more informed of how the insulation worked to reduce energy use in the building, he might have been able to bring his own practical building experience to the construction detail in order for it to be better installed and presumably more robust. He reiterated this same sentiment later in the interview when asked what, if anything, he would suggest to improve the process. He said that he was not involved with the energy modeling process and wished someone had explained the results to him in terms that he was used to. His main concern, stemming from his affordability goal for the project, was to keep cost low. Sometimes, because the terminology was not consistent with normal performance measure he was used to, he was not able to bring his expertise to help improve the efficiency of the building and make decision both cost and performance reasons.

The above story illustrates that there can be a disconnect between how the implementation of technology is assumed to be seamlessly applied in the model, yet in real life, the particular building culture of the place influences the actual implementation. The inclusion of edge slab insulation might not have been a surprise to a builder in a northern climate. But in Austin, it was a technology that was not readily known. This caused installation problems and, since the homes are only a few months old at this time, how the edge slab insulation will be maintained cannot be determined. But it is reasonable to assume that if people are not accustomed to this feature on their home, chances are that it might not be maintained well. Hence, the energy savings attributed to this measure in the mode might degrade over time. Again, these contingent factors is something that is not accounted for in the model.

In all of the cases described above, a common theme is that while each group was given the same data from the model, each group needed to interpret the data in their own terms. This is consistent with techno-economic framework of energy models as described in chapter 3. This framework assumes that all that is needed from the technical community is to provide data to consumers and the consumers, being rational actors, will make the appropriate decisions. The problem, though, is that because the nature of energy modeling is biased towards a particular logic, a technical one as demonstrated in chapter 4, it is difficult for each group to make prudent decisions based on their each unique definition of the problem. In the following chapter, then, I will make recommendation, based on my findings, how we might better improve the methodology of energy modeling in order to facilitate more sensible decision-making.

Chapter 6: Conclusion

In this thesis, I demonstrated how the origins of the energy analysis methodology used in the energy modeling software tools used today for energy code development and compliance, can be traced to the early days of the air conditioning industry. Importantly, these methods were not developed to ascertain actual energy use of the systems they were designing. Rather, the methodology was used to specifically, and rationally, analyze the behavior of air conditioning systems under assumed conditions in order to properly size the equipment for comfort. The ways in which the design conditions might change were not of particular concern to mechanical engineers. Their primary objective was to guarantee their systems under the specific conditions for which they were designed.

Prompted by the energy security crisis in the 1970s, the energy modeling software methodology developed by the air conditioning industry was enlisted for energy use regulation. The same rationalized understanding of building performance held by the technical community was incorporated into the methods used to regulate energy consumption, which heavily relied on the use of energy modeling. A decade later, with the recognition of the environmental impact of fossil fuel consumption (mainly in the form of electricity), these same compliance tools used for code enforcement also became the means used to grant economic incentives and bestow civic esteem through environmental certification of individual buildings.

However, as the studies cited in this thesis demonstrate, the methodology's ability to predict actual energy consumption on a project-specific basis is inconsistent at best. The primary reason for the lack of consistency of asset energy modeling results for individual buildings, I argued, is that only a single, rationalized and averaged, operational scheme is considered by a code compliance energy model at a time. Further, no analysis methods for how the operational characteristics of a building might change, evolve or differ from the assumed average conditions is provided. While the methodology developed by the technical community might be effective in regulating the thermal efficiency required for the greater building stock (as demonstrated by the studies showing that the models are effective in measuring average energy use over a large sample size), its effectiveness in predicting the energy performance of an individual building is disputed.

The consequence of inconsistent energy modeling results for individual buildings is that the technical decisions we make, in conjunction with the use of code compliance energy modeling software, might not help us to lower the actual energy consumption of a particular building. Further, as the case study in this thesis alludes, the use of energy models compels designers to employ certain technological solutions, sometimes against their professional judgment. In addition, code compliance energy models tend to preclude the analysis of strategies that fall outside the logic of the model, yet might be proven to be effective otherwise.

Discussion

The above conclusions are consistent with Guy and Shove's (Guy & Shove, 2000) hypothesis, presented in the opening chapter, which contends that the technical community operates within a *techno-economic* framework. As mentioned in the introduction, a techno-economic paradigm assumes that consumers of information are rational economic actors and will, given sufficient knowledge and the absence of any market distortions, make rational, and *therefore similar*, choices with regards to efficient and proper use of technology. Therefore the use of rationalized and average operational assumptions for buildings as inputs into energy models is consistent with a techno-economic approach to regulation.

However, as discussed in Chapter 3, people use buildings in varied and unexpected ways and buildings themselves are constantly reacting to the changing conditions in which they exist. Therefore, while analytic methods that rationalize the dynamic nature of building performance might be good predictors of average energy use across a varied building stock, they are not good predictors of actual, real-world energy use of individual buildings.

For example, if a building that was designed to be naturally ventilated at night in order to reduce cooling loads during the day, was built in a city where there was a persistent pollution problem (Beijing for instance), and the occupants do not open the windows at night as intended, then the energy consumption predicted by the energy model would overestimate the actual energy savings of the building because it would assume that the building would always be used as intended. However, different groups of people working and inhabiting different spaces prioritize or understand energy use differently. *Energy*, for a building science researcher, has a different meaning, in a practical sense, than for a homeowner. While perhaps a researcher will describe energy in terms of kilowatt-hours (kWh) and speak of it in terms of the laws of thermodynamics and efficiencies, the homeowner might think of it as a cost of living concern or a luxury of convenience; they each demonstrate "interpretive flexibility."

To the researcher there is no doubt about the "proper" way to use the building. But, to the homeowner, perhaps concerned with the health implications of smog in their city, – *a factor not readily entered into an energy model* - the choice to leave the windows open at night in the example above is not so obvious. It is not necessarily the occupant's improper behavior in this case that prevents the proper use of the building, but rather more often, the particular condition of the building's context that prohibits the intended use of the building. This realization, I argue in this thesis, is crucial to understanding how to address the energy problem in a practical way.

From this perspective, the pollution in the city, in the example above, becomes a full-fledged actor (or "actant" in Actor-Network Theory terminology) in the energy consumption of the building since its presence directly influences how the building is operated. The pollution's influence on energy use is just as important as the thermal performance of the walls or any other technical characteristic of the building. The exclusion of pollution, in this case, as a full-fledged actor prevents a comprehensive understanding of the problem. As such, an analysis that did not include the conflict between the night ventilation strategy in relation to the pollution in the city, and only considered the context-free technical characteristics of the building, would not be able to uncover a significant factor contributing the building's energy use.

Recommendations

The example above suggests that more types of data and information needs to be able to be entered into energy models to allow for a richer understanding of how energy is consumed in buildings. This information must not only include a wider range of extra-technical factors, but also information about how these factors might change or evolve overtime. For instance, in terms of the night ventilated building, there might be times of the year when pollution levels are greater than other times. If this site-specific information could be added to the energy analysis, the model could be used to analyze how the building might be used differently during times of high pollution- knowing that it is unlikely that night ventilation system would be used during these times. The results of this model would then reflect a more accurate portrayal of the changing the conditions in which the building is operated. Both the technical (thermodynamic) and social (inhabitant's behavior in relation to context) can be accounted for in this process. This enhanced analysis contextualizes the technical knowledge and compels more prudent action.

It is not necessarily that energy models are incapable of this type of analysis currently. While I have focused my research on asset energy models used for code compliance, there are many other types and uses for energy modeling other than for code compliance. Customized energy models, used by energy efficiency consultants for economic analysis purposes, for instance, do have the capability of accepting complex schedules into a model. With these customized schedules, an analyst could input annual pollution data for the example above and associate the information with the cooling system schedules. This would result in a much more accurate prediction than a standardized schedule which might be prescribed by an energy code.

The problem, though, and the reason why my research presented here is important, is that for code compliance purposes, building designers are forced to use the code-mandated, rationalized building assumptions. Yet it is not always transparent, especially to the stakeholders not directly involved with the modeling process, that the results of asset energy models only represent an efficiency rating and not an accurate prediction of future energy use.

Therefore, as a conclusion and recommendation for further research, I suggest that energy modeling methodologies used for code compliance incorporate more contextual data in its analysis. This is especially important with the recent movement to incorporate measurement and verification requirements in codes and green building certifications. For instance, the Living Building Challenge, perhaps one of the most progressive green building certification programs to date, requires that the energy performance of the building be verified one year after completion in order to achieve its certification. In addition new versions of the LEED rating system, also provide additional credits for post-occupancy verification of energy performance. While the verification requirement is not mandatory yet for LEED, as pressure mounts to accelerate the reduction of carbon emissions, more regulations are going to require verification of lowered consumption and not just efficiency ratings. So, there will be a need, as verified energy saving requirements become more common, for a tool that will not only provide verification of code compliance and efficiency, but of actual energy performance as well.

Khazaii (Khazaii, 2012), a mechanical engineer provides a model of how this might be accomplished in his doctoral thesis. Khazaii suggests that probabilities and performance ranges should be added to the input parameters of energy models. Making similar arguments that I have made in this thesis, he contends that the idealized metrics we use to describe the technical characteristics of buildings rarely are precise measurements of the actual performance of the building component. For instance, manufacturing standards for most buildings products allow for tolerances in their manufacturing process. So while a roll of batt-type insulation might be rated at a certain R-value, the manufacturing process might hypothetically allow for that the R-value to vary plus or minus five percent. However, when entered into an energy model, only the given “nameplate” value is used. In reality, as Khazaii argues, the insulation value that gets installed in a building can vary from the value entered into the energy model by up to the maximum manufacturing tolerance allowed.

In addition, I contend, the quality of the installation of building components can vary quite considerably as compared to the ideal installation assumed in the energy model, as similarly discussed in Chapter 5 by the homebuilder in relation to the slab edge insulation. As well, the conditions of building components degrade over time. For instance, insulation will settle within a wall cavity, leaving patches of wall area exposed, or ballasts in fluorescent light fixtures will lose their efficacy over time. This argument can be made for most building components including the efficiency rating and installation quality of mechanical equipment or window assemblies. This suggests that there is a great deal of uncertainty in the performance of actual building components we use yet which are not accounted for in what Khazaii calls "deterministic" energy models used for code compliance. Khazaii reports that these uncertainties in the manufacturing process of building components could account for up to a 15% discrepancy in energy modeling predictions as compared to measured results – similar to the studies I cited in this thesis. However, as I have suggested in this thesis as well, Khazaii notes that these uncertainties are not evident in the results produced by deterministic energy models. Therefore simply through manufacturing inconsistencies, an energy model might compel a building designer to specify more or less insulation than is actually needed or might compel the designer to over or under specify the appropriate efficiencies for mechanical equipment. Khazaii suggests, then, that energy models should "be revised so that it can allocate uncertainties to the inputs of the design building and present a probabilistic output."

While Khazaii focuses his analysis on the technical components of a building, the methodology he proposes could easily be extended other operational assumptions of the model. For instance, take the example of the clothesline from case study in Chapter 5. Through a negotiated process with Austin Energy, the design team, with their specific knowledge of the residents, was able to reduce the energy expenditure of clothes dryer reported by the model by half by including a clothesline in the design. In the chapter, I argued that the reduction of 50% of the energy use was somewhat arbitrary because there was no practical way to analyze the expected use of the clothesline. But in fact, I claimed, that there were circumstantial factors that might affect how the clothesline might be used. For instance, because the clothesline is located on the ground floor, the downstairs unit, with easier access to the clothesline probably has a better chance of using the clothesline than do the people in upstairs unit. If there was a way to input the difference in probabilities that each unit would use the clothesline, as Khazaii proposes for inputting the performance range of technical components, then the model could produce a better prediction of the probable energy use of each unit based on its contingent use. This method provides a means for the design team to use their situated knowledge of the design contingencies to populate the model with more relevant information.

The suggestion to add contingent performance probabilities into an energy model used for code compliance poses a problem for regulators, though. First, by allowing the user to manipulate the performance probabilities of building components, there is potential for the user to be able to "game" the model by adjusting the performance tolerances used to his or her benefit. Khazaii poses a solution to this problem by calling for manufactures to publish more data regarding the measured performance tolerances of their products. This will allow the values entered into the model to be verified by a code official, not dissimilar to how nominal performance data is verified currently.

While perhaps possible for mass-produced, standardized building products, verifying the probabilities of varying ways a building can be operated over a large population can be difficult (and is one of the reasons why the current code compliance energy models rely of average information). For instance, without any empirical evidence, how would a code official be able to verify the probability that the tenant in the downstairs unit, in the example from the case study in Chapter 5, would in fact be more likely to use the clothesline more often that the person in the upstairs unit. This is a difficult problem, yet is important to address if more a contextually based mode of analysis is going to be pursued.

This suggests that further research is needed into the factors that influence occupant behavior. While, I cannot suggest a specific suggestion in this thesis, recent developments in "Big Data" demographic information analysis, where large amounts of data can now be more readily collected, analyzed and parsed into useable and highly specific metrics, is promising in this respect. Newly installed "smart" utility meters on most homes and businesses, provide more granular consumption data than ever before (minute by minute electricity consumption data as opposed to the old manually read meters which only provided monthly data). This data can be linked with building type information and other building design and demographic characteristics to build a more sophisticated and empirical understanding of circumstantial energy consumption. This type of data collection might be able to provide evidence, for instance, that people living in temperate climates who have easy access to clotheslines, tend to use them instead of electric dryers x% of the time. This information could be collected in a repository available to energy modelers to provide inputs and for code officials for verification. While seemingly a large task, this is not too dissimilar to the amount of research that the technical community has invested in material research for the thermal performance of thousands of building products, such as published in the ASHRAE Fundamentals Handbook. The difference, I suggest though, is that the information be presented as a range of probabilities instead of a single rationalized number, as is the case for most performance data available currently.

The second problem for regulation is the metric used to determine compliance. Currently, an asset energy model will provide a single predicted consumption value for a building. But as Khazaii suggests, and the research I presented supports, a better means of presenting energy modeling results would be by reporting the probability or range of a certain level of consumption. These types of results could easily, and verifiably, be calculated by the computer based on the individual probability values entered into the model for the building component's performance range and the operational probabilities as described above. Khazaai suggests then, the metric used for code compliance could be changed to require a certain probability of a consumption level instead of a single pass/fail metric. For instance, the code could read: 'that the building must demonstrate that there is an x% chance of performing y% better than the code minimum.' This way there would be some latitude by the design team in the means at which they can comply with code as well managing the expectations of the stakeholders and general public in understanding what it means to comply.

It is the transparency afforded by probabilistic modeling and reporting which I believe to be the most helpful suggestion in this thesis. The models, in fact, have always presented a probabilistic prediction of consumption – it just was not always readily apparent to the user. This is partly to blame, as I have argued, because of the dominance of the technically deterministic concept of building performance used to certify buildings. Probabilistic modeling represents a more nuanced understanding of building performance which accounts for the uncertainty of the real world contingencies which influence energy consumption as much as the technical characteristics of buildings. This socio-technical understanding of building performance, ultimately I believe, will lead to more prudent action with regards to our technological choices.

Closing Remarks

Latour and Yaneva (Latour, 2008), with a very similar understanding of architectural performance as I have presented in this thesis, provide a general critique of how buildings are typically described which provides some insight on the problem of describing the dynamic complexity of a building and serves as an appropriate closing thought for this thesis. Latour and Yaneva argue for a new conceptual understanding of how to better document buildings in order to capture the time-based conception of architectural performance. Architecture, they point out is typically presented as an image constructed in two-dimensional Euclidian abstraction. But if architecture is judged by how it performs over time, how can a static representation of architecture, such as floor plan, a single photograph, or as I argue in this thesis, an energy model, be an accurate portrait?

Latour and Yaneva use stop motion photography as a metaphor to explain how to conceptualize what a more proper documentation of a building should be. They make the argument that if you follow and take notice of all the documents and drawings in the course of the design, construction and inhabitation of a building, they will be constantly changing. These changes represent the different conditions over the lifetime of the building. From the quick napkin design sketch capturing its "essence" to the muddied and hand annotated construction drawing at the construction site – all represent different versions, conditions and understandings of the building. Only the totality of these documents can accurately represents the building.

While an energy model is perhaps a possible improvement to the Euclidian representation of architecture – it does account for time (8,760 hours in fact) – the inputs that are entered still only represent the static, rationalized state of the design at the time of input - just a single snap shot in the stop motion photography needed to accurately document a building. So if an energy model returns a result of 7,561 kWh annually for example, what it is really reporting is the performance of the building as if it were to be constructed and inhabited in the exact same conditions of the *design at the time of input.*

The assumption that there is only one version of the building to be modeled has the effect of rationalizing the otherwise un-rational context in which the building actually exists. In other words, it is the concept of what is "likely" that the energy model gets wrong. This, I would argue, is a beneficial explanation for the problem of inconsistent energy modeling results. It is not one of input accuracy, but rather of understanding the nature of architectural performance that considers more dynamic possibilities of the inputs.

Appendices

Appendix A: Mappings

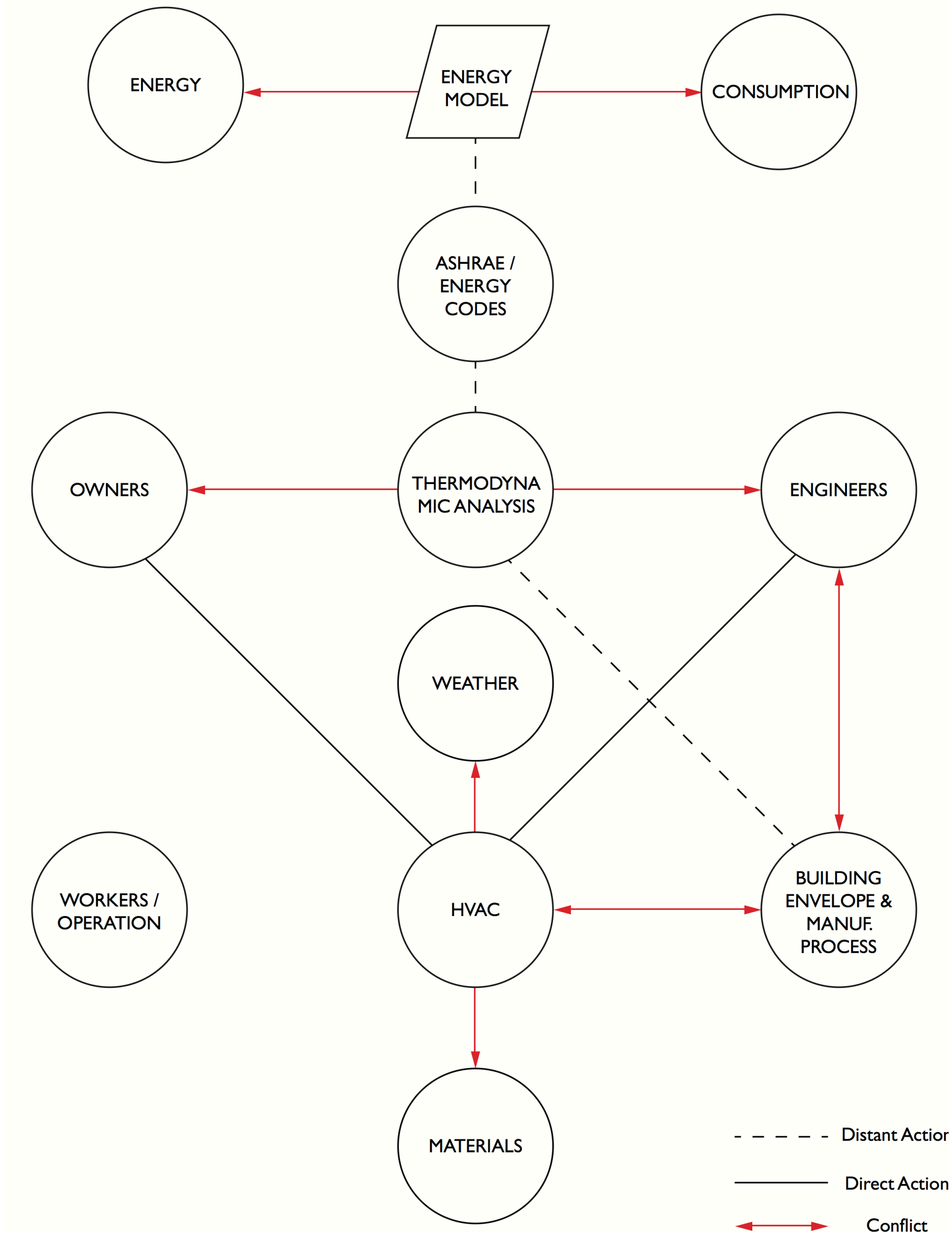


Fig. 4. Historical Analysis Mapping. [by author].

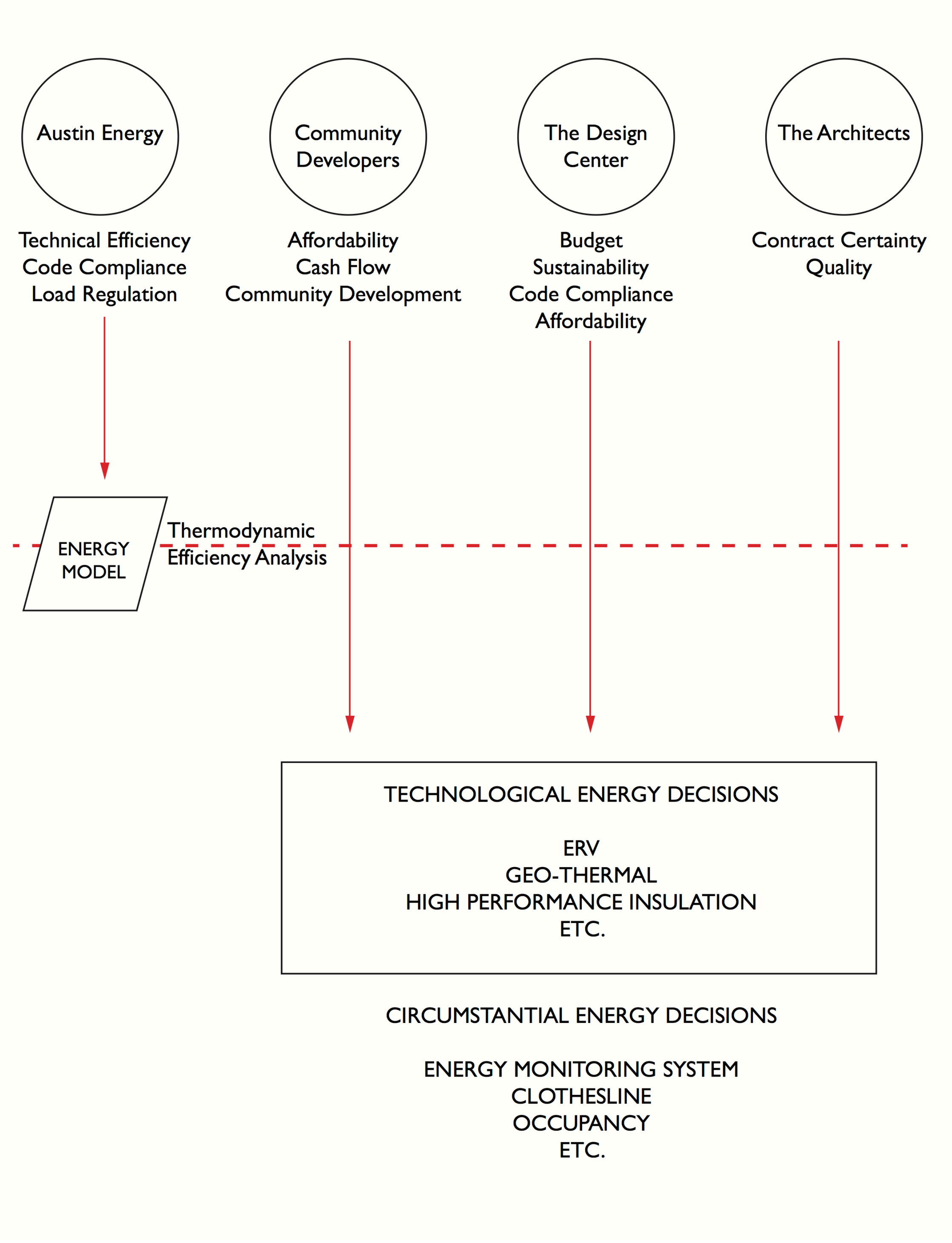


Fig. 5. Empirical Analysis Mapping. [by author].

Appendix B: Interview Protocol

1. How would define your role in this project?

2. What were your intentions for the project?

3. What do you believe the intentions were of other stakeholders?

4. What frustrations did you experience in realizing your intentions?

5. Based on your intentions, how successful on a scale 1-9 was the project? Why?

6. Based on your impression of the other stakeholders, how successful on a scale 1-9 do think the project was for them? Why?

7. What was your impression of/describe the modeling process?

8a. Have you worked on a project that used energy modeling in the past and if so, what ways was it different than this process?

8b. Would you welcome working on another project that employed energy modeling based your experience this project (or past experiences with energy modeling)? *[This question's intention is to draw out if they believed that the modeling process was in their interest]*

9. What knowledge did you gain from the energy model and how well do you believe the knowledge gained from the model got incorporated into the design?

10. How might you suggest improving the process?

11. Is there anything that you consider important about the project that I haven't asked you about?

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