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Diffusion of green building technologies in new housing construction☆

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ABSTRACT

We analyze the selection of high efficiency windows by builders of new housing units in the United States from 2000 to 2010. Windows are among the five most important technologies impacting energy use in structures. Focusing on windows provides insights into the decisions that result in energy efficient houses and the factors affecting those decisions, which can be muted or completely missed when looking at building ratings or other aggregated estimates. The study analyzes a large data set for the continental United States, applying the Least Absolute Shrinkage and Selection Operator (LASSO) model selection and cross validation of the training set model with a randomly selected validation data set. Our findings strongly support the importance of climate and energy costs in decisions on energy efficient housing, with important but smaller effects for public policies and incentives. We also find that taxing and insurance policies that increase the overall costs of construction can have negative impacts on the diffusion of energy efficient products.

The construction industry and particularly residential construction have been noted for low levels of innovation and path dependency [1–3]. However, innovation in construction is increasingly important to meet the challenges of energy conservation and climate change, particularly since buildings consume a substantial portion of energy consumption. In addressing the diffusion of Energy Star and LEED building certifications in the commercial building market noted the importance of occupied structures in aggregate energy consumption and green-house gas emissions, and the so-called "energy paradox" [4]. Housing epitomizes the same problems of durability and energy consumption, and the energy paradox, as noted by Kok, McGraw and Quigley. In 2013, the residential and commercial sectors accounted for 40% of total U.S. energy consumption, with residential alone accounting for 22% [5]. Based on the most recent survey data available, residential buildings accounted for 11% of total energy consumption (2009 Residential Energy Consumption Survey) while commercial buildings accounted for 7% (2003 Commercial Buildings Energy Consumption Survey) and office buildings only 1%. Very clearly, housing is the most important building related consumer of energy.

Kok et al. [4] modeled the diffusion of Energy Star and LEED certified office buildings. They reported positive effects from income level and growth, the supply of office space per employee, commercial property prices, average electricity price, and local policies encouraging energy efficiency, with negative effects for vacancy rate. The percent of LEED accredited professionals was positively related to LEED certifications and negatively related to Energy Star certifications. Since LEED certification includes incentives for use of LEED accredited professionals, a positive association would be expected although it is uncertain as to whether this reflects a human capital effect. Climate as measured by heating degree days and cooling degree days was mainly insignificant and had inconsistent effects, with only cooling degree days having a positive association with LEED certifications. The lack of consistent effects for climate (and thereby heating and cooling loads) and several other variables suggests that certifications might not be a good proxy for measuring energy efficiency in buildings [6,7].

The "energy paradox" juxtaposes previous slow levels of adoption of energy efficiency in new buildings against the expected profitability of more efficient technologies. Regulatory changes in building codes and efficiency requirements in both Europe and the

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United States have increased the pace of diffusion of energy efficiency in buildings, and the band of expected performance and cost of adoption have increased the probability of realizing anticipated returns on investment primarily using proven technologies that add little to no cost [8–10]. Additionally, there is mounting evidence that these gains are capitalized in the prices of commercial [11–15] and residential buildings [16–19].

1. Green building technology selection model

Due to the importance of residential energy consumption, we model the decision of builders to use specific energy efficient products, in this case high efficiency windows. Windows are among the five most important technologies impacting energy use in structures [10] and window area is used in estimating energy consumption [20]. Focusing on windows provides insights into the decisions that result in energy efficient buildings and the factors affecting those decisions, which can be muted or completely missed when looking at building ratings or other aggregated estimates. A product focus also provides better direction to manufacturers and public policy makers on builders' decisions about product choice, which is the fundamental driver of building innovation in residential construction [21].

There is a large body of scholarship on innovation (see e.g. [22–25]). Decisions to adopt innovations are more generally an element of the rational choice model of decision making, which researchers have progressively adapted to complex decision environments with varying degrees of uncertainty, including in construction engineering [26,27]. Digital technologies such as Building Information Models are rapidly expanding the potential of decision models and analysis in construction [28–30]. Most of the work on decision-making in construction has focused on improving decision-making models that incorporate multi-criteria and uncertainty, including for housing construction [31,32]. Although this research often involves some elements of verification with decision stakeholders, it is largely prescriptive and rarely models the actual decision making process.

Systematic studies of decision making for innovation adoption in housing construction are rare [33–36,46] and generally involve case studies or small surveys. Case studies provide depth of context but limited generalizability and it has become difficult to obtain voluntary participation by businesses in even major governmental surveys [37]. Directly researching decision processes is complicated, very time consuming for participants and relies heavily on perceptions and recall that are subject to significant bias. Research on adoption and diffusion of innovations typically focuses on modeling the factors associated with the decision outcome. Theory and previous research findings help in identifying the variables to include, but there are numerous potential candidates available from the broad field of innovation research.

Koebel et al. [35] proposed a general model for adoption of innovations in housing construction that included nine multi-dimensional arrays covering Adopter's Human Resources, Adopter's Organizational Structure, Adopter's Organizational Culture and Decision Process, Adopter's Market Context, Industry Characteristics, Communication Channels and Social Networks, Technical Attributes of the Innovation, Economic Attributes of the Innovation, and Supplier/Vender Characteristics, and identified over 60 characteristics that could be measured. Weidman et al. [38] provided an integration of the Innovation Diffusion, Technology Acceptance, and Health Belief models as applicable to adoption of health and safety innovations in construction. In recent reviews of the innovation adoption literature, Wisdom et al. [24] and Chor et al. [25] identified 20 theoretical frameworks with 27 multi-dimensional predictors and 118 potential measures. There are obviously many possibilities to consider in specifying an appropriate model.

2. Green building model analysis

A general model proposed for green building technology adoption is shown in Fig. 1 and includes seven multi-dimensional arrays identified in diffusion and adoption theory and in previous research, grouped into the seven multi-dimensional categories of product, market area, climate, time, firm, industry, and public policy. A detailed description of the arrays and potential measures is provided in McCoy et al. [39]. Several arrays identified in earlier work are combined in this model for ease of presentation, particularly in combining several characteristics of the adopter under one broad array for firm characteristics. This simplification also reflects the scarcity of data on the multiple attributes of firms that could be potentially influential. The general model shown in Fig. 1 is used to provide a comprehensive framework for creating the operational model shown in Fig. 3. The operational model needs to be much more parsimonious than the general model, while also noting what is excluded from the general model. This can serve as a useful heuristic guide to developing and testing models, and in refining future work that can incrementally address over and under specification of the tested model reported here.

A brief description of the general model follows (a detailed description is provided in McCoy et al. [39]) starting with product characteristics and progressing clockwise through Fig. 1. Data sources used in this study are documented in McCoy et al. [39] and arrays with little or no available data coverage in the operational model are identified below.

Rogers' seminal work on innovation diffusion suggested several product characteristics that potentially influence the adoption decision. Relative advantage compares the new product with previous versions based on price, productivity and performance and is expected to provide one of the primary justifications for adoption. Many building products are substitutes for similar products and do not add completely new functions to buildings. Substitute products are expected to be evaluated against competing products. Data on relative advantage are not easily obtained but data on prices is available through industry sources. Data on functionality, productivity

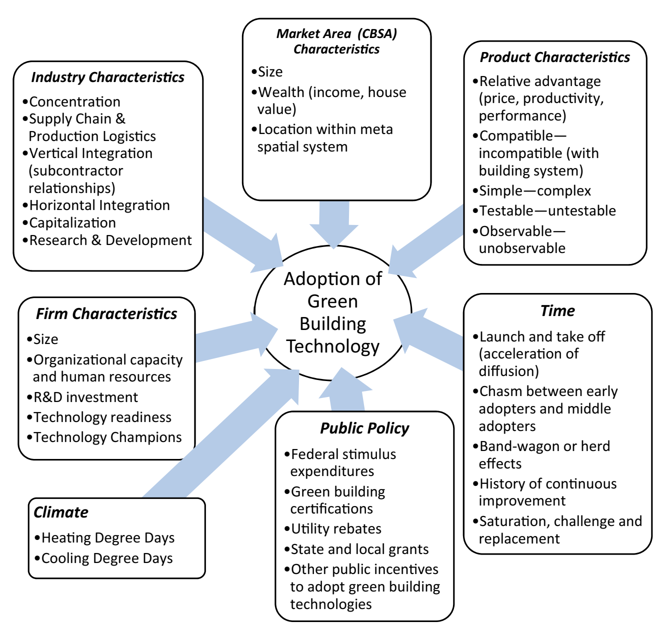

Fig. 1. General model of green building technology adoption.