CRGP Working paper #0069

Fragmentation inhibits innovation: Overcoming professional and trade lock-in

Editor's reference: BR7606

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January 17, 2012

Submitted to *Building Research and Information*,

Special Issue on New Professionalism

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Abstract

The building sector is the largest energy consumer and, hence, emitter of greenhouse gases, in the US economy. Yet many promising energy-efficient building technologies with positive net present values and short payback periods do not get implemented. Increasing technological complexity has transformed building professionals from "master builders" before about 1900 into highly fragmented specialists that span increasingly narrow domains. Today's building industry is highly fragmented, both vertically across project phases, and horizontally by profession or trade. Specialized sub-consultants employ different design professionals, and specialty sub-contractors employ different building trade workers. This paper explores the impact of this industry fragmentation on adoption rates of energy-efficient technologies.

Building industry specialists—professions and trades—can operate independently with little need for external coordination due to extensive product standardization and strong professional and craft traditions. Analysis of adoption rates of energy-efficiency technologies in US buildings finds "modular innovations" that align well with industry standards and specialty firm/professional/craft boundaries diffuse rapidly. However, "integral innovations" that involve new interfaces and/or new integration procedures across the boundaries of firms/professions/trades are adopted far more slowly. Mediating this effect, vertical and horizontal integration of design and construction specialty firms involved in integral innovations significantly increase their rates of adoption.

Keywords

Building energy-efficiency; construction industry; craft institutions; professionalism; industry structure; innovation diffusion; innovation strategy; coordination; organizational learning; organizational networks; codes and regulations; modularity; supply chain.

Introduction

The building sector consumes more energy and emits more CO_2 globally than any other sector (DOE). Moreover, the stock of existing buildings—and many new buildings—use energy extremely inefficiently. This has created a tremendous opportunity to reduce energy use and attendant greenhouse gas emissions. The past three decades have seen a surge in the development of new energy-saving technologies for use in existing and new buildings (USPTO 2009). With technologies that exist today, energy use could be lowered by 25 to 30 percent by 2030 (NAS 2009). In fact, increased implementation of energy-saving technologies is widely agreed to be the nearest-term, lowest-cost way to reduce greenhouse gas emissions in both developed and developing countries and meet our nation's energy consumption needs.

Moreover, many of these energy-saving technologies represent attractive investment opportunities. They have positive net present values (NPV), a payback period of two to three years, and are likely to remain competitive in the future (NAS 2009). Yet NPV-positive opportunities worth over $130 billion go unrealized, because many promising, technically-feasible innovations diffuse very slowly, or sometimes not at all, through the building industry (Choi Granade, Creyts et al. 2009; NAS 2009). Not only are opportunities foregone, but energy intensity has recently (1985-2004) increased by 12% in the commercial buildings sector (DOE). Finding ways to increase the rate and magnitude of adoption of energy-saving technologies in new and existing buildings has tremendous potential. This research investigates the role that building industry professional and craft traditions plays in the slow diffusion of energy-efficient technologies.

Until quite recently, construction was carried out by “master builders” who were proficient in all aspects of the building craft (Port 1967; Yates and Battersby 2003). However, since the Industrial Revolution, buildings and building systems have grown increasingly complex, requiring a growing amount of technical knowledge from building professionals (Nam and Tatum 1988; Cushman and Loulakis 2001). To cope with the increased knowledge requirements, master builders were replaced over time by highly specialized building professionals who mastered particular domains rather than the entire building craft. Today, the building industry is extremely fragmented in three dimensions: *horizontally* by disciplines, *vertically* by stages of a project’s lifecycle, and *longitudinally* across successive projects (Fergusson 1993). Project teams for major buildings are comprised of professionals and craft workers from hundreds of firms with narrow specialties that come in and out over the project’s lifecycle. Moreover, team composition changes dramatically from one building project to the next, especially in liberal market economies (Hall and Soskice 2001) such as the US, where specialty firms are typically selected by competitive bidding. These hundreds of professionals and up to thousands of trade workers follow the set of professional and trade standards and guidelines of their respective professional and craft institutions (Stinchcombe 1959) and are constrained by construction’s extensive standards, codes and regulations , so they require very little external, centralized coordination to work effectively. As long as a building project and building systems and technologies do not deviate from standard procedures, coordination among professionals and trades is tacit and internal, as Stinchcombe (1959) pointed out.

The high degree of fragmentation among professionals, coupled with strong inertial forces in the industry, make even a small deviation from professional jurisdictions and procedures extremely challenging to implement. This is not to say that innovation is impossible in construction. The industry has steadily accepted various energy-efficiency innovations such as daylight sensors (Sheffer 2011). Other energy-efficiency innovations, such as under floor air distribution or cooling tower condensate recycling, have been much slower to diffuse (Sheffer 2011). Why do some innovations diffuse faster than others? Can a simple answer such as relative costs explain most of the variance? Previous research on innovation diffusion in construction helps explain why the industry is generally slow to innovate, citing a variety of factors ranging from the existence of "social heuristics" that industry members share (Beamish and Biggart 2010) to the abundance of codes and regulations (Oster and Quigley 1977; Tatum 1986), low labor costs (Goodrum and Haas 2000) and "broken agency" (Sheffer and Levitt 2010). One stream of research that is especially insightful has cited industry fragmentation and the one-off, project-based structure of construction as major barriers to innovation diffusion (e.g., Bowley 1966; Nam and Tatum 1988; Haas, Borcherding et al. 1999; Barlow 2000; Gann and Salter 2000; Dubois and Gadde 2001; Lutzenhiser and N. 2003; Taylor and Levitt 2004; Sheffer and Levitt 2010; Sheffer 2011). However explanations for why some innovations diffuse faster than others are sparse (for exceptions, seeTaylor and Levitt 2007; Sheffer and Levitt 2010; Sheffer 2011). Taylor and Levitt (2007) begin to address this weakness by proposing that innovations that are misaligned with existing industry structure are slower to diffuse. In this paper, the authors build on their work by validating their propositions empirically and clarifying the role of fragmented professionals in inhibiting innovation diffusion.

The purpose of this paper is to elaborate and validate empirically the effect that the fragmented scope of building industry professionals has on innovation diffusion. The authors distinguish between two types of innovations – innovations that match existing industry standards, professional and craft boundaries and processes ("modular innovations") and innovations that challenge those and require changed integration interfaces and processes ("integral innovations"). Modular innovations are hypothesized to diffuse faster than integral innovations since they do not require a deviation from existing professional boundaries and industry standards which serve as embedded coordination mechanisms in the decentralized building industry. Further, the authors hypothesize that new, more integrated project team arrangements can ease the implementation of integral innovations and increase their rates of diffusion.

The research found empirical support for both hypotheses. These findings have important theoretical implications for academics studying innovations in buildings and other fragmented industries, and practical implications for all players in the building industry attempting to innovate in general and to improve energy efficiency, specifically.

Background

The Changing Role of Building Industry Professionals

Since the industrial revolution, the construction industry has transitioned from a vertically and horizontally integrated industry to a highly fragmented industry (Sheffer 2011). Prior to about the 1850s, construction was performed by "master builders" who were proficient in all aspects of the building craft. These master builders played the roles of architects, engineers, and superintendents" (Yates and Battersby 2003). In fact, at the turn of the nineteenth century, the construction industry was still vertically integrated (Port 1967). For example, material producers (such as bricklayers) assembled their materials into individual building modules (bricks) and installed them on site. Around the time of the Industrial Revolution, new methods, materials, and technologies were introduced and the complexity of construction products has increased exponentially. The increasing complexity of construction products, along with the sheer number of different products and modules within each product, requires extensive domain-specific knowledge. In order to deal with this overwhelming knowledge requirement, individuals and firms within the industry began to fragment (Port 1967; Nam and Tatum 1988; Cushman and Loulakis 2001; Yates and Battersby 2003). The first step was to fragment vertically into design and construction specialties, but over time these specialties were further separated into the narrower horizontal specializations – the craft and professional disciplines and specialized firms that employ each of them – that we see today (Eccles 1981; Eccles 1981) [1]. Thus, the construction industry today is fragmented in three ways: vertically, horizontally, and longitudinally (Fergusson 1993).

Vertical fragmentation is a separation of firms and workers into different stages of a project's life cycle (i.e., project planning, design, construction, commissioning, operations and maintenance) (Fergusson 1993). One of the factors that solidify the vertical fragmentation in construction is the use of traditional procurement methods. A procurement method, or project delivery method, refers to "the process of managing how a project will be planned, designed, and built" (Kenig 2007). Procurement methods are distinguished based on the number of separate contracts that the owner holds, the selection criterion, and the degree of integration among project team members. The most common and traditional procurement method is Design-Bid-Build (D-B-B). In this scenario, an owner contracts separately with the architect or engineer responsible for

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[1] Building trade workers include some of the highest skilled blue collar workers in all industries. To become a journeyman plumber or electrician, a worker must complete four or five years of 144 hours per year classroom instruction and 2,000 hours of work experience under the supervision of a journeyman and pass a state licensing examination, in order to become a journeyman. Hereinafter we will refer to both construction trade workers that staff specialty construction firms and the architects and engineers that staff the specialty design firms involved in construction as "professionals."

the design and the general contractor responsible for construction, who in turn awards individual subcontracts with multiple subcontractors. This method is aligned with and perpetuates the fragmented structure of the industry. It specifies a linear process in which planning, design, bidding, construction, and occupancy are sequential without overlap. Under D-B-B, a contractor is hired separately from the design team only after the design process is complete, with the primary (or only) selection criterion being the lowest construction bid price (Kenig 2007). Over the past few decades, more integrated, delivery methods have been introduced. The most common example is Design-Build (D-B), which is characterized by a single contract between the owner and an entity responsible for both design and construction. By definition, this process involves a greater degree of vertical integration among project members (Cushman and Loulakis 2001). While this method is gaining traction in the industry, the highly fragmented design-bid-build process remains the dominant procurement method for US buildings.

Horizontal fragmentation is a separation of firms and individuals into crafts, trades, or disciplines (i.e., mechanical, electrical, structural, civil, structural) (Fergusson 1993). Craft institutions provide socialization and training for workers and ensure a level of occupational competence, as well as provide a method for administering the work itself. In fact, they replace bureaucratic methods of administration (Stinchcombe 1959) and allow the decentralized modular clusters of firms in the construction industry to function relatively smoothly. Because construction technology is so complex and requires a vast amount of domain-specific knowledge, construction firms tend to specialize in one trade. Although some firms employ multiple specialties, the vast majority are experts at only one trade. Thus, on any given construction project, most tasks are subcontracted in order to fill the knowledge gaps that the lead design firm and general contractor lack. The prime contractor on a typical US major building project subcontracts about 90% of the cost of construction to specialty firms. In homebuilding, technical, labor, and material trades are almost always subcontracted, and even the basic and unskilled trades are subcontracted fifty percent of the time (Eccles 1981).

Longitudinal fragmentation is a separation of firms and individuals into distinct projects, with a different set of firms working together on each successive project (Fergusson 1993). Longitudinal fragmentation in an economy is affected to a large extent by the economy type – liberal or coordinated market (Hall and Soskice 2001). In liberal market economies, such as the United States, longitudinal fragmentation is high as relations between clients and contractors, and between contractors and subcontractors, tend to be one-off and arms-length, relative to those in more coordinated market economies like Finland or Japan (Taylor and Levitt 2007). Another factor that affects the degree of longitudinal fragmentation is regulation of the bidding process. Many clients in the US, including virtually all public construction buyers, require three or more general contractors to submit lump-sum bids and then choose the "lowest qualified bidder"[2] (Cushman and Loulakis 2001). General contractors, in turn then solicit lump-sum bids from multiple specialized subcontractors, either at large, or from a list of approved prequalified subcontractors. Thus, individuals and firms at every node in the supply chain tend to select the bidder with the lowest price for each component's materials and subsystems rather than working with the same set of players from project to project. The resulting makeup of the core team of architects, engineers, building contractors, subcontractors, and component suppliers required to deliver significant building projects tends to change significantly from project to project, even in

2 "Qualified bidder", in this context, means simply a contractor that can secure a surety bond guaranteeing completion of its work and payment of its subcontractors and vendors on the project.

the same metropolitan area: "one and the same team is only seldom (and then rather by coincidence than by conscious planning) working together in more than one project" (Dubois and Gadde 2001).

In sum, the complexity of construction products has given rise to vertical and horizontal fragmentation in construction industries worldwide. Longitudinal fragmentation is more extensive in liberal market economies such as the US. Further, in the manufacturing industry finished products are transported to the market place. However, buildings are large and relatively immovable, so they are generally constructed or assembled from smaller prefabricated modules at the point of consumption, thus making construction industries around the world very localized. Together, the three-way fragmentation and localization of construction result in a highly specialized industry with literally millions of small firms (Sheffer 2011)[3]. These self-employed individuals, who operate very small unincorporated businesses and account for the vast majority of construction firms, represent only about 8% of construction's value of business (Census 2007). Although recent trends point to some consolidation in the industry and the emergence of "super builders," who are responsible for a growing share of the industry's volume, small- and medium- sized firms remain the norm (Alexander 2000).

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[3] The US construction industry includes nearly three and a half million small, specialized local firms, seventy eight percent of which have zero employees (Census 2007) and are thus "mom *or* pop" firms (Sheffer & Levitt 2010). The top 400 construction firms in the US account for less than 15% of industry volume (ENR 2009).

Coordination among Fragmented Professionals

The hundreds or thousands of highly specialized workers from many different subcontractor firms that come and go at specific times during a building project's lifecycle require very little external coordination. General Contractors are assumed to play the role of central coordinators, but they provide a very thin layer of coordination, and the network of subcontractors on a construction project essentially self-synchronize and coordinate themselves quite effectively (Stinchcombe 1959). This self-synchronization is possible due to craft administration (Stinchcombe 1959) and extreme standardization in construction (Sheffer 2011). So long as a building project does not deviate from standard components, materials or procedures, coordination is relatively simple and effective.

"Craft institutions in construction are more than craft trade unions; they are also a method of administering work" (Stinchcombe 1959). They have clear jurisdictions within which they set professional standards, provide technical training to workers, enforce preferential hiring rights to its members, define what constitutes legitimate communications and procedures, and determine the divisions of work. Members of a craft institution have shared sense-making and collective understandings of the roles, expectations, and processes within their crafts. In fact, the "professionalization of the labor force in the construction industry serves the same functions as bureaucratic administration in mass production industries" . Subcontractors on a construction project coordinate themselves by following well-established procedures that are enshrined by their respective craft institutions, and general contractors need only provide very minimal coordination (Sheffer and Levitt 2010; Sheffer 2011).

In addition to craft administration of work, the extensive standardization in construction serves as an additional enabler of the high degree of self-synchronization among subcontracting firms on construction projects (Sheffer 2011). With approximately 1,300 industry standards (NAHB 2010) that include thousands of codes, construction is one of the most institutionalized and regulated industries, perhaps comparable only to pharmaceuticals with its host of drug safety regulations. These standards make clear what building products are acceptable, how they should be connected to one another, what dimensions are acceptable, etc. A strong central coordinator is not needed to set standards case by case, as industry members conform to overall standards. The set of codes and standards in construction essentially formalize the dominant design (Abernathy and Utterback 1978) that has emerged in construction, encoded in the *UniFormat* set of construction component and subsystem definitions (Construction Specifications Institute 2010). Like design rules in other industries (Baldwin and Clark 2000), they specify three things: The overall architecture by which individual building modules can be integrated, the interfaces between modules, and the integration process. Thus, craft and professional institutions dictate the roles of all industry players, and extensive codes and standards dictate the processes by which specific modules can be integrated into a completed product.

Effects of Professionals on Innovation Diffusion

The fragmentation of construction industry professionals poses a high barrier for innovations. The authors distinguish two types of innovations – modular *vs.* integral – because industry fragmentation and decentralization have different effects on their diffusion (Sheffer and Levitt 2010; Sheffer 2011).

Modular innovations (Sheffer and Levitt 2010; Sheffer 2011) affect only a single building module (e.g., flooring, roofing, HVAC). In comparison to the technology that they replace, modular innovations do not alter interfaces with adjacent modules nor the installation process of that module within the building. On both the design and construction sides, a modular innovation can be designed and installed in a similar fashion to the standard alternative technology that is being replaced. These innovations fit within existing industry standards and the jurisdictions of craft institutions. Examples of modular innovations are high efficiency light bulbs that fit into the same light sockets as incandescent bulbs and CO2 monitoring equipment with interfaces and installation that are essentially the same as those for smoke detectors.

In contrast, *integral innovations* (Sheffer and Levitt 2010; Sheffer 2011) affect multiple building modules. In comparison to the technology that they replace, integral innovations alter the interfaces between modules, the installation process, or both. An integral innovation has implications for the design phase, construction phase, or both. These innovations do not fit within existing industry standards or the jurisdictions of craft institutions. An example of an integral innovation is radiant floor heating that significantly affects both the design and construction phases by altering the interfaces and installation processes in comparison to typical floor construction.

These definitions build on Henderson and Clark's (1990) classification of innovations based on their effect size and the location of the innovation within or across modules; and on Taylor and Levitt's (2007) extension of this classification to the network level of organizations. The focus of this research is on whether the innovations are contained within a single module or cross modular boundaries at the network level without taking into account effect sizes; thus, we needed to introduce new terminology.

Any building technology needs to be properly installed and integrated with related technologies in order to function properly. Because each building is very complex and distinctive to some degree (Nam and Tatum 1988), each building project potentially poses unique technology integration challenges. Thus, unless a technology is very mature and standardized, its integration within a building can be challenging to implement, at first.

Integral innovations challenge the status quo of professional boundaries, work processes, and communication channels by requiring that professionals follow new integration processes. Thus, they are likely to be especially difficult to implement and therefore slower to diffuse, because the embedded coordination that was a byproduct of standardization is no longer valid. When integral innovations are introduced into a construction project, professionals from disparate firms all need to re-orient themselves and adapt to the innovation's changed interfaces and resulting installation processes to properly implement the innovation. Doing so without a central coordinating body or regulation to mandate the change, clarify the new procedures, and conduct relevant training is difficult. Moreover, shifting team membership from one project to the next impairs the accumulation of necessary knowledge at the network level, resulting in even slower diffusion of integral innovations.

Hypothesis 1 (H1): *In the fragmented construction industry, integral innovations are less likely to be implemented than modular innovations.*

In general, integral innovations offer greater overall benefits (Ulrich 1995). When it comes to energy efficiency, greater gains can be made by technologies that affect overall buildings rather than individual components. Therefore improving their likelihood of implementation is a worthwhile pursuit. Since a primary obstacle to the implementation of integral innovations is industry fragmentation, integrating the supply chain vertically and/or horizontally through mergers or long term alliance contracts should increase their rate of implementation. Horizontal integration keeps the involved players together from project to project even in liberal market economies. It thus eliminates longitudinal fragmentation for the professions involved, allowing for the build-up of tacit knowledge about the integral innovation at the network level.

Moreover, integration allows for centralized control or at least easier coordination among specialists who were previously in separate firms. Hence, integrated firms transform an integral innovation contained within their enlarged scope into a new kind of "super-modular" innovation, increasing the likelihood that it will be implemented on a given construction project, based on H1 above.

> ***Hypothesis 2 (H2)**: Supply chain integration moderates the negative effect that innovation integrality has on the probability of implementation; in other words, supply chain integration increases the likelihood of implementation for integral but not modular innovations. The higher the degree of integration, the stronger is the moderation effect.*

Methodology

To test these two hypotheses, the authors analyzed the factors that affect the implementation of twenty three different energy-efficient technologies in one hundred and twelve LEED-certified buildings in the US from 2000 to 2009. *Leadership in Energy and Environmental Design (LEED)* is the most common green building certification system in the US today, and one of the most common systems in the world. Specifically, the effects of innovation integrality and supply chain integration on the likelihood of implementation of these technologies were examined. Multiple control variables were included about the technologies (e.g., cost), building projects (e.g., year, LEED score, owner type), and firms (e.g., size and core values). Binary logistic regression in general estimating equations was used to predict whether, in each project, each innovation would be implemented or not.

Data and Sample

The data for this study consists of case studies and LEED scorecards collected on the USGBC's website (USGBC 2010). To limit external variance, this study focuses on US projects certified under *LEED for New Construction and Major Renovations* in versions 2.0, 2.1, and 2.2. All building projects that fit these criteria and for which case studies and LEED scorecards were available were included in the study, resulting in a sample of 112 buildings.

These buildings represented a wide variety of building types and sizes, owners, geographies, and procurement methods. All were registered with the USGBC between 2000 and 2007 and certified between 2000 and 2009. A third of the projects are commercial office buildings, a quarter are educational buildings, and the remaining include multi-unit residential buildings, assembly or interpretive centers, laboratories, health care facilities, public order or safety buildings, and military facilities. Building ownership is roughly equally spilt into three types: government (36%), non-profit organizations (33%), and profit organizations (25%). Building sizes range from approximately 3,000 to 1.5 million square feet, with an average size of 120,000 square feet and a standard deviation of 190,000sf. Project costs range from $350 thousand to $165 million, with an average of $26 million and a standard deviation of $33 million.

Hard costs of expenditures on equipment per square foot range from $59 to $345, with an average of $179 and a standard deviation of $75. Soft costs of design and consulting per square foot range from $3 to $310, with an average of $53 and a standard deviation of $66. The projects were well distributed geographically. Most of the projects were certified under LEED-NC 2.0 (56%) or LEED-NC 2.1 (41%), with only four projects under LEED-NC 2.2 (3%). Procurement information was available for only 59 of the 112 projects. Of those, the two most common procurement methods were the traditional design-bid-build (23 projects) and the more integrated design-build (26 projects). LEED scores in the sample range from 21 to 61, with an average of 39 and a standard deviation of 9 points.

This sample is somewhat skewed toward “trophy buildings.” In the overall population of certified projects only 5% are assessed as “Platinum” (the highest possible rating); in this sample 20% achieved Platinum certification. The study’s goal is to untangle the effects of innovation integrality and fragmentation on innovation implementation. Trophy buildings can be expected to try to implement the most significant energy-saving integral innovations at even higher rates than other LEED buildings, so this sampling bias further strengthens our findings.

Measures

Dependent Variable

The main dependent variable was *implementation*. With 112 projects and 23 technologies, there were 2,576 possible occasions for technologies to be implemented. When a technology was implemented, the event was coded as “1” and when a technology was not implemented, the event was coded as “0”.

The credits and points structure of the LEED system provides a clear measure of building technology implementation. Points are awarded only once documentation has been submitted to prove that the requirements of particular credit were met. Thus, the list of technologies implemented was verified by a third-party via the LEED scorecards. To make sure that no technology was missed or miscoded, each project description and LEED scorecard were read by three independent coders who were asked to list all the technologies that were implemented on each project. Overall, technologies were implemented 28% of the time.

Independent Variables

Two independent variables were included in the study: *innovation integrality* and *integration among professionals.*

Innovation integrality

This study considered only innovations related to energy efficiency. An important measure of integration among professionals, the other independent variable in this study, is ownership integration of mechanical, electrical, and plumbing (MEP) firms. Thus, only technologies related to these trades were included in the study, as independently assessed by two project managers at large US general contractors who are LEED accredited.

Each technology was coded as *modular* (=0) or *integral* (=1) as assessed by eight construction industry professionals. For each technology, coding as modular or integral was done in relation to the most common basic technological alternative. A technology was considered modular if it did not involve any alteration to interfaces with adjacent modules or modifications in the design or installation process. A technology was considered integral if the interfaces were changed, the design or installation processes were changed, or both. It is important to note that a technology can be modular in some respects and integral in others. However, since coding technologies is a somewhat subjective process that depends on factors such as the coder's industry expertise, the particular model of the technology, and the particular site descriptors, the authors chose to dichotomize innovation integrality for simplification and to achieve consensus in coding. The resulting list of technologies includes 23 technologies, twelve integral and eleven modular.

Integration among Professionals

Measuring supply chain integration is challenging, as there is no consensus on what true integration among construction team members entails (Khanzode 2010). This study uses two indicators to construct a measure of integration among professionals. The first is *horizontal ownership integration* of mechanical, electrical, and plumbing (MEP) firms. Horizontal ownership integration may also be correlated with longitudinal integration, however this is not an assumption of the research. The second indicator is *procurement method,* as a proxy for levels of vertical integration.

Horizontal ownership integration was discerned from a list of key project participants in the case studies. A project team was coded as *integrated* (=1) when the mechanical, electrical, and plumbing engineers worked at the same firm, and *not integrated* (=0) when the mechanical, electrical, and plumbing engineers came from three separate firms. Of the 112 projects in the sample, only 55 listed the names of the MEP engineering firms that were involved and fit into the full MEP integration (1) or no integration (0) categories. Projects that did not fit into either category of completely integrated or completely fragmented or had missing information were excluded. There are almost no statistically significant differences between the 55 projects that were included and the remaining 57. Analyses of Variance (ANOVAs) compared the two samples on the number of LEED points achieved, owner type, building size, project type, registration year, procurement method, and total project costs. The only statistically significant difference is in owner type: For-profit owner organizations were more likely to provide information on MEP firms. Thirty six percent of projects that provided MEP information were for-profit organizations as compared to 14% of those that did not provide this information ($F=7.467$, $p=.007$). There were no other statistically significant differences.

Procurement methods were used as proxies for vertical integration. Projects procured via the traditional design-bid-build (D-B-B) approach had separate design and construction contracts and were considered as *not integrated* (=0), whereas projects procured with design-build (D-B) approach had a single contract between the owner and an entity responsible for both design and construction and were considered vertically *integrated* (=1). Procurement information was available for 49 of the 112 projects: 26 were design-build and 23 design-bid-build. Of the remaining 63 projects, 53 had missing information and 10 represented a variety of other procurement approaches, each with too few projects to be included in the statistical analyses. Again, there are almost no statistically significant differences between the 49 D-B and D-B-B projects and the others, except that non-profit owner organizations were less likely to provide procurement information than other owner types ($F=4.818$, $p=.03$).

Using these two indicators of horizontal and vertical integration, a three-level measure of integration was constructed: projects without any integration (neither vertical nor horizontal), projects with only one type of integration (either vertical or horizontal), and projects with both types of integration (vertical and horizontal). See

Figure 1 below. In the analyses, the two medium categories were combined as there is no clear theoretical justification to assume that one would be better than the other.

Control Variables

Control variables were chosen based on what prior literature and background interviews suggested could influence technology implementation. Given the nested structure of the data (opportunities to implement multiple technologies per building project), both technology-level controls and building level-controls were included. At the *technology level*, technology costs are included, and at the *project level*, registration year, owner type (1=profit organizations, 0=other owner types), LEED score, average MEP firm size, and MEP core values were included (1=sustainability or innovation is claimed to be a core value, 0=neither).

The estimation of technology costs requires some explanation, as cost estimations are exceedingly difficult to obtain. This study measured technology costs as the added capital costs over the most common alternative technologies in dollars per square foot of building space, adjusted for inflation as measured by the Construction Cost Index, and changes in real technology prices for those innovations that were scaling up and experiencing resulting lower costs over time. Costs were estimated by two field experts and ranged from no cost premium to $40 per square foot, with an average of $7.07 per square foot and a standard deviation of $8.94. Modular technologies cost an added $3.12/sf on average (SD=$3.54), and integral technologies cost on average $10.10/sf more (SD=10.69).

Analytic Approach

Logistic regressions were used to test the probability that a technology will be implemented in a building project. Each of the 23 technologies can be implemented in any of the 112 building projects, so there are 2576 implementation opportunities. The number of observations equals the total number of implementation opportunities. Since in each implementation opportunity a technology was either implemented or not, binary logistic regressions were used.

Given the nested structure of the data of multiple technologies per project, the Generalized Estimating Equations (GEE) regression method was used. The GEE method is an extension to the array of General Linear Models (GLMs). The main difference is that GLMs generally use maximum likelihood methods for independent observations (Hardin and Hilbe 2003), whereas the GEE method is based on quasi-likelihood without assuming anything about the distribution of observations. The GEE method controls for subject-level heterogeneity by accounting for the autocorrelation among the multiple observations per subject (Liang and Zeger 1986) and is therefore an appropriate regression method for data with multiple or repeated measures for each subject. The GEE method is commonly used in biomedical data such as longitudinal clinical and epidemiological studies (Pan 2001; Hardin and Hilbe 2003; Cui 2007). In this sample, the subject variables are the building projects and the within subject variables are the technologies. An independent working correlation matrix was assumed and used a robust estimator covariance matrix. All variables are centered.

To test each model's fit, Pan's (2001) quasi-likelihood under the independence (QIC) model criterion is used. It is an alternative to Akaike's information criterion that is widely used for model selection in general linear models and is inapplicable for GEE (Pan 2001). Lower QIC score indicates a better model fit.

Results

Descriptives and Correlations

Table 1 includes descriptive statistics and correlations for the variables. On average, technologies were implemented in 28% of all possible opportunities. The independent variables have a high degree of variance. The correlation matrix reveals low correlations among independent variables. Most correlations are below 0.3. The only two exceptions are a correlation of 0.38 between innovation integrality and cost, and a 0.44 correlation between team integration and the owner being a for-profit organization. Nonetheless, these correlations are sufficiently low to be included without concern. Moreover, regressions in which these were omitted reveal the same result patterns.

Some relationships are interesting and worth noting. As hypothesized, innovation integrality is negatively correlated with implementation ($r=-.25$). Cost is also negatively correlated with implementation ($r=-.22$). Innovation integrality is correlated with cost ($r=.38$), as integral innovations tend to be more expensive than modular ones. Profit organizations tend to select more integrated teams ($r=.44$), but they tend to obtain lower LEED scores ($r=-.12$). As the years in the sample passed, projects tended to include more integrated teams ($r=.24$) and achieve higher LEED scores ($r=.23$). LEED scores are in themselves correlated with team integration ($r=.12$). Higher LEED scores have a very weak association with technology implementation. Although the correlation is statistically significant at the $p<.001$ level, the practical significance is nonexistent since the Pearson r score is 0.07. Integrated teams tend to include smaller MEP firms ($r=-.25$) and indicate that innovation or sustainability is their core value ($r=.24$).

Hypothesis 1

The hypothesis that innovation integrality will be negatively correlated with implementation was tested using the entire sample (112 projects, 2576 implementation opportunities). As reported in Table 2, the hypothesis was strongly confirmed. In other words, technologies that are integral are less likely to be implemented than modular ones, even after accounting for technology costs, LEED score, owner type, and year.

Three models were compared: The first includes the main control variable, technology cost; the second includes additional controls (LEED score, owner type, and registration year); and the third introduces innovation integrality. The negative and highly significant coefficient for innovation integrality ($b=-.86$, $p<.001$) in the third model provides strong support for the first hypothesis. A comparison of the coefficients of all the predictors in the model reveals that innovation integrality has the greatest effect on the probability of implementation, and the QIC scores indicate that the third model has the best fit.

Hypothesis 2

The hypothesis that integration among professionals moderates the relationship between innovation integrality and implementation was tested using the reduced sample for which integration data was available (23 projects, 528 implementation opportunities). As visually demonstrated in Figure 2 and reported in Tables 3 and 4, the hypothesis was strongly confirmed. In other words, as integration increased from low to medium and from medium to high, so did the rate of implementation of integral, but not modular, technologies.

Figure 2 provides a visualization of the results in a graph of the average implementation rates of modular and integral innovations by supply chains with low, medium, and high integration. Consistent with the hypothesis, the rate of implementation of modular technologies does not vary by the extent of team integration. High and low integrated teams implement on average the same number of modular innovations (47% of all implementation opportunities), and medium integrated teams implement slightly fewer modular innovations (44%). In contrast, as predicted the rate of implementation of integral innovations increases as team integration increases: Low integrated teams implement only 10% of all possible integral innovations, medium integrated teams 18%, and high integrated teams 26%.

Table 3 reports the regression results. Models 1 and 2 replicate the results of the first set of analyses that used the entire sample to test the first hypothesis, but use more control variables due to their availability in the reduced sample size. Model 3 introduces the main effect for integration among professionals, which failed to achieve statistical significance, indicating that professional integration on its own does not significantly affect the probability of technology implementation. Model 4 includes the interaction terms between innovation integrality and high and medium team integration, both of which are positive and significant. The non-significant main effects for team integration but the positive and significant interaction terms support the second hypothesis. Integration among professionals does not have a general effect on technology implementations. However, integration does increase the likelihood of implementation of integral innovations (but not modular). The coefficient for high team integration ($b=1.34$, $p<.01$) is both higher and more significant than the coefficient for medium team integration ($b=.84$, $p<.05$), indicating that as teams become more integrated, the likelihood of technology implementation increases. In other words, the combination of vertical and horizontal integration yields greater implementation of integral technologies than just one type of integration (either vertical or horizontal); and either is better than no integration at all.

The coefficients from the final model (Model 4 in Table 3) were used to calculate the effect sizes of the variables and are listed in Table 4. A few effects are especially noteworthy. The odds of implementation of integral innovations are 84% lower than for modular innovations. This effect is dramatic, especially in comparison to the smaller effect of technology costs, which decrease by a mere 8% for every dollar increase in cost above a standard technological alternative per square foot of building space. Cost becomes a more critical factor when the increase is greater than $11 per square foot, which is only the case for five of the twenty three technologies in this study. Even more dramatic, integral innovations have 186% higher odds of implementation if the supply chain is characterized by medium as compared to low integration, and 542% higher odds of implementation if the supply chain is characterized by high compared to low integration.

Discussion

This paper examined the effects of fragmentation among building professionals on adoption and implementation of modular and integral energy-efficient technologies. Results demonstrate that fragmentation among professionals does not affect innovation implementation so long as the innovation is aligned with the fragmented industry structure and does not challenge current industry standards, craft traditions, supply chain boundaries, and work processes. However, integral innovations – no matter how cost efficient or promising in terms of energy saving potential – are unlikely to be implemented unless project professionals integrate to some degree. The greater the degree of integration, the more likely are integral innovations to be implemented.

This study has important implications about the role of professionals in innovation adoption in the building industry. The authors find clear support for the widely-held view that team integration is beneficial to project outcomes. Research across industries has found a positive correlation between integration and organizational performance (e.g., Barney 1991; Hoegl, Weinkauf et al. 2004; Barki and Pinsonneault 2005). This paper provides additional support for this assertion and demonstrates the important role that integration has when it comes to integral innovations.

The positive effect of supply chain integration on the adoption rate of integral innovations can be explained by several mechanisms. When the supply chain is integrated, coordinating the changed standards and procedures brought about by the innovation is easier. Further, integrated teams have broader expertise which helps them better understand the system-wide effects that integral innovations bring about. Horizontal integration eliminates longitudinal fragmentation of the involved professions and trades; they stay together project to project even in liberal market economies and can thus accumulate tacit knowledge associated with integral innovations over time. . Moreover, integrated teams are more likely to adopt a broader lens and a system-wide perspective, and therefore to welcome and even promote global improvements. The horizontal and vertical integration of the supply chain also helps align the diverse interests of the disparate players. Finally, integration helps bridge the abyss between silos of professions and fosters trust development and knowledge sharing.

While this research clearly demonstrates some of the advantages of integration, it also suggests that the effects of integration on innovation implementation are more nuanced. Contrary to prevailing wisdom among many in the industry, integration is beneficial only under specific conditions. Integration is only necessary when project teams attempt to implement integral innovations. When it comes to modular innovations, supply chain integration has no advantage over its fragmented counterpart. Modular innovations fit within existing system architectures and protocols and can rely on those to coordinate their integration into the whole system. Further, even when it comes to integral innovations, not all integration options are created equally. For example, an integrated procurement method such as Design-Build, by itself, has relatively little influence on the likelihood of implementation of integral innovations. However, when Design-Build is combined with horizontal integration, integral innovations are much more likely to be implemented.

Moreover, not only is supply chain integration unhelpful when it comes to modular innovations, it can be even detrimental. Other researchers have indeed found a positive correlation between localized innovations (modular) and industry modularity (Ethiraj and Levinthal 2004). Thus, integrating could lower the rate of modular innovations. Further, integrated firms with greater responsibility and higher capital costs bear a greater amount of risk and exposure to fluctuating industry demand in this notoriously volatile industry.

Moreover, while integration can be helpful in integral innovation adoption, if the firms remain integrated across certain specialty areas, they may be ill-suited to deal with the next wave of integral innovations that involve different combinations of specialty areas. For example, Afuah (2001) found that vertically integrated firms outperformed non-integrated ones when a new technology was introduced. However, if those same firms remained integrated when a newer technology was introduced, they performed worse than firms that were not integrated. Further, since integration may reduce the cost savings and incentives for modular innovations that accrue from competitive bidding and also poses risks of overall increased liability and greater susceptibility to fluctuations in demand, integration should be used cautiously. Integration is clearly a double-edged sword.

This research has implications for other industries with similar types of fragmentation. The transition from vertically-integrated hierarchical organizations into networks of specialized firms each producing individual modules that make up whole products is not limited to construction and can be observed in a large number of industries (Achrol 1997; Baldwin and Clark 2000; Schilling 2000; Jacobides 2005; Sinha and Van de Ven 2005; Staudenmayer, Tripsas et al. 2005). Industries characterized by this type of modular clustering (Baldwin and Clark 2000) can be either centralized or decentralized. In *centralized modular clusters*, such as the automobile or aerospace industries, network firms are tied to a powerful lead firm. In contrast, in *decentralized modular clusters*, such as the construction industry, network firms are connected to each other without a powerful coordinating firm (Langolis and Robertson 2003). The findings from this research – that integral innovations are slow to diffuse unless the supply chain is re-integrated to some degree, while modular innovations remain unaffected by integration – likely extend to other industries characterized by decentralized modular clusters. This highlights an important limit of modular product architecture and the corresponding industry modularity and fragmentation among professionals. While modular systems are advantageous in reducing complexity (Simon 1962) and even in increasing the rates of invention and adoption of modular innovations (Langolis and Robertson 2003), modularity has a detrimental effect on integral innovations. Given the importance of innovation to organization and industry development and survival (Teece and Pisano 1994; Eisenhardt and Tabrizi 1995; Nelson

1995; Utterback 1996), and the greater system-wide benefits that integral innovations can often provide in comparison to their modular counterparts, it is clear that modularity and fragmentation among professionals need to be considered very carefully.

Perhaps the most important practical implication of this research is that bundling and subsequent unbundling of involved specialty firms can be used strategically to drive the adoption of valuable integral innovations that would otherwise not diffuse (Sheffer 2011). Strategic integration can be effected through merger and acquisition of specialty firms involved in a given high-value integral innovation by a lead firm that takes on the system integrator role, or through long term strategic alliances among the involved specialty firms. Even in mature and extremely fragmented industries, such as construction, the supply chain can be deliberately reintegrated to define new and broader scope "super-modules" in order to diffuse integral innovations, thereby essentially transforming them into new modular innovations (Sheffer and Levitt 2010). This kind of strategic integration can help firms introduce integral innovations to mainstream markets and drive them "across the chasm" (Moore 2002) until they become new industry standards.

For example, Johnson Controls has acquired about 200 firms to create a new broad-scoped "super-modular" cluster for "lifecycle delivery and operation of intelligent building control systems" (Sheffer 2011). Eventually, as an integral technology gains enough market share, professional and trade practice and training will come to incorporate it, industry standards will develop to include it, and the industry will begin to re-fragment to take advantage of the benefits of finer grained modularization and risk reduction. The now-standard –"super-module" can again be procured as a series of modular packages through competitive bidding my firms delivering each of the redefined modular components, and strong third party integrators will no longer be necessary.

Acknowledgements

The authors thank Riitta Katila and John Taylor for their very significant contributions to this research. This research benefited from excellent research assistance by Sean Brennan, Tom Elson, Roshan Mehdizadeh, Jonathan Rowe, Kelly Shultz, and Richard Tsai. Special thanks to Dick Scott, Chuck Eesley, Adhamina Rodriguez, Jiffy Bennet Vermylen, Alexandra Chouldechova, Peter Morris, and Pete Samaras. This research was funded by the generous support of Stanford University's Collaboratory for Research on Global Projects and Precourt Energy Efficiency Center. Finally, the authors appreciate helpful comments from the editor and anonymous reviewers.

Table 1: Descriptives and Correlations

Descriptive Statistics and Correlations

Variable		Mean	S.D.	N	1	2	3	4	5	6	7	8
1	Implementation	0.28	0.45	2,599								
2	Innovation span	0.52	0.50	2,599	-0.25***							
3	Integration	2.04	0.68	551	0.06	-.002						
4	Cost	5.86	6.66	2,599	-0.22***	0.38***	0.01					
5	LEED score	39.12	8.96	2,599	0.07***	0	0.12**	0.01				
6	Profit organization	0.25	0.43	2,599	0.03	0	0.44***	.003	-0.12***			
7	Year	2002	1.80	2,599	0.03	0	0.24***	0.04*	0.23***	0.10***		
8	Firm size	1.66	0.74	2,116	-0.01	0	-0.25***	-.003	0.07**	0.02	-0.05*	
9	Firm core values	0.87	0.34	2,116	0.01	0	0.24***	.003	0.07**	0.09***	0.07***	0.02

* p<.1, ** p<.01, *** p<.001; two-tailed tests.

Table 2: Regression Results – Hypothesis 1

GEE Logistic Analysis of the Likelihood of Technology Implementation (N = 112 projects, 2576 implementation opportunities)

Variable	Model 1	Model 2	Model 3
Intercept	-1.04****	-1.05****	-1.07****
	(.11)	(.05)	(.05)
Innovation span			-.86****
			(.09)
Controls			
Cost	-.11****	-.11****	-.08****
	(.01)	(.01)	(.01)
LEED score		.02****	.02****
		(.004)	(.005)
Profit organization		.18*	.19*
		(.11)	(.12)
Year		.02	-.02
		(.02)	(.02)
Quasi Likelihood under Independence Model Criterion (QIC)	2920.68	2907.73	2832.99

* p<.1, ** p<.05, *** p<.01, **** p<.001; two-tailed tests. Robust standard errors are in parentheses.

Table 3: Regression Results – Hypothesis 2

GEE Logistic Analysis of the Likelihood of Technology Implementation (N = 23 projects, 528 implementation opportunities)

Variable	Model 1	Model 2	Model 3	Model 4
Intercept	-1.006****	-1.04****	-1.104****	-1.3****
	(.10)	(.10)	(.17)	(.20)
Innovation span		-1.02****	-1.02****	-1.82****
		(.17)	(.17)	(.32)
Team integration (High)			.31	.52*
			(.28)	(.31)
Team integration (Medium)			.03	.21
			(.27)	(.29)
Innovation span X Team integration (High)				1.34***
				(.39)
Innovation span X Team integration (Medium)				.84**
				(.40)
Controls				
Cost	-.11****	-.08****	-.08****	-.08****
	(.02)	(.02)	(.02)	(.02)
LEED score	.005	.005	.001	.001
	(.01)	(.01)	(.01)	(.01)
Profit organization	.55***	.58***	.51**	.50**
	(.20)	(.20)	(.23)	(.22)
Year	-.04	-.05	-.05	-.05
	(.06)	(.06)	(.05)	(.05)
Firm size	.17	.18	.17	.17
	(.11)	(.11)	(.11)	(.11)
Firm core values	-.36*	-.38*	-.44**	-.47**
	(.22)	(.23)	(.22)	(.22)
Quasi Likelihood under Independence Model Criterion (QIC)	620.47	599.29	599.92	596.71

* p<.1, ** p<.05, *** p<.01, **** p<.001; two-tailed tests. Robust standard errors are in parentheses.

Table 4: Effect Sizes

Effect Size Calculations

Variable	Coefficient	Effect Size
Innovation span	-1.82****	-84%
Integration (High)	.52*	68%
Integration (Medium)	.21	23%
Innovation span X Integration (High)	1.34***	542%
Innovation span X Integration (Medium)	.84**	186%
Controls		
Cost	-.08****	-8%
LEED score	.001	0%
Profit organization	.50**	65%
Year	-.05	-5%
Firm size	.17	19%
Firm core values	-.47**	-37%

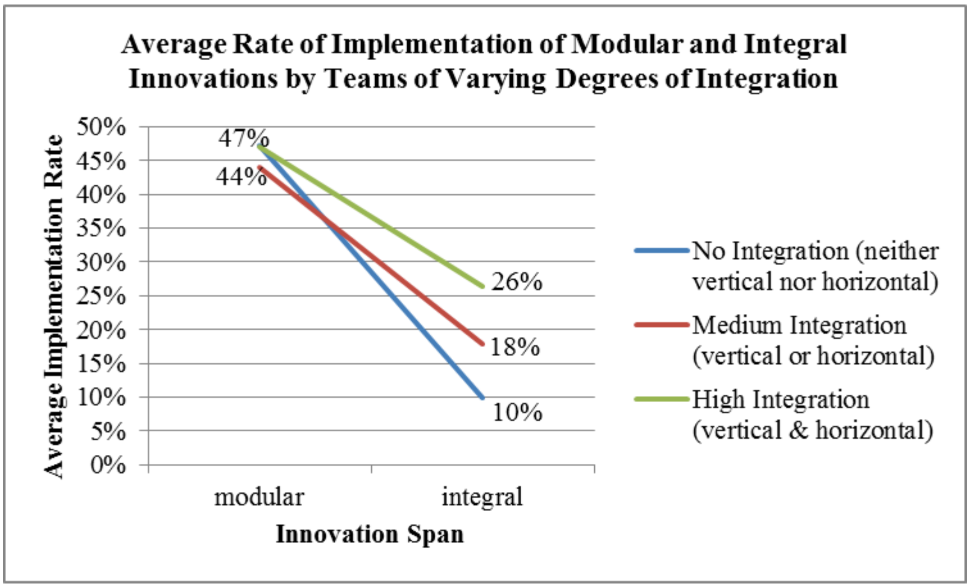
Calculations: effect size = (EXP(coefficient)-1*100%

Figure 1: Integration among Professionals

Integration Levels

		Horizontal Integration	
		No	*Yes*
Vertical Integration	*No*	Low	Medium
	Yes	Medium	High

Figure 2: Integration Levels and Innovation Implementation



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