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Eco-efficient Construction: The Utilization of Nanotechnology and 3D Printing in the Sustainable Building Practices of the AEC Industry

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Eco-efficient construction is a broad topic that incorporates many facets of high-performance building practices, sustainability principles, life-cycle analysis considerations, and cost valuation of implementing methods, materials, and processes. New technologies play a significant role in the development of sustainable materials and methods in the architecture, engineering, and construction (AEC) industry. Nanotechnology and 3D printing are on the cutting edge of current research and development and exemplify sustainably focused eco-technologies. The study and implementation of nanotechnology and 3D printing are essentially emphasized by the focus on sustainability. This study investigates the advancement of nanomaterials and 3D printing and seeks to determine their current state of development and implementation in the AEC industry. In addition, concepts of sustainability are reviewed to reveal how they are aligned with eco-construction. Methods of evaluation are explored to better understand how sustainable building practices are supported in the AEC industry.

Keywords: 3D Printing, AEC industry, eco-efficient construction, eco-technology, nanotechnology, sustainable building.

Introduction

Innovation and advancement are often understood as underlying credos in the promotion and implementation of sustainable building practices. Sustainable building practices encompass far more than just the implementation of new technologies; however, it is the innovation in materials and systems technologies that are often hailed as exciting remedies to the problems faced in the built environment. While developments in materials, processes, and performance-based systems in the architecture, engineering, and construction (AEC) industry are integral to the evolvement of industry practices congruent with sustainable objectives, it is important to understand how these improvements play a role in eco-construction as well as the comprehensive concept of sustainability. In 1987, a report called "Our Common Future" was published by the Brundtland Commission and established the principle of the capacity to achieve sustainable development as a paradigmatic pursuit that "ensure(s) that it meets the needs of the present without compromising the ability of future generations to meet their own needs"

(UNGA, 1987). This was an important step in highlighting the need for renewed focus and a change in thinking in design and construction practices. The United Nations General Assembly at the 2005 World Summit described three components of sustainability (Huang et al., 2014) that outlined a collaborative framework of the environment, economy, and society working towards sustainability-derived goals which are further reinforced through cleaner technology, comprehensive decision-making, and education to act as an initiative in moving forward in sustainability across industries and institutions.

Sustainable building practices have become key objectives in the AEC industry. The implementation of sustainable technologies represents a substantial part of the endeavor to integrate sustainable building practices and employ high-performance design. The understanding of this synergism introduces the concept of eco-efficiency. The World Business Council for Sustainable Development drafted its initiatives around the idea of eco-efficiency by highlighting a holistic approach that integrates sustainable objectives with acceptable economic interests of businesses and communities alike (WBCSD, 2006). According to the WBCSD, "eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring the quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity". Eco-construction incorporates eco-efficiency as part of its efforts to achieve high-performance buildings. A high-performance building according to House Resolution 6 (2007) is a building that integrates and optimizes on a life cycle basis all major high-performance attributes, including energy conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations (United States Congress, 2007).

The development of advanced technologies often fundamentally pursues properties or processes that are more efficient and at least indirectly, more sustainable. New technologies such as nanotechnology and 3D printing should not singularly be legitimized by the attainment of scientific and manufacturing achievements but should be understood to act within the comprehensive scope of sustainable development. The U.S. National Nanotechnology Initiative states that "nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications" (NNI, 2020). 3D printing, also known as additive manufacturing, refers to the various processes of rapid prototyping used to synthesize a 3D object with the support of 3D computer-aided design (CAD) data. In 3D printing, successive layers of material are deposited under computer control to create the desired object (Casini, 2016). The collaboration between eco-technologies and sustainable business practices reinforces the concepts of eco-construction and forces it to provide a construct that goes beyond the confines of the underlying precepts of mere efficiency. Analyzing new technologies or what can be considered "eco-technologies" and how they fit into the overall framework of sustainable AEC industry practices provides a more informed idea of eco-construction and better ways in which it can be implemented in the larger scope of sustainability. Eco-technologies are a series of technologies developed to generate goods or services that meet human needs while minimizing environmental damage. In addition, these technologies are developed to efficiently take advantage of natural and material resources so that we can guarantee their sustainable use (Arquinetpolis, 2020).

The three components of sustainable development—environment, economy, and society all work in collaboration to support sustainable development. The intended outcomes of this whole-systems-based approach are legitimized because the participants of the system are constantly responding to one another and continue to adapt. It is not enough to provide efficient solutions because efficiency only approaches a problem by improving the processes involved and does not address the bigger issue of limited resources or the drawbacks to the pursuit of new technologies without taking into account the whole system of a building and the micro and macro environment to which it is connected. The purpose of this study of available literature and case studies sought to highlight the new and ever-evolving technologies of nanomaterials and 3D printing, their current state of implementation and production, how they fit into what is deemed "eco-construction", and how this supports sustainable building practices in the AEC industry.

Methodology

The methodology of this study took an integrative approach through a critical literature review establishing a narrative with an informed position on sustainable business practices in the realm of eco-construction. Figure 1 illustrates the research process framework used in conducting this study. The process involved first identifying innovative construction techniques and methods. The concept of 3D printing and nanotechnology implementation in the construction industry was identified, and literature was reviewed to begin to understand what these technologies were and what role they played within the AEC industry. In researching articles and case studies, a problem concerning the application of these technologies began to emerge. Terms such as eco-construction and eco-technologies were being boasted much in the same way as terms such as green technologies and sustainability are used glibly, thereby missing key issues in the application of holistic sustainable business practices with a focus on comprehensive positive outcomes across industries.

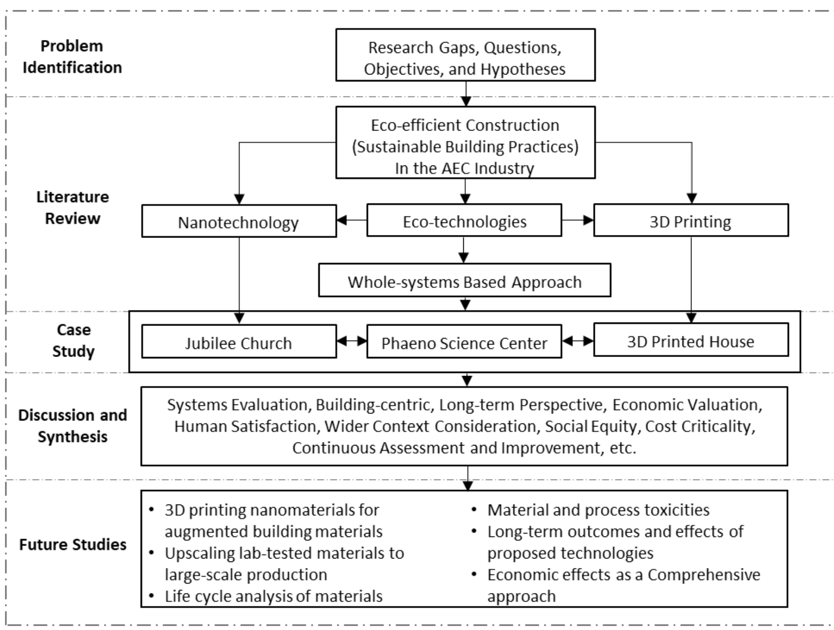

Figure 1: Research Process Framework

Often the prevailing attitudes within the AEC industry and the science and research community focus on one aspect of a generalized definition of sustainability and understanding of efficient use of resources. In addition, immediate economic interests can often be an overshadowing goal leaving all other considerations by the wayside. Within the research, questions were posed to understand the processes in developing and implementing new technologies, and the objective of the research became investigating the outcome of the performance of these eco-technologies in real-world case studies. The investigation was spurred by a hypothesis that reports of new materials or processes and their uses in built projects can often be a contrived delusion ignoring long-term outcomes, missed opportunities, or leave out detrimental effects. Inherent to this problem is the available literature and the presentation of built projects in various forms of media that perpetuate this strategy either deliberately to mislead or through a genuine mistake is failure to consider additional factors. Therefore, the methodology of this research collected a sampling of literature that in part forms a basis of knowledge for the AEC industry. The content presented in the literature and case studies was analyzed in order to develop a narrative of how eco-technologies were being presented in the literature. A synthesis of these viewpoints and findings within the reviewed literature and case studies provided the elements of this narrative that acted as a springboard in beginning to answer the question of how can eco-efficient construction better incorporate new technologies to promote a more comprehensively sustainable building practice.

Whole-systems Based Approach

Integrated building and cross-scale evaluation that uses a whole-systems-based approach provide a better framework for sustainability measures. Conte and Monno (2011) argue that sustainable building evaluation systems such as LEED (Leadership in Energy and Environment Design) are too "building centric" in that these evaluation systems are focused on making assessments detached from the built environment and have questionable value as the focus may be geared towards certification or the acquisition of "eco-technologies" for the sake of being labeled "green". Eco-technologies can be inappropriately used as the sole determinant in sustainability practices (Conte & Monno, 2011). While these eco-technologies may be eco-efficient, the more these eco-technologies are used in buildings does not necessarily correlate to an increase in sustainable cities or environments.

Expanded Scope of Sustainable Building Practices

The labels of sustainability, efficiency, and green building in addition to the idea of new and exciting technologies can be misused and treated as sole pursuits that end in achieving insufficient results. Berardi (2013) claimed that the problem with the building sector's criteria for sustainable development is that it supposes that a building is sustainable if it represents a healthy built environment, based on ecological principles and resource efficiency. This is limiting in that the measure is based on achieving efficiency which is often confined to the systems of the building itself with no regard to its relation to the environment and often in terms that measure or express quantifiable ecological terms (Berardi, 2013). Berardi concluded that a sustainable building has to promote in a long-term perspective its economic value, a neutral environmental impact, human satisfaction, and social equity. It is this expanded scope that encompasses a better representation of sustainable principles. Nanotechnology and 3D printing are complex and are still in their infancy in providing commercially viable products for the building industry which may not be able to offer complete prescriptions for an integrated approach to sustainability and business unless a more long-term value can be assessed.

Nanotechnology and 3D printing as Sustainable and Viable Eco-technologies

New eco-technologies either are not developed enough for use or oftentimes come at a higher price without a commensurate level of benefit. For example, Hanus and Harris (2013) found that at the time of their research the large-scale production of carbon nanotubes for use in cement composites was too costly. However, Pirard et al. (2017) have now claimed four years later that "technological innovations have allowed mass production of high-quality Carbon Nanotubes (CNTs) at a competitive cost and now represent a viable industrial nanomaterial" which allows for use in stronger concretes. Cost is a critical component in the development and use of materials and processes of any aspect in the building industry.

British economist Chris Freeman outlined five criteria in a 1984 article that were paramount in identifying emerging "technologies with the greatest impact" which listed drastic reduction in the costs of many products and services (Archibugi, 2017). In addition to cost, environmental acceptability was listed as the fifth criterion. Pacheco-Torgal et al. (2019) highlighted the importance of the 2030 United Nations Agenda for Sustainable Development's initiative for the construction industry as well as the implications for new technologies such as nanotechnology and 3D printing. New and emerging technologies research, as well as real-world testing, have provided evidence for the positive influence in the future of meeting sustainability goals not only in energy efficiency or reduction but also in improving safety for people and decrease in costs. El-Sayegh et al. (2020) have pointed out that 3D printing is still in its early stages of development and at this time is faced with several challenges and risks that cause barriers to fully realizing anticipated benefits. They further list the benefits of 3D printing in construction and separate these between constructability and sustainability. While there has been gradual progress in 3D printed building technology in the AEC industries, it is still a technology that is not at a stage in development that is able to produce large-scale eco-efficient construction or widespread sustainable impacts in the built environment. In addition, El-Sayegh et al. (2020) noted that the label "construction sustainable design" is to be used to increase quality while reducing the negative impact on the environment and that LEED is used as a quantifier of sustainability in projects. Using this kind of evaluation system is what Conte and Monno (2012) noted as causing a "building-centric" mentality that limited the scope of sustainable building practices.

A summary of this limited look into available literature reveals a wide array of perspectives and interpretations from differing market sectors. There are the material scientists, the AEC industry, and the environmental proponents who all have specific goals –some are in line with each other, merely similar, or completely different altogether. The literature review provided a small picture of how these differing viewpoints found commonalities but also highlighted diverging viewpoints. An examination of selected case studies demonstrated these perspectives on sustainable building practices. The findings are summarized in Table 1 and reveal the result of the endeavors.

Selected Case Study Applications of Nanotechnology and 3D Printing

The Jubilee Church in Rome was designed by Richard Meier in 2003 and was built with photocatalytic, "self-cleaning" precast concrete panels to achieve the gleaming white curved shell- structure (Povoledo, 2006). The self-cleaning properties are derived from nanoparticle titanium dioxide (TiO_2) that was integrated within the concrete along with Carrara marble aggregate (Cardellicchio, 2019). The intended clean white surface was supposed to combat pollution and act as a symbol of the pursuit of a more sustainable future (Traverso, 2019). However, the promise of self-cleaning was not completely met due to unexpected effects with a dirty façade (Cardellicchio, 2019). Rome has pozzolanic dust or a high concentration of volcanic ash made up of silica particles which TiO_2 cannot oxidize and therefore cannot initiate the reaction that is needed for self-cleaning (Cardellicchio, 2019). Cardellicchio pointed out that rain dust or rain that has a high concentration of desert dust caused an abrasive action to occur on the convex surfaces of the façade which increased the bond between the dust particles and concrete leading to diminished aesthetics and increased maintenance costs.

Architect Massimiliano Locatelli in collaboration with Arup Group developed a 3D-printed house with 35 modules printed in 48 hours with specially formulated concrete (Watkin, 2018). This technology would allow for housing to be built for the 1.2 billion people in the world that lack suitable shelter and would support temporary disaster relief housing. The project is named '3D housing 05', a name that refers to the five themes that relate to the house: creativity, sustainability, flexibility, affordability, and rapidity. The architect spoke further about the sustainability of the 3D printed house, which repurposes waste from demolitions — giving the production a zero net impact.

Self-compacting concrete has been developed through nanotechnology and offers concrete that does not need to be vibrated for consolidation which decreases energy, labor cost, and completion time (Babuka, 2016). The Phaeno Science Center in Wolfsburg, Germany was designed by architect Zaha Hadid and completed in 2005 with extreme forms and "tilted walls where concrete cannot be compacted with vibrators" (Tokarz, 2007). Self-compacting concrete not only features sustainable benefits but also offers additional innovation by allowing for the creation of concrete structures that were previously impossible to achieve.

Table 1
Case Study Analysis of Sustainable Business Practices

Jubilee Church	**3D Printed House**	**Phaeno Science Center**
Background Information		
• Rome, Italy • Built in 2003	• Milan, Italy • Built in 2018	• Wolfsburg, Germany • Built in 2005
Eco-technology		
• Self-Cleaning Precast Concrete Panels • TiO_2 integrated into concrete • Photocatalytic reaction	• 3D printed house • 35 Modules built in 48 hours • Specially formulated concrete • Built with a specialized printer	• Self-compacting concrete • No vibration for consolidation
Sustainable Building Practice		
• Attempt to employ an innovative material • Supposed to self-clean concrete façade and absorb surrounding air pollution • Symbol for the pursuit of a sustainable future	• Rapid housing production for a large population • Flexibility, affordability, and rapid construction for shelter in disaster relief recovery • Repurposes waste from demolitions	• Decreases energy, labor cost, and completion time
Results/Outcomes		
• Pozzolanic dust in Rome has silica particles which TiO_2 cannot oxidize preventing self-cleaning reaction • TiO_2 was found to convert NH_3 to NO_2 - proliferation of harmful ozone pollution • More maintenance problems with increased staining and negative environmental effects	• Project named '3D housing 05', referring to the five themes that relate to the house: creativity, sustainability, flexibility, affordability, and rapidity • Still in its infancy and yet to find a foothold in widespread implementation	• Innovative design methods to create tilted wall forms • Decreased energy, labor cost, and completion time • Increase in design innovation and environmental impacts

Discussion

Eco-construction has at its base sustainable intentions, but economic output has to be considered which can sometimes counteract sustainable pursuits. A common method used in the AEC industry to validate sustainable practices is the implementation of life-cycle analysis (LCA). Life-Cycle Analysis is a comprehensive method of describing the environmental impacts of a material or product, accounting for all phases of its life from resource extraction through final disposal or reuse. Also called cradle-to-grave analysis (Allen & Iano, 2019). According to Bidokia et al. (2006), eco-efficiency is seen as an effective method in achieving "environmentally friendly" goals that "maximize efficiency while minimizing the impact on the environment", and this includes studying "the lifecycle of a product from cradle to grave." Cucurachi and Rocha (2019) claimed that the LCA could be hampered by generalizations from the scientific community involving sustainability and safety. Nanotechnology still poses unknown risks, particularly with toxicity. It was found that only 8% of LCA studies done on nanomaterials "effectively quantified the effects from potential release and exposure" (Wu et al., 2019). These issues can greatly interfere in efforts to achieve sustainable practices and lead to hazardous situations. For example, in a study done by Kebede et al. (2013), TiO_2 coatings that are meant to clean the surface of concrete and glass and surrounding air of pollutants were found to convert ammonia (NH_3) to nitrogen dioxide (NO_2) which could lead to the proliferation of harmful ozone pollution. In an assessment of nanotechnology in eco-construction, Pacheco-Torgal (2019) claimed that there still has not been enough research or substantial evidential findings regarding the recyclability of nanomaterials or the effects of potential toxic exposures.

The research performed by reviewing selected literature and case studies revealed some prevailing attitudes that often focused on singular claims that simply touted sustainability as a stamp of approval merely in terms of efficiency or through singular implementations of innovative technologies, materials, and processes without performing a more comprehensive critical analysis taking into account important factors including LCA, material and process toxicities, long-term outcomes of proposed technologies, and economic conditions. The AEC industry's employment of eco-efficiency in its pursuit of high-performance design and sustainable building practices can often rely solely on quantifiable evaluation methods such as LEED and LCA. This systems-based approach as well as an overemphasis on the expected benefits of new technologies can misconstrue endeavors to reach a more comprehensive and authentic achievement in sustainability goals. Table 2 summarizes the common themes found within the selected literature and depicts a framework for comparative analysis within the context of eco-technologies used in the case studies presented.

Table 2
Comparative Analysis of Common Eco-technology Themes in Case Study Projects

Jubilee Church	**3D Printed House**	**Phaeno Science Center**
• Systems evaluations such as LEED	• Cost is critical	• Long-term perspective in its economic valuation
• "Building-centric"	• "Progress and the long road -Energy efficiency & safety"	• Human satisfaction and social equity
• Eco-technologies—sole determinant in sustainability practices	• "Evaluation systems -LEED—commonly used -LCA—more comprehensive"	• Wider context to consider

While a whole-systems-based approach provides a better framework for sustainability measures, it can focus too much on the building or project and be what Conte and Monno (2011) referred to as "building-centric" which can evaluate every factor solely from the perspective of how the building is affected. In much of the building sector literature, LEED was used as a quantifier of sustainability. Using this kind of evaluation system is what was noted as causing a "building-centric" mentality that limited the scope of sustainable building practices. This analysis reveals that there is a wider context that must be considered that examines the building, end product, or technological endeavor and its connection to its environment. This means that not only the immediate surroundings must be considered but also the project's connection and influence with the larger local and global community. Cost is a critical component, and implementing new eco-technologies is costly. However, advancement can improve energy efficiency, safety issues, decrease costs, and provide for large-scale commercial production, especially in the long-term perspective.

Conclusion

While further research is needed, there exists great potential for nanotechnology and 3D printing to impact the built environment in positive and sustainable ways. However, it is also evident that a stronger consensus is needed on how eco-construction can better support sustainability. The WBCSD (2006) highlighted the fact that eco-efficiency is not meant to achieve full sustainability ideals on its own. The problem involves exclusively looking to individual methods of assessment, singular technologies, or evaluations based on isolated systems and not integrated connections between building and larger context. The implementation of nanotechnology and 3D printing in the sustainable building practices of the AEC industry is highly influenced by cost and profitability. Within the collaborative framework of environment, economy, and society, costs and profits play a role in achieving sustainability, but perhaps more of a consensus could be reached by integrating Berardi's proposal of long-term economic perspective and social equity.

Other problems with the development of nanotechnology and 3D printing involve long periods of study and development of these technologies. For instance, the advancements currently being made in the processes of 3D printing nanomaterials for the development of augmented building materials offer a glimmer of the possibilities of new and promising technology while illustrating the problem of a lengthy timeline. Upscaling lab-tested materials to large-scale production pose yet another hurdle in reaching viable commercial products or processes. Methods of analyzing the life cycle of materials is also a long process that requires continual assessment, especially under the lens of sustainable building practices and goals. Implementation of eco-technologies should be carefully discerned so that expectations of performance and safety are met. Additionally, understanding of the need for a more complete appreciation and fulfillment of sustainable practices should be affirmed with evaluation methods that follow a whole-systems-based approach. Costs and profits, while integral to the viability of the business and the community, should be realigned with a long-term economic value perspective.

The concerns found to be evident through the qualitative research in the selected literature and case studies noted in this study highlight the need for a more comprehensive strategy of research, reporting, education, and implementation of sustainable business practices involving eco-technologies and eco-construction. The ideas identified through this critical literature review are novel and supportive of successful sustainable business practices but are found to be lacking and at times detrimental to the larger picture of sustainability and efficiency when they become singular pursuits and fail to come together to include all aspects of pursuing sustainable business practices. Future research and plans of action on the part of the AEC industry and scientific community should consistently and as a matter of protocol not only address LCA, material and process toxicities, long-term outcomes and effects of proposed technologies, and economic effects as a comprehensive approach but should also ensure within their research and presentation through published literature and publicized projects that these measures become part of a consistent multi-faceted program in which to pursue new technologies and sustainable eco-construction.

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