Drivers of Technology Adoption – the Case of Nanomaterials in Building Construction

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Abstract

With the building and construction sector contributing significantly to global greenhouse gas emissions, there is great demand for resource- and energy-efficient construction materials. Manufactured nanotechnology products (MNPs) are expected to realize resource and energy efficiency through performance improvements in the strength, lightness and insulating properties of construction materials. However, the actual adoption of MNPs has lagged. This article examines how the construction sector in the United States assesses MNPs for adoption. Through patent analysis and interviews, we gauge the supply of MNPs and identify actors' roles in technology adoption. Results indicate that awareness of MNPs is more extensive than anticipated. Yet, stakeholders across the supply chain obstruct MNPs adoption in a multi-layered technology assessment process. We conclude that barriers to MNPs adoption can be overcome through intermediary activities such as product certification, comprehensive technology assessments, and "real-world" demonstrations.

Keywords

Nanotechnology; nanomaterials; building construction; diffusion; adoption

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1. Introduction

The building and construction sector, including through its stock of completed homes, offices, and multiple other types of buildings, accounts for 40% of greenhouse gas emissions globally [1] and 48% of greenhouse gas emission in the United States [2]. In 2011, President Obama cited improved energy efficiency in buildings as "one of the fastest, easiest, and cheapest ways to save money, combat pollution, and create jobs" [3]. Manufactured nanotechnology products (MNPs) are expected to realize resource and energy efficiency through increased strength, lightness, corrosive resistance, and other performance improvements of construction materials [4,5,6]. Yet, the building construction industry, which generates $989B of annual output in the U.S. [7], is often criticized for its recalcitrant approach to new technology adoption [4]. The industry is generally considered more risk-averse and fragmented than other sectors of the economy [8,9].

This article examines how the construction sector in the U.S. assesses MNPs for adoption. This case contributes to explaining how knowledge and learning, networks and strategic linkages, institutions and market forces drive technology innovation and adoption. In its simplest form, through knowledge acquisition, firms incorporate technological inputs to generate products and/or services. Yet, sectors change over time in response to technological innovations [10], while demand plays an important role in the adoption of technology [11]. Our study pays special attention to the barriers to the adoption of potentially advantageous technologies [12]. In particular, we investigate how the construction sector responds to evolving product demand and the rapid development of technological inputs, asking three questions:

(1) How do firms obtain knowledge about evolving technologies?

(2) In which ways do industry and organizational factors enable and constrain the adoption of new technological inputs?

(3) What is the role of market demand, voluntary programs, and public policies in the adoption of new technological inputs?

We address these questions through patent analysis and interviews in the construction sector in order to gauge the supply of MNPs and identify actors' roles in technology adoption.

This paper contributes to three domains of innovation research. First, with the focus on firm-level decision-making as a precursor to sectoral change, the study contributes to evolutionary economic research on the drivers of technology adoption, including both enabling and constraining factors [13, 14, 15,]. Second, the study contributes to research on sectoral systems of innovation by evaluating the impact of high technologies, such as nanotechnology, on supplier-dominated industries that experience limited incentives to adopt new technologies. Third, this research contributes to the literature on the diffusion of innovations [16] by examining a critical transition phase in the innovation pathway when patented prototypes are assessed for wider uptake by firms who are hesitant to act as first movers.

The paper is organized as follows. First, we review the literature on the functional role of MNPs in building construction inputs, accounting for potential determinants of MNP adoption. Second, we outline our methods, and third, we present results from the patent analysis, surveys, and interviews. Finally, we discuss implications for public policy, limitations, and potential avenues for future work.

2. Literature Review

Several streams of literature set the foundation for our analysis of MNP use in building construction. We draw upon work on firm capabilities and industry effects; forms of organizing; market demand, policy, and standards; and characteristics of the technology as determinants of and barriers to adoption.

2.1. Intra-firm capabilities and industry effects

The building construction industry can best be characterized as supplier-dominated [9]. The firms in the sector are often distant from science-based research, with those innovations used by building construction firms typically produced exogenously in other industries such as materials manufacturing or instrumentation. Building construction is the 9th largest industry in the US, employing over 5.5M people and contributing about 4% to gross domestic output [7]. Firms may specialize in services outside of on-site construction, e.g. architectural and civil engineering firms, to produce designs and construction specifications and to ensure that plans and renderings comply with local building ordinances. Principal architects, engineers, and lead contractors can be viewed as systems integrators [17]. Thus, building construction is an amalgamation of manufacturing and services, with innovation in the industry occurring across "a wide variety of economic and productive arenas" (Marceau et al., 1999, as cited by [8]).

The average firm size in the building construction sector, as measured by the ratio of total private sector employment to number of establishments, was just over 10 in 2007 [18]. Consequently, most building constructions firms, which generally employ small workforces, are limited in their R&D capabilities and absorptive capacity [8,19]. Absorptive capacity refers to the extent to which a firm can assess and then assimilate exogenously generated information to internal applications or problems for commercialization purposes [20]. Without absorptive capacity or in-house R&D talent, builders find it difficult to identify new inventions and/or understand the full implications of incorporating new innovations into their projects [8]. At the same time, firms will resort to *ad hoc* problem solving if a cost-benefit analysis cannot justify investments in higher level operating routines that give rise to innovative capabilities (c.f. [21]).

Architecturally sophisticated projects, however, may require firms to develop absorptive capacity and improved ad hoc problem solving, leading to the inclusion of new technologies. Technological progress may inform the cutting-edge of possibility in certain contemporary and experimental designs. It is equally plausible that firms conceiving avant-garde architecture search for new technologies to fulfill their development and aesthetic goals. Poole [22] discusses how innovative designers look to work closely with engineers in an effort to push beyond the existing boundaries of their design. This approach led to novel structural designs for the Millennium Wheel in London and the Bridge of the Future, a design concept for a bridge across the Grand Canyon. In such cases, architectural design explores the adoption of multi-functional materials that reduce resource and energy consumption [23].

As an alternative to developing absorptive capacity, some firms may exploit knowledge about emerging innovations through interactions with lead users, who incorporate and modify products to solve context-specific problems [24,25], even in "low-tech" fields such as construction [26]. In sum, search processes for new information may be diverse, mediated by costs of acquisition and processing and subject to project requirements.

2.2. Contracts and new forms of organizing

Economic activity is frequently organized in markets, hierarchies, or networks [27], though scholars explain such phenomena in diverse ways. For example, Williamson [28,29] argues that transactions characterized by recurring interactions under high levels of uncertainty and asset specificity are better exploited by firms than by markets. In addition, firms may be more efficient than markets because agents cannot write contracts to address all possible contingencies, and because hierarchies are more likely to curb self-serving behavior.

Powell [27] eschews both market and hierarchy in favor of *networks*, which offer a number of salient characteristics vis-à-vis the firm or market. For instance, whereas prices transmit information in markets, and whereas routines transmit information in the firm, relationships diffuse information in networks. Hansen [30] finds that complex tacit knowledge (i.e. sticky information) transmitted over weak ties is more likely to result in severe transfer problems and delays when compared to instances where information is conveyed via strong ties. (See also Granovetter [31] and Coleman [32] for detailed expositions of the strong and weak tie theses.) This is a salient concern for construction firms and project stakeholders, where time delays are often associated with budget overruns [33]. Hansen [30] contemplates the implications for organizations that may wish to reorganize around information needs, with management identifying and implementing the appropriate types of links to facilitate the diffusion of information across organizational boundaries. Given the complexity of implementing new technologies, we posit that networked forms of organization at the project level may positively impact the successful adoption of MNPs to satisfy project requirements.

One recent development in organizational design relevant to the building construction industry is the advent of integrated project delivery (IPD). IPD consists of three key actors – contractors, designers, and owners – who otherwise interact through contract-for-bid arrangements [33]. IPD reorganizes these actors to theoretically leverage complementary assets and capabilities in the construction, design, and financing of a project. However, in one example from the broader literature on contracting, Stinchcombe [34] explains how contracts may incorporate certain aspects of hierarchical organization, including command structures and authority systems, incentive systems, standard operating procedures, conflict resolution mechanisms, and non-market pricing. Thus, the effect of IPD on technology adoption is open to empirical validation as it may encourage innovative behavior, when for instance risk is more evenly dispersed across stakeholders, or it may restrict innovation (e.g. when contractual specifications are rigidly drawn to constrain new approaches).

2.3. Market demand, policy, and standards

Employing a market lens, Pinske and Dommisse [35] contend that the demand for and implementation of resources- and energy-efficient products in building construction is highly dependent on an expected distribution of benefits and costs. New technologies are inherently risky to adopt because relatively little is known about installation and maintenance requirements, as well as overall performance vis-à-vis more traditional technologies. Consumers, on the other hand, are unlikely to spend more on energy efficient appliances unless they can quantify cost savings and/or environmental benefits. Thus, with respect to potentially advantageous technologies, market forces alone may result in a form of market failure due to information asymmetries between builders and buyers.

Intermediaries have the potential to address such market failures. For instance, the U.S. Green Building Council (USGBC), through its suite of Leadership in Energy and Environmental Design (LEED) certifications may stimulate both supply and demand for green construction products [36]. As an example, architects and builders can use the LEED 2009 New Construction and Major Renovations Rating System to achieve green goals and subsequently attain LEED certification for a project. The checklist in LEED 2009 reflects a fairly diverse green commitment, ranging from, for example, energy and atmosphere to indoor environmental quality. Some of these goals may rely on new, innovative technologies to realize. In an industry where builders specialize in construction-related organizational competencies, it is likely that the pursuit of a LEED standard acts an incentive for builders to seek new knowledge and to identify products that help meet a client's green goals. Manufacturers, too, are cognizant of LEED as a demand enabling force for their products. Doran and Ryan [37] find that voluntary approaches to regulation result in a higher likelihood of "eco-innovation", even if such green practices are part of a larger marketing campaign intended to differentiate the firm from its competitors.

While USGBC maintains LEED's foundational principles of being "voluntary, consensus-based, and market-driven" [38], other public policies and standards involve more compliance-oriented measures. We provide two examples here, emphasizing difficulties with monitoring, enforcement, and maintenance. First, although not uniform across the United States, many states have adopted versions of the ASHRAE standard for commercial buildings [39]. Depending on the version, ASHRAE requires a certain level of energy efficiency compliance, suggesting that firms will search for new technologies to meet regulatory constraints. However, states routinely fail to monitor and enforce ASHRAE compliance [39], calling into question the level of awareness and search activity that firms engage in as a result of regulation. Second, updated building codes may promote innovative responses to environmental challenges [40]. However, local building codes are numerous and often slow to change. Outdated requirements encourage, if not require, construction sector firms to stick with conventional materials and methods.

2.4 Nanotechnology materials in building construction: Science, technology and innovation policy

Nanotechnology ("nano") is a prominent new and emerging science and technology that involves the measurement, characterization, and manipulation of particles at the nanoscale (one billionth of a meter). The nanotechnology domain embodies a diverse and growing array of interdisciplinary research, including the design and production of improved and new materials [41]. The President's Council of Advisors on Science and Technology maintains that in addition to its size characteristics, nanotechnology offers distinctive physical, chemical, and biological properties and [42]. The US National Nanotechnology Initiative (NNI) has sponsored over $18 billion in nanotechnology related research to-date and continues to outspend all other countries in the world. The 2014 Federal budget proposes $1.7 billion for the NNI [43].

Policymakers and industry acknowledge that addressing environmental health and safety (EHS) concerns is vital to the long-term success of nanotechnology as a catalyst for large-scale economic development [44]. For example, exposure to nanoparticles via inhalation, ingestion, or skin contact may result in biological effects such as inflammation, chromosome damage; interference in the nervous system; and impacts on mitosis, cardiac function, and the immune system [45]. Eco-toxicological impacts on the environment are possible, as well. These risks may persist throughout the product lifecycle from manufacturing and installation to onsite use and disposal [5]. EHS related research accounted for 5% of the NNI budget by 2010.

Despite current high costs and the aforementioned risk profile, the rate of adoption of nanotechnology materials in building construction is expected to increase due to 1) their highly advantageous properties (e.g. increased strength, durability, flexibility, lightness, and insulating properties), 2) new, non-incremental applications, 3) and falling costs as economies of scope and scale are realized [5]. A number of nanotechnology-enabled products are currently on the market [46,47]. For instance, self-cleaning windows, such as those installed at the London's St.

Pancras International Railway Station, use a thin-film of titanium dioxide layered onto the glass surface to break down dirt, which is then washed away from a hydrophilic surface. Nano-modified steel offers value across a range of applications due to its high strength, malleability, and anti-corrosive properties. Table 1 lists five different nanotechnology materials and their forecasted development timescale as stated by Lee et al [5].

[INSERT TABLE 1 ABOUT HERE]

3. Research Framework and Methods

A tool used to focus our investigation is the "innovation-chain +" framework, offered by Robinson [48], which in turn builds upon a model of technological innovation offered by Klein-Rosenberg [49]. The framework depicts a temporal sequence of technological development with overlapping phases that is understood and replicated by practitioners working on innovation [48,49,50,51]. On one side of the chain are institutional forces exogenous to the firm that act to coordinate and control technology (e.g. public policy or manufacturing standards). On the other side are "technology developers" (e.g. research councils, science districts and centers, or industry associations), which coordinate and promote the technology development platform. These forces may constrain or enable innovation. For example, public policies (e.g. building codes) may facilitate or obstruct MNP adoption depending on the nature of the regulatory requirements and the evolution of resource and energy efficiency, as part of broader sustainability goals in society.

Following the "innovation-chain +" framework, the reviewed literature suggests forces for facilitating and limiting the adoption of nanotechnology materials in the building construction sector. One the one hand, non-adoption is suggested in the distinctive characteristics of building construction as a risk-averse supplier driven industry, while on the other hand, new forms of organizing, policies and standards such as LEED, and government and private sector funded developments in nanotechnology may encourage adoption. Our research investigates the transition phase in the innovation pathway when patented MNPs are brought into compliance with industry and regulatory standards and assessed by a diversity of stakeholders for wider uptake [51].

Methods

We pursue a multi-methods approach, combining patent analysis and qualitative interviews with stakeholders, in addition to drawing on available secondary documentation. To examine the supply-side of MNP inventions for the building construction sector, relevant patents applied for and/or issued between 2000 and 2010 were captured. The search process for patents employs a modular approach, which specifies seven query components consisting of nanotechnology related keywords [52]. Additionally, the set of patents applicable to building construction is limited by: 1) searching for "building" or "construction" in the record or patent classification scheme, and 2) searching for records that contain one of the five keywords (e.g. concrete, steel, window, insulation, and brick, or related synonyms) identified in Table 1.

A patent is essentially an invention, with "further entrepreneurial efforts are required to develop, manufacture and market it" [53]. Rather than examine how suppliers fare with respect to their entrepreneurial efforts, we instead investigate the adoption environment downstream within the supplier-dominated industry. In particular, we identify three potential factors critical for MNP adoption:

- Internal firm capability – the set of routines used to *assess* new products prior to incorporating new materials into the building's *design.*
- The value chain – the forces that govern the *supply-chain* and *inter-firm organization* and *competition*.
- The policy environment – the framework of normative *regulatory* and *incentive* structures that encourage or inhibit the search for and implementation of MNPs.

The seven sub-components, italicized above, inform our analysis as both constraining and enabling forces in the technology adoption process at a critical transition phase in the innovation process (see Fig. 1, which also includes the supply of MNPs produced outside the industry).

[INSERT FIGURE 1 ABOUT HERE]

While there have been numerous attempts to quantify absorptive capacity and firm innovation, particularly in network contexts [e.g. 54], few readily available data sources exist to measure drivers and barriers of adoption. Thus, we employ qualitative methods. We sample in a selective yet *purposive* way from stakeholder groups in five organizational categories: architects, contractors, owners, engineers/consultants, and lead users. Our approach was purposive in that we actively sought to include firms that appeared to have a higher *a priori* likelihood of adoption. Using directories and web sources, we identified construction sector firms involved in complex building projects. Nineteen interviews (some in person, others by phone) were completed (from mid-2012 to early 2013) with respondents in the five groups covering a range of employment size ranges (seven firms of <500 employees; seven firms of >500 and < 5000 employees; and five firms of >5,000 employees). Eleven of the nineteen respondents were self-identified as technology-focused, although an effort was made to interview smaller firms not exposed to new research developments. Table 2 shows the distribution of the nineteen interviewees by actor type, number of employees, U.S. metropolitan area, and technology-focus. The interview protocol followed a logic model used to organize, in a causal sequence, the determinants of adoption. Data sources from the interview include notes, transcripts, and a survey. A separate researcher, not present at the interview, analyzed the transcripts.

[INSERT TABLE 2 ABOUT HERE]

Surveys responses capture three levels of increasing engagement – awareness, assessment (i.e. exploration prior to use) and use – with fifteen pre-selected MNP applications.[1] Responses were coded 1 if marked "yes" or 0 if blank or marked "no". Surveys that indicated "use" were coded 1 for use, assessment and awareness, while those that were marked "assessment" were additionally coded 1 for awareness. Responses were averaged individually and then grouped by stakeholder-type for reporting and analysis. A maximum score of 15 and minimum of 0 are possible. Levels of engagement are evaluated as: none (0), low (1-5), and moderate to high (6-15).

4. Results

4.1 Supply of MNPs – Number of MNP-related Patents

We applied our patent search and filtering approach to PATSTAT – a database of patent records from patent offices worldwide, including the United States, Europe, and Asia [55]. There

[1] MNPs selected from the Nanotechnology in City Environments Database by the Center for Nanotechnology in Society, are available by selecting "construction materials" in the advanced search at http://nice.asu.edu/.

were 1,454 MNP-related patent applications or grants registered from 2000 to 2010, which accounts for less than 1% of all nanotechnology patent applications or grants over the same time period [55]. There was a steady increase in MNP patent activity since 2000 in all five input areas (i.e. glass, concrete, ceramics and insulation). From a total of just under six relevant patents in 2000, 341 MNP patents had been applied for or granted internationally in 2010. The greatest proportion of MNP patents was in the window and glass category, accounting for over 50% of the patents issued each year from 2006-10, followed by concrete (33% in 2010), ceramics (23%), insulation (16%) and steel (14%).

Nearly two-thirds (64%) of these patents are assigned to corporations and are hence most likely to be incorporated into a commercial product, with the remainder assigned to individuals, government, universities, or non-profits. Many of these patents are general in nature such that the underlying technology could be applied to multiple MNPs: 363, or about 25.0% of the patents, are reported as applicable to more than one of the five inputs; 78 (5.4%) to two or more inputs; and 11 (less than 1%) to three or more inputs. In sum, this analysis confirms that there is an available and growing *supply* of MNPs with potential applications in building construction, which is more or less in line with expectations from prior technology forecasts. Patenting activity alone does not infer that downstream actors will be receptive or willing to adopt new innovations resulting from this inventive activity. However, our interviews with stakeholders were designed to provide information and insight on awareness and use, as discussed in the next section.

4.2 Awareness, Assessment, and Use of MNPs in the Construction Sector

We obtained responses on MNP awareness and use from eighteen of our stakeholder respondents (Table 3). Eleven stakeholders reported moderate to high levels of MNPs awareness (>5 MNPs identified). Four of these individuals had implemented an MNP, while an additional four were unable to assess any MNP for project implementation. Two of the eleven respondents with particularly high levels of awareness reported moderate levels of effort in undertaking any further technology assessment. Notwithstanding the relatively broad awareness of MNPs across actor types, there were relatively low levels of further technology assessment across architects, engineering consultants, and general contractors. MNPs with the highest levels of awareness include concrete reinforced with carbon nanotubes, self-cleaning glass enabled by titanium dioxide, and thin-film photovoltaic printed on reel-to-reel fabricators. MNPs with the highest levels of assessment include the self-cleaning glass and nano-porous bound nitrogen enabled insulation (e.g. Cryogel^{TM}).

[INSERT TABLE 3 ABOUT HERE]

In sum, across all stakeholders, a precipitous decline in engagement exists from awareness (40.0%) to assessment (12.2%) to use (1.5%). The gap between the high level of awareness and the low levels of use focuses attention on the means by which stakeholders assess novel MNPs. Still, given that MNPs are relatively new to building construction, and because research is still ongoing, overall awareness of MNPs is more widespread than anticipated, notwithstanding the purposive research design. These findings belie the rich and complex nature of awareness of MNPs and suggest that MNPs continue to offer future promise, yet few are poised for immediate, broad adoption. In the next three sections, qualitative considerations that limit or enhance potential adoption of nanotechnology are presented through interview descriptions and quotations (see Table 4).

[INSERT TABLE 4 ABOUT HERE]

4.2.1. Internal Firm Capability

Assessment Capacity

Many respondents noted that deliverables in building construction are qualitatively different than in other sectors of the economy, observing, for example, that product lifecycles span 50-60 years in contrast to much shorter durations in personal electronics. When the long-time horizon is salient to project stakeholders, actors value MNPs that are both cost competitive (in terms of up front expenditures) and offer enhanced features, such as energy efficiency and reduced operating cost.

> None of our property managers or engineers has ever done any of this. It's a pretty significant uptick in cost, but a dramatic cost savings in energy over the lifecycle of the building. We had people go to training seminars at [component supplier] to understand them. [We do] a lot of due diligence before we jump into this. (Owner, No. 2)

Yet, for most actors, MNPs must address problems specific to a given project in a narrowly defined context in order for assessment to occur. Moreover, when assessment does occur, the risk profile of the MNP may dissuade further exploration.

> I looked at nano-insulation, but it is easy to puncture, and then there are environmental and health issues related to breathing in the particles. (Architect, No. 2)

Four of the nineteen respondents tend to avoid new products, citing obstacles in cost, project timelines, and organizational resistance.

> New stuff is more expensive and then you need to go and justify it and get everyone to agree to it and that is just a waste of time. … You didn't want to lose a bid because you had some fancy idea to increase the R-value of the windows. Those things are set and then owner and architect get all upset about it, because it is like you're trying to tell them how to do their jobs. (General Contractor, No. 3)

> We need to finish projects on time and on budget, we don't get paid for creativity. Efficiency, yes, creativity, no? [laughing]. (General Contractor, No. 5)

> Do you know how hard that was, just to get away from the stick and mortar s*** everywhere, just for that one project. I mean, no one wants anything new. We had to fight like crazy for that [new technology]. (Owner, No. 3)

In contrast, the several respondents that do actively explore and experiment with new technologies emphasized the role of due diligence and testing and/or simulation in the assessment phase. Many times the capacity to explore and exploit new technologies lies with specific human capital (e.g. those who have a personal commitment and the requisite education to assess MNPs), though less frequently this competency is institutionalized within organizational processes:

> We can do some simple studies in-house. For instance, we heard about corroding caulking at one of our sites, so we had someone re-create the problem in an in-house experiment. We'll do mock-ups on our projects or finishes. That's embedded in our process. (General Contractor, No. 2)

Design and Implementation

Many of the interviewees emphasized the role of design in encouraging consideration of new technologies. For example:

> That is what we do right? It is really our designs that force others to change. (Architect, No. 4)

General contractors, conversely, questioned the extent to which novel design regularly occurs. Rather, they suggest that economies of scale and traditional processes limit innovative behavior:

> [Question: What could be pushed further?] Like the materials and design styles. They get stuck, I mean they will call a design novel or "game changing" but really we still pour the concrete and affix the glass exterior to the shell. What is new about that? When was there really something new and different in architecture? (General Contractor, No. 3)

> The drawings are what we go by when we build, but I haven't seen much new in the last decade. (General Contractor, No. 5)

Overall, the relationship between design and choice of technology is inconclusive. Our results show that one does not cause or advance the other. Still, although the design and implementation of a building project may not demand any particular choice of technology, adoption requires interaction across actors to achieve successful integration beyond the assessment phase.

> The place where we install the technology is not simple and there are all these codes about how much weight can be on the roof and you need [to work with the contractor]. (Lead User, No. 2)

4.2.2. Value Chain

Inter-firm Organization

In general, firms with high levels of liability exposure must carefully approach innovation.

> We are in a litigious environment. I have 3-4 lawsuits that I'm helping the company defend. It's a small percentage of all our projects, but it takes a lot of resources. Therefore, we need to select projects cautiously, and we need to defend our cause by stating whether what we've done is consistent with our industry. So by definition, innovation is somewhat inconsistent. It doesn't mean that innovation isn't important, but it has to be measured (Engineering Consultant, No. 4).

This perspective was echoed by others, who view well-established and clearly delineated relationships based on contractual obligations as constraining inter-firm relations and information sharing. Liability concerns and potential conflicts stemming from change orders prevent stakeholders from adopting novel materials. In contrast, owners expressed that legal action was an effective means to resolve conflict:

> I just sent a gentle e-mail to the CEO [requesting] them on the phone now with my attorneys and low-and-behold they apologize for the oversight and they deliver the materials in the very short-term. (Owner, No. 1)

Few stakeholders, except the architects, had experience with alternative forms of interaction, including integrated project delivery (IPD). While acknowledged by some as an intriguing way of sharing goals, risk, and a space for generating innovative solutions, few had heard of it and fewer trusted it.

> Heard of it, but it's a significant paradigm [change] for the industry, not every developer is set up to shift that risk. (Owner, No. 2)

New forms of inter-firm organization, such as IPD, had not been successful according to one general contractor.

> We build in the risk and clearly delineate the roles and responsibilities; it's about the [contractual] language and the team. Success is the end result we care about. … If something goes really wrong, everyone is going to be suing each other. The IPD projects we've seen in the industry to-date have not really been that successful. We've seen non-IPD projects do better. (General Contractor, No. 2)

One architect, on the other hand, felt IPD and other novel forms of organization are critical to innovation, allowing architects to revise their designs to realize more cost-effective solutions.

> The sooner you can get to integrated project delivery, it is huge for innovation. You can get real time pricing. … We were working with [company]. We looked at the traditional spec office buildings that could be converted to lab buildings. We re-imagined and looked at different skins. We were getting cost information. We looked at the traditional HVAC system for a specific office building. [Then], I looked at a different way to do it. We reworked it, so it ended up being the cheapest system. (Architect, No. 3)

Supplier Driven

The interview subjects appeared to be well integrated with various knowledge sources. The architects we spoke to participated in university workshops, and some had their own internal training or internal speakers programs. Several of them mentioned trade magazines, and some showed us product samples. More than one respondent mentioned product specifications as being critical to manufacturing and technology adoption:

> We have to negotiate production specifications because it's not possible to fabricate as-is." (Engineering Consultant, No. 5)

Difficulties in coordinating across the supply chain with respect to new products may span years of discussion and mediation. One engineering consultant described inter-firm knowledge transfers in the construction industry beginning from knowledge creation in the university environment to eventual application and post hoc assessment. This interviewee underscored the extensive amount of communication and testing needed to develop buy-in and commitment from stakeholders for new product and process adoption to occur. Because there is no precedent for the new approach, and because of the high-stakes involved with new projects, the quantity and quality of pre-implementation evidence substantiating expected benefits must be well-defined and articulated. In other words, in some projects, there can be very little on-site experimentation once implementation begins.

4.2.3. Policy Environment

Regulatory Drivers

Most interviewees did not reference particular legislation in terms of its ability to encourage technology adoption in building construction directly. For example:

> [Question: Are there any policies or regulations that makes you more sustainable or thinking about new products?] No, this is just my purpose. I do what I do for my kids for what needs to be done. (Owner, No. 2)

Some architects, however, did reference specific legislation and regulatory initiatives, beyond building codes and some of which are specific to particular geographies. For example, one architect noted that some California municipalities require "build-it green checklists", directing firms to certain compliance behaviors. Another respondent cited the near passage of the Energy and Security Act of 2009, which could have dramatically altered the energy efficiency requirements over a period of approximately twenty years [56].

With respect to building codes, the nature of the code's language may encourage the adoption of novel technologies by offering project stakeholders the latitude to search for innovative solutions:

> Requiring buildings to be more efficient will encourage innovation. But I'm not sure regulation will. If you can get codes to be more performance oriented and less prescriptive; for example, it has to be this tall and made of R20 insulation. In reality if you tell me that this is how it needs to perform and let me figure out how to get there, that is better. (Architect No. 3)

Similarly, one respondent noted that recent versions of the building code are inclusive but do not specifically encourage MNP adoption:

> The challenge is that the way the codes are written is based on consensus… But it [the code] doesn't do a lot of knee jerk changes, which may not be a bad thing. The building codes are really focused on life safety issues. If I build this beam will it fall down? By its nature, it is very conservative and inclusive... The nano products [established in the survey] don't fit into the building code. We hear people say that all you have to do is get it into the building code. Maybe there is too much reliance on satisfying the code. The code is just the minimal level of acceptable practice. (Engineering Consultant, No. 2)

This finding concerning barriers to technology adoption in regulations and codes is echoed by a contractor:

> Specifications are laid out pretty clearly beforehand … There seems to be a lot of attention on ergonomic work styles that eliminate certain types of injuries that happen on the job site … But there's been nothing new from the government as far as regulation or informal mechanisms of changing our way of work. (General Contractor, No. 1)

LEED program

Many interviewees highlighted the importance of LEED certification in influencing their green practices. However, LEED was not viewed as a facilitator of new technology adoption according to more than one interviewee:

> We have [resource- and energy-efficiency] goals, but they do not direct us toward new technology. They tell us to reduce waste, that is a design challenge, that is not a new material. (Owner, No. 4)

Two architects we interviewed, while echoing this negative perspective on the role of LEED in discouraging new technology use, believed that LEED indirectly drove innovation in the industry.

> Specifically with LEED, [we] encouraged people to be certified with the standard. We hold monthly LEED round-tables to share lessons-learned. (Architect, No. 2)

> Sustainability has increased the demand for innovation. … My approach is not to let LEED drive the project, but let LEED serve as a device for framing conversations, talk about what the customer wants. (Architect, No. 3)

Interviews with engineering consultants further suggested that LEED had the potential to encourage adoption of MNPs, but the ability to get credit for them in the LEED framework and the role of standardization and benchmarking limited this potential:

> When we started pursuing LEED credits for projects, we were forced to look into more detail about the effects of fly ash and slag cement from a structural engineering standpoint. For us, nanotechnology is big, because of the large quantities [of] fly ash and silica fumes … [that we] used to get LEED credits [as recycled materials]. (Engineering Consultant, No. 1)

> To get LEED certified, you can be novel in certain aspects. But, you have to use very well-known materials. Standardized function and benchmarking is important to prove standard performance. This [innovating] is very expensive in all ways. (Engineering Consultant, No. 5)

5. Discussion

Our analysis finds that there is an expanding supply of MNPs that could be adopted by the building construction sector with potentially significant resource and energy-efficiency benefits. Although not all of the MNP inventions we identified were "market-ready" and able to be applied without additional development, testing, and production scale-up, other MNPs had been commercialized and were available for use. At the same time, it was evident from our interviews that the system of actor relationships, capabilities, and practices within the building construction system itself is often not conducive to adopting materials innovations, including MNP innovations. Few firms in the sector have the capacities to comprehensively assess financial, technical, health, and safety aspects of a novel MNP. Currently, public policy, in the form of regulations and building standards does little to promote MNPs that increase resource and energy efficiency. This constellation leads to a mismatch between the supply of MNPs for resource and energy efficiency and the lack of adoption by firms in the construction sector.

The stakeholders we interviewed are largely of the view that MNPs currently offer few competitive advantages in either cost savings or significant features or benefits, or that any benefits are mitigated by a series of countervailing forces (e.g. cost and risk). Demand for construction solutions is usually framed by non-technical problems, and rarely do leading-edge technical solutions justify investments in assessment given their cost and uncertainty. Instead, process innovations and completing projects on-time and within-budget are the main drivers of competitive advantage in this industry.

Our results suggest that awareness of MNPs, while highest among the lead users, is not necessarily higher among architects and engineers than among contractors and owners. However, in line with the supplier-dominated industry thesis, the further upstream one travels, the more likely an organization is able to maintain formal, coordinated R&D capabilities to test new products and processes and to isolate performance variations. The difference in *assessment* capability may also reflect primary points of liability when introducing new innovations. Furthermore, most actors (with notable exceptions among lead users and some of the engineering consultants) rely upon historical case studies (a "lessons learned" approach) to evaluate technologies and new products. This places a heavy burden on "others" to innovate first, and as a result, this learning style does little to prepare firms to assess a novel MNP that has not been used previously. Every stakeholder is positioned to assess MNPs, yet few demonstrate the capacity to comprehensively evaluate the financial, technical and health and safety aspects. In sum, while awareness of MNPs is moderate, a series of systemic barriers obstruct a deeper level of technology assessment that can prepare the firm for implementation.

Our results indicate that, unlike other groups of actors, owners are uniquely positioned to influence project design and modes of inter-firm organization. Owners initiate projects, and as part of that process, they lay the ground rules for inter-firm interaction. This initiating action may include active input from other stakeholders throughout the value chain to influence decisions, as evidenced by 1) the problem solving abilities of engineers, 2) the design creation and material selection by architects, and 3) although relatively infrequent in current contractual arrangements, input from contractors. The structure of inter-firm relations can create an environment conducive to knowledge generation and sharing, or it can reinforce hierarchies and power asymmetries through contractual obligations enforced by threats of legal action. Our results indicate that any change in organizational form must be an owner-led undertaking.

Our research also indicates that government regulation does little to promote the search for new technologies, in part, because of the lack of a uniform, up-to-date, and widely disseminated code that increases energy efficiency requirements. Stakeholders asserted that LEED and other market based drivers, however, may encourage the adoption of MNPs and other leading edge products, though we found no clear causal relationship to exist. Often, interviewees considered LEED to be a barrier to adoption of MNPs since LEED places emphasis on supply-chain management and energy efficiency, not novel materials. Still, if society expects to increase resource and energy efficiency significantly as part of the transition to sustainability on a system-wide level, experimentation in certain niche markets may be a prerequisite to successful evolution [57].

This synthesis implies mismatches between the supply and demand of new relevant technologies as moderated by a complex system of industry-specific factors: On one hand, improved energy efficiency in buildings is a creditable sustainability goal, and new MNPs may offer one avenue to achieve more robust performance. On the other hand, the highly decentralized and risk-averse nature of the building construction firms may not be able to bridge this gap on its own. Although public policies have the potential to address systemic failures by "facilitating the coordination and growth of knowledge in markets" [12], our interviews suggested that they have limited effects on technology adoption.

Given this demand for policy intervention, we offer two related policy proposals to facilitate the assessment and diffusion of MNPs in building construction. First, an opportunity exists to sponsor more "real-world" application laboratories and demonstration buildings to showcase novel MNPs and conduct implementation studies and comprehensive technology assessments. Pilot projects can partially defray costs for early prototyping and testing experienced by small to medium sized businesses. This approach requires coordination across innovation system actors, however, and entails multi-scalar governance between the federal government, states, and municipalities. Such initiatives could be pursued in the private sector in locations like The Center for Innovation, Testing & Evaluation[2] (CITE) under development in New Mexico [58].

Second, established programs, such as the Small Business Innovation Research (SBIR) program, reach private entrepreneurs through US agency funding (e.g. links between the National Nanotechnology Initiative and the Department of Energy) to encourage the development of product innovations with public sector uses. Here, we offer a services-based analogy for the construction sector. Consider an applied research project with funds from NNI, which are dispersed by the Department of Energy through a SBIR Phase II award. The call for proposal might direct small firms to submit a novel design to construct a prototype wall section that demonstrates the best electricity generation and storage, maintains the highest R-value, exhibits the highest load, and offers the most lighting to an interior space. The grant could be awarded based on a multi-criteria assessment, and additional resources (e.g. from a university) could be funded to help measure technical proficiency and evaluate EHS risks. Once awarded, the grantee would build their proposed wall section at a DOE testing facility to demonstrate the multiplicative advantages offered by converging novel MNPs. Technology assessments that report performance indicators and cost data on prototypes would then offer a baseline for industry groups and public sector buyers.

Applying the insights gained from this study also informs the development of a model of MNP adoption in building construction. In Figure 2, we position overlapping phases of innovation ascending in a technology adoption cycle [59]. Each phase sits atop a pillar, signifying the goal (or intended outcome) and fraction of new adopters in each successive time period. In between these pillars, where the phases overlap, critical transitions and transfers of responsibility and knowledge occur between actors. One important transition found in the middle of a new MNP's lifecycle represents a critical interface between the R&D system and the

[2] CITE will be built as an unpopulated settlement to make possible a broad range of testing and evaluation of emerging technologies in a complex system environment.

supplier-dominated construction industry. It is here that we position our two policy interventions, and it is at this point that construction firms take on greater responsibility to acquire the knowledge required to adopt an MNP. We acknowledge that the figure is a linear simplification of innovation and that feedback loops between agents and industries, as well as environmental influences, contribute to more complex system phenomena. Still, the diagram suggests that the degree of success experienced in transferring innovations from one sector to another may determine the extent of system-wide adoption (i.e. saturation), particularly in later time periods.

[INSERT FIGURE 2 ABOUT HERE]

6. Conclusion

This study explores the mismatch between supply and demand of novel MNPs in the construction sector. The results indicate an increasing trend in nanotechnology patents in five different building construction inputs. However, stakeholders display moderate levels of awareness and low levels of assessment and use of MNPs. The study identifies critical aspects of the technology adoption process that impact adoption of MNPs and concludes with policy implications and recommendations.

The study is limited in that our sampling strategy was not random and therefore yields illustrative results, rather than "statistically significant" findings. Despite these limitations, the findings do highlight the dynamics found in the industry. Moreover, our exploratory approach and mixed-methods inquiry may inform future research design and more quantitative forms of modeling, as well direct researchers, policy-makers and decision-makers to a broad yet inter-connected set of innovation indicators. By exploring the critical transition into the construction sector this article builds on the concept that innovation is a sequential process influenced by social and technological governance factors [50,51]. Understanding stakeholders' routines that guide the adoption of technology in the construction sector to more embedded research approaches, including taking socio-technical integration research [60] out of the laboratory and into the field of organizational management and innovation studies more broadly.

Probing the innovation dynamics of a sector at one particular time offers an opportunity to assess potential pathways for social-welfare inducing progress within that sector. To that end, our work is positioned within the sustainability transition literature (cf. [61,62]) in that it links innovation capacity (i.e. R&D system capacity) with transition pathways (i.e. the adoption determinants) required for meta-level adoption of resource- and energy-efficient technologies. Our research is an antecedent to transition management and the creation of transition arenas, which host multi-level governance actors to develop long-term visions and practical guidance to realize sustainability goals [63]. A first step toward surmounting the identified barriers could include the creation of transition arenas for policy-makers, industry associations, firms, intermediaries, and academic researchers. The arena would offer an opportunity to reflect upon challenges and initiate a strategy to harmonizing industry and societal goals. The arena may also create a novel forum in which to assess MNP performance characteristics, costs, and risk profiles in a broader social context.

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Tables and Figures

Application	Nano-enabled Properties	Enhanced Functionality	Development Timescale
Steel Coating	Nano-polymer bonds to material surface, eliminates oxidation.	Steel coated with nano-polymer has higher resistance to corrosion.	2007 - 2016
Glass Coating	Titanium dioxide film affixed to surface of glass.	Decomposes organic materials upon contact which self-cleans glass surface.	2007 – 2012
Ceramics	Carbon nano-tubes or other nano-tube based materials are grown through bottom up approach to form nano-structured ceramics.	Improved resistance to stress; increased strength and flexibility; reduced deterioration; less volume and weight; surfaces can conduct electricity.	2012 – 2026
Concrete Strengthening	Carbon nano-tubes are mixed into the concrete replacing steel rebar.	Improved strength and reduced thickness; less volume and weight v. strength.	2012 – 2026
Insulation	Nano-pores of air or nitrogen are created within gels or polymers	Efficiency increased due to high surface-to-volume ratio. Reduced toxics and non-renewables.	2007 – 2016

Table 1. Nanomaterial improvements to existing building construction inputs. The development timescale is as foreseen in 2006 [5,19,20,46,51].

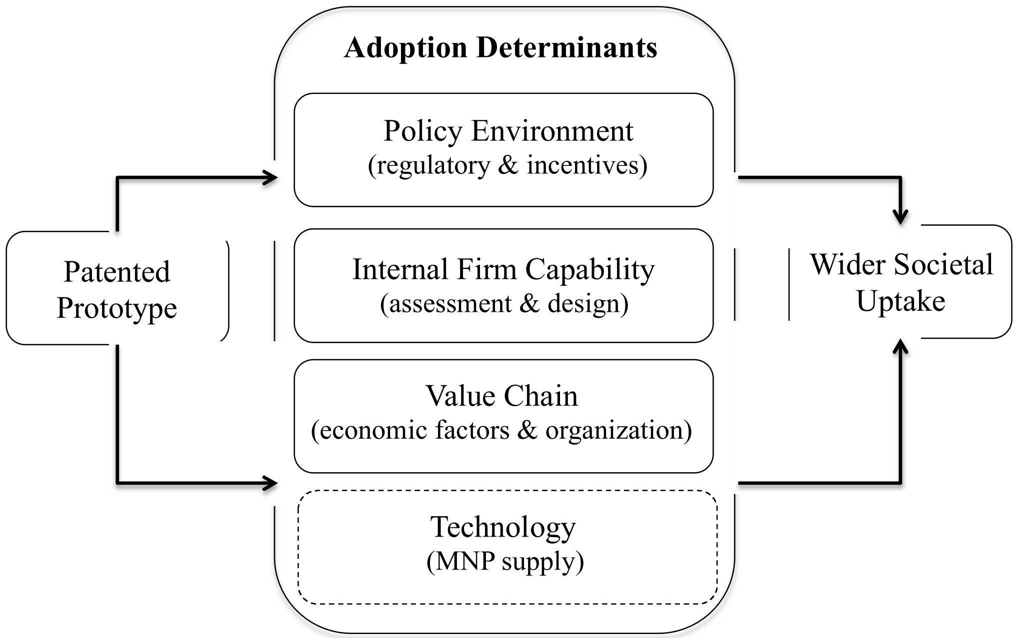

Figure 1. Adoption determinants in the construction industry at a key transitional phase in the sequential innovation process.

Firm Type	**Number of Employees and Metropolitan Area**	**Technology -focused**
Architect, 1	<25; San Francisco, CA	No
Architect, 2	75-125; Atlanta, GA	Yes
Architect, 3	>500; Chicago, IL	Yes
Engineering and Consulting, 1	>500; Houston, TX	Yes
Engineering and Consulting, 2	>5,000; Lafayette, IN	Yes
Engineering and Consulting, 3	<25; Detroit, MI	Yes
Engineering and Consulting, 4	>5,000; Detroit, MI	No
Engineering and Consulting, 5	<25; Atlanta, GA	Yes
General Contractor, 1	<25; Toronto, OT	No
General Contractor, 2	>500; St. Louis, MO	No
General Contractor, 3	>5,000; Phoenix, AZ	No
General Contractor, 4	>500; Phoenix, AZ	No
General Contractor, 5	>500; Phoenix, AZ	No
Owner, 1	>500; Atlanta, GA	Yes
Owner, 2	>500; Seattle, WA	Yes
Owner, 3	>5,000; Phoenix, AZ	Yes
Owner, 4	>5,000; Phoenix, AZ	No
Lead User, 1	1; Los Angeles, CA	Yes
Lead User, 2	1; Phoenix, AZ	Yes

Table 2. Characteristics of firms participating in the study. Firms listed by type, size, and region. Participants self-identified their firm as technology-focused (or not).

Technology	**O1**	**O2**	**O3**	**O4**	**A1**	**A2**	**A3**	**C2**	**C3**	**C4**	**C5**	**E1**	**E2**	**E3**	**E4**	**E5**	**L1**	**L2**
Concrete reinforced with carbon nanotubes	A	R	A			A	A	R					A	A		A	A	A
Self-Cleaning glass-enabled by Titanium Dioxide	A	R	U			A	R	A	R		R	R	A				R	R
Nano-coatings for steel surfaces that are hydrophobic	A		A					A		A	A	A	A	A				
Carbon nanotube, low density, high strength ceramics	A	A						A					A				A	A
Stainless steel surface coatings with nano-silver as biocides						A		R	A				A			A	A	A
Nano-porous, nitrogen enabled insulation (e.g. Cryogel^{TM})			A			R	R	U			R			A			R	R
Thin-film photovoltaic printed on reel-to-reel fabricators	A	R	A		A	A	R	A		A		A		A		A	R	R
Nano-polymer Coated Corrosion Resistant Concrete		A				A							A				A	
Organic Light-Emitting Diodes Embedded in Wall Paint	A	R	A	A		A				A		A						A
UV reducing glazes for glass with lanthanum hexaboride		A																R
Self-repairing concrete (reseals cracks via bio-active agents)	A	R	A									A	A	A	A			R
Alumina Foam Sandwich (AFS) Panels		R											A				A	
Coupled insulation and fire protection (e.g. Pyrogel®)	A	A						R			R					A	U	R
Self-compacting Concrete (SCC)			A									U	A					A
Nano-enabled high capacity and high-density batteries		A							A	A				A		A	R	R

Table 3. Stakeholders engagement levels. Individual stakeholder responses are A (aware), R (researched, shaded in grey), or U (used, white on shaded black). Key: O (owners), A (architects), C (general contractors), E (engineering consultants) and L (lead users). There are at total of 270 possible values with 108 A responses (40.0%), 33 R responses (12.2%), and 4 U responses (1.5%).

Interviewee	Key Facilitators	Key Barriers
Architect 1	Architectural design primary driver of change	History guides future projects
Architect 2	Architectural design drives innovation, but depends on the client	Construction management process
Architect 3	Sustainability has increased the demand for innovation	Find something that works and stay with it as long as possible.
Engineering and Consulting 1	Suppliers work to test, approve, and standardize new materials	95% of what we do already is with existing products
Engineering and Consulting 2	Cost: Value ratio is the mediator for competitive advantage	Foresight is limited to 5-years and not on long-term benefits
Engineering and Consulting 3	We pair architects, private home owners, commercial owners, GCs	Standards constrain, delay innovation.
Engineering and Consulting 4	Decreased cost, increased features	Only "tried and true" innovations offer competitive advantage
Engineering and Consulting 5	Reducing labor costs without increasing material costs	Building codes are restrictive
General Contractor 1	Architectural design is a primary driver of change	Bid specifications are pre-set
General Contractor 2	Firm shares knowledge about failures	Client-designer relationship is conservative, constrained by short-term budget
General Contractor 3	Any innovation will come from the owner and/or architect	New stuff is more expensive and everyone agrees it is just a waste of time
General Contractor 4	Material advancements come directly from architects	Novel designs are not considered early enough in the design-build process
General Contractor 5	Market demand drives innovation	I haven't seen much new in the last decade with regard to design
Owner 1	All new and remodeled buildings must meet LEED Gold standards	Bid method pre-determined due to institutional constraints, as are materials specifications
Owner 2	The architect or third party will vet the new material or product	New materials are more expensive
Owner 3	It is really our designs that force others to change	I mean, no one wants anything new
Owner 4	Brings user groups together to discuss construction project	We have goals, but they do not direct us toward new technology
Lead User 1	Community groups; green-friendly organizations	Bids contractually manage relationship and identify materials to purchase.
Lead User 2	Taking the time to evaluate new technologies to save on costs and energy	Sunk costs of existing investments

Table 4. Key facilitators and barriers as related to MNP adoption. Selected content is based on four rounds of synopsis of interview quotations.

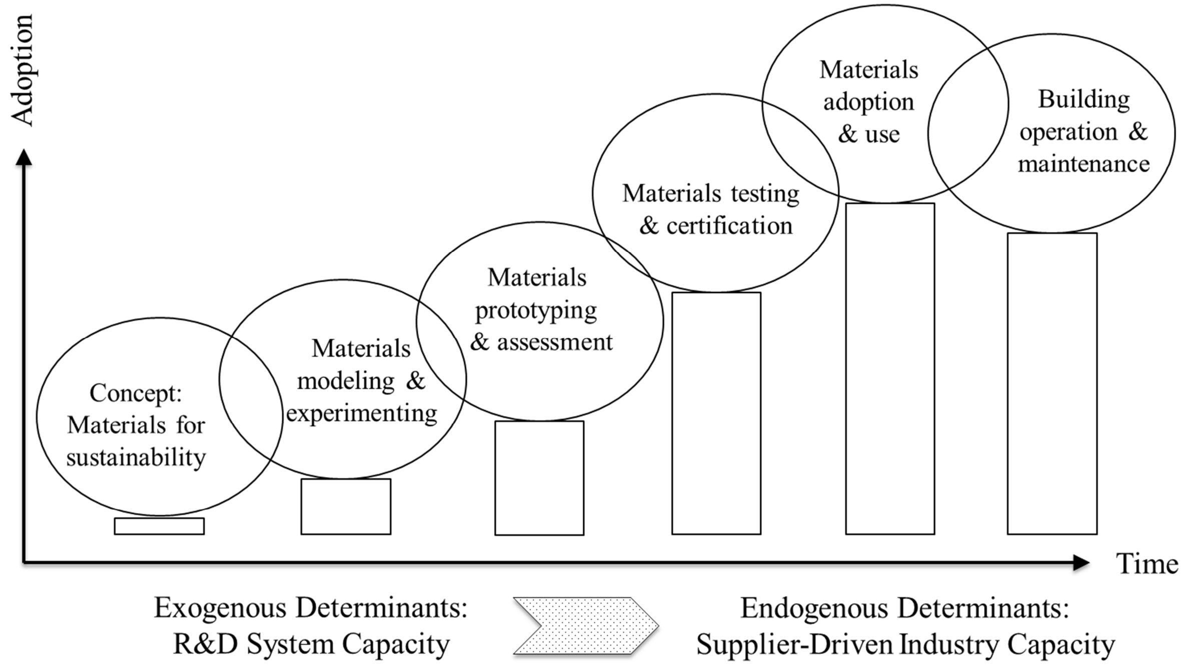

Figure 2. Temporal sequence of material innovation in the construction industry. The R&D system's capacity to push technological innovation encounters the construction industry's capacity to absorb new innovations. Figure adapted from Robinson, Kline and Rosenberg, and Sheffer and Levitt [49,50,59].