

3D PRINTING IN CONSTRUCTION SECTOR: CHALLENGES, OPPORTUNITIES, SUSTAINABILITY AND FUTURE PROSPECTS

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Cite This Article: Anil Kumar & Lucky Kumar, "3D Printing in Construction Sector: Challenges, Opportunities, Sustainability and Future Prospects", Indo American Journal of Multidisciplinary Research and Review, Special Issue 1, Date: 26th May 2024, Page Number 11-21, 2024

Name of the Conference: 12th Indo American International Conference on Multidisciplinary Research

Organized By: DK International Research Foundation, Perambalur, Tamil Nadu, India, www.dkirf.org

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Abstract:

This paper provides a comprehensive examination of the potential transformative effects of 3D printing technology on the construction sector which is currently poised for a technological revolution. Characterized by its ability to create structures directly from digital designs using additive manufacturing 3D printing offers a myriad of advantages including enhanced precision, faster construction speeds, cost efficiency and substantial waste reduction. These attributes not only promise to alter the landscape of construction practices but also the environmental footprint associated with building. Despite its vast potential the implementation of 3D printing in construction faces significant hurdles including technical limitations, regulatory barriers, the need for workforce retraining and issues of scalability. This study explores these multifaceted challenges and the opportunities that 3D printing presents particularly in fostering architectural innovation and sustainability. By leveraging an integrative approach that combines current technological assessments with practical case studies, this research outlines the current applications and predicts future trends of 3D printing within the sector. Additionally, it suggests strategic methods for the incorporation of 3D printing into mainstream construction activities aiming to maximize both economic and ecological benefits. This paper serves as a resource for Sector stakeholders and policymakers, offering insights that could help shape future practices and encourage the adoption of digital fabrication as a fundamental element of contemporary building technologies. The proliferation of 3D printing across major developed nations including the USA, China, Japan, Germany, the UK, France, South Korea, Saudi Arabia, Australia and India illustrates its global impact and adaptability in various settings from urban development to educational complexes.

Key Words: 3D Printing, Construction Sector, Sustainability, Opportunity, Challenges, Cost-Effective, Future Prospects.

Abbreviation: 3DCP: 3D Concrete Printing; BIM: Building Information Modeling; CAD: Computer Aided Design; FDM: Fused Deposition Modeling; SLS: Selective Laser Sintering; DMLS: Direct Metal Laser Sintering; SLA: Stereolithography; ABS: Acrylonitrile Butadiene Styrene; PLA: Polylactic Acid; IoT: Internet of Things; PETG: Polyethylene Terephthalate Glycol; ROI: Return on Investment; PBF: Powder Bed Fusion; DED: Directed Energy Deposition;

Introduction:

In the rapidly evolving landscape of construction 3D printing technology has emerged as a revolutionary force [1] poised to redefine traditional building practices. This innovative approach which synthesizes physical objects from digital data through a systematic layer-by-layer addition of materials represents a significant shift from conventional construction methods. With its unique ability to enhance speed precision and flexibility 3D printing offers numerous advantages including potential cost reductions decreased material waste and a boost in architectural [2] creativity. These benefits [3] suggest a promising future where 3D printing could fundamentally alter how structures are conceived, designed and constructed. However the transition to 3D printing in construction is not without its challenges [4]. The technology currently faces a variety of obstacles that hinder its full-scale implementation in everyday construction [5] activities. These include technical limitations such as the range of materials that can be used regulatory hurdles that need to be navigated the necessity for workforce skill adaptation and scalability issues that must be addressed to meet the demands of large-scale construction projects.

This research paper delves into a systematic examination of how 3D printing technology is influencing the construction sector by identifying these key challenges [6] and exploring the emerging [7] opportunities it presents. The study also aims to forecast the future prospects of 3D printing assessing its technological advancements, economic viability and sustainability impacts. Employing a detailed review of current technologies, augmented with case studies and expert interviews this analysis provides a comprehensive look at the current state of 3D printing in construction. Furthermore, it outlines a strategic roadmap for the technology's future development and integration into mainstream construction practices aiming to unlock its potential for enhancing economic viability and environmental sustainability.

Through this exploration the paper illuminates the transformative capacity of 3D printing technology suggesting that it has the potential to revolutionize the building processes of tomorrow making them more efficient, cost-effective and environmentally friendly. This study not only aims to contribute to academic knowledge but also seeks to inform sector practices and guide policy-making in the construction sector shaping a future where digital fabrication becomes a cornerstone of building technologies.

- Eduarda A. de Souza et al. (2024) [8], highlight 3D Concrete Printing (3DCP) as a ground-breaking technology in the construction Sector known for speeding up building processes and promoting sustainability through the use of eco-friendly materials. The study also identifies ongoing challenges such as the need for specialized equipment and skilled labour urging further research to enhance its application especially in underdeveloped regions.
- Toiba Tabassum and Ajaz Ahmad Mir (2023) [9], explore advancements in 3D printing for concrete, highlighting its potential to revolutionize construction by reducing costs and enabling complex designs with sustainable materials. They stress ongoing challenges in structural integrity, regulatory compliance, material testing underscoring the need for continued research and innovation.
- Rutuja R. Mhamunkar et al. (2022) [10], discuss the impact of 3D printing on construction, focusing on enhancing sustainability and efficiency through innovations in concrete mixtures and nozzle designs. The review also addresses key challenges such as interlayer adhesion and structural integrity emphasizing the need for more experimental data to overcome technological and regulatory hurdles.
- Asena Karslioglu et al. (2022) [11], highlight 3D printing as a revolutionary force in construction, enabling precise, efficient and cost-effective building methods with advanced materials like optimized cement-based mortar. The review notes challenges in scalability and technology acceptance with a call for further development in Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) for broader Sector adoption.
- Yin et al. (2021) [12], delineate the profound impact of 3D printing technology on the construction sector transitioning from conventional to prefabricated building techniques. The review discusses the use of gantry, robot and crane-based 3D printing systems for complex structures, while stressing ongoing challenges and the need for material innovation, rigorous structural testing, and regulatory development to realize its full potential in construction.
- Abhishek Pandit and Aditi Kumari (2021) [13], critically evaluate the advancements and challenges of 3D printing technology in the construction sector, highlighting its potential for faster, cheaper and less labour-intensive building methods. While the technology promises significant environmental and economic benefits, the review points out significant hurdles like material limitations, concerns about structural integrity and scalability issues that must be addressed through continued research and development to achieve full integration into mainstream construction practices.
- Lotfi Romdhane and Sameh M. El-Sayegh (2020) [14], discuss the transformative impacts of 3D printing in construction, highlighting its ability to enhance speed, reduce costs and allow for greater design flexibility and environmental sustainability. The review acknowledges that while 3D printing enables the creation of complex structures reduces waste and significant challenges such as material limitations, technological integration, regulatory compliance and workforce training need addressing to fully leverage this technology in mainstream construction.
- M K Dixit (2019) [15], explores the role of 3D printing in reducing the substantial energy use of buildings through improved construction processes and materials. The review highlights ongoing challenges like technology adoption and scalability suggesting further research to enhance material properties and integrate sustainable practices.
- Mehmet Sakin and Yusuf Caner Kiroglu (2017) [16], examine the integration of 3D printing with Building Information Modeling (BIM) in construction, emphasizing its potential to enhance sustainable development. Their study highlights how this synergy could streamline building processes, reduce waste and improve overall project efficiency.

The comprehensive review of existing literature underscores the transformative potential of 3D printing technology within the construction sector, highlighting both its vast opportunities and significant challenges. Advantages like increased construction speed, cost efficiency, design versatility and enhanced sustainability suggest that 3D printing could revolutionize architectural practices and construction methodologies. However, the sector must also confront and overcome several hurdles including the need for advancements in material properties, adaptations to regulatory frameworks, development of a skilled workforce and scalable operational models. As the construction sector nears a crucial technological tipping point, it is essential that ongoing research and collaborative efforts among sector stakeholders intensify. These efforts are vital to addressing the existing challenges and fully exploiting the capabilities of 3D printing. This review not only catalyzes further empirical investigations but also encourages the development of innovative strategies that could facilitate the integration of 3D printing technologies into mainstream construction practices, marking a potential revolution in the sector.

Objective:

To systematically examine how 3D printing technology influences the construction sector by identifying its key challenges, exploring the emerging opportunities it presents and forecasting its future prospects in terms of technological advancements, economic viability and sustainability impacts.

3D Technology & Material Used [17] [W.R-1-9]:

3D printing, also known as additive manufacturing refers to a group of manufacturing processes that create a physical object from a digital design by adding material layer by layer. Unlike traditional manufacturing methods that often require cutting away from a larger block of material or assembling components 3D printing builds objects directly from a computer-aided design (CAD) model increasing efficiency and reducing waste.

Historical Context:

The technology (Invented by Chuck Hull in 1983) began in the 1980s with stereolithography (SLA), where light was used to solidify a resin in a layer-by-layer process. Since then a variety of other techniques have been developed, including Fused Deposition Modeling (FDM), selective laser sintering (SLS) and direct metal laser sintering (DMLS) among others.

Core Technologies:

- Fused Deposition Modeling (FDM): Uses a thermoplastic filament, which is heated to its melting point and extruded layer by layer to build an object.
- Stereolithography (SLA): Uses an ultraviolet laser to precisely harden the resin in a vat layer by layer.
- Selective Laser Sintering (SLS): Uses a laser to sinter powdered material binding it together to create a solid structure.

Materials Used:

- Plastics: The most commonly used materials in Fused Deposition Modeling (FDM) includes Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG) and nylon.
- Resins: Used in SLA printing known for their fine details and smooth finishes.
- Metals: Used in DMLS and SLS includes stainless steel, titanium and aluminium.
- Ceramics and Other Materials: Expanding in use as technology progresses.

Challenges [18] (Figure 1):

Technical:

- Material Limitations: Current 3D printing technology is often limited to certain types of materials which may not meet all the structural and durability requirements of traditional construction materials like concrete and steel.
- Size Limitations: Many 3D printers have restrictions on the size of the objects they can print which poses a significant challenge for the construction of large-scale structures.
- Resolution and Accuracy: Achieving high resolution and accuracy in printed objects is essential especially in construction where structural integrity depends on precise specifications.

Regulatory and Compliance:

- Building Codes and Standards: There are currently few building codes that specifically address 3D printing in construction leading to uncertainty in compliance and safety standards.
- Certification of Materials: Getting new building materials certified for construction use is a lengthy and complex process often not aligned with the rapid innovation cycle of 3D technologies.

Economic Challenges:

- High Initial Costs: The initial cost of 3D printing technology, including the printers and materials can be quite high compared to traditional construction methods.
- Return on Investment (ROI): For construction companies the ROI of investing in 3D printing technology can be unclear, especially without widespread regulatory acceptance and proven durability of 3D-printed structures.

Workforce Challenges:

- Skill Gaps: There is a significant skill gap in the current workforce as many professionals are not trained to design for or operate 3D printers.
- Workforce Resistance: Traditional construction sectors may resist adopting new technologies due to the fear of job losses or the need to significantly alter their skills.

Scalability Issues:

- Production Speed: While 3D printing can be faster than traditional methods in some cases scaling it to the level needed for large construction projects remains a challenge.
- Integration with Traditional Methods: Integrating 3D printing into existing construction workflows without disrupting them is a significant challenge.

Sustainability:

- Waste Management: Although 3D printing is often touted for reducing waste, the actual environmental impact of the materials used and the end-of-life disposal process of these materials needs further evaluation.

- **Energy Consumption:** The energy consumption of 3D printing can be substantial depending on the technology and scale affecting its overall sustainability profile.

Environmental Impact:

- **Plastic Use:** Many 3D printers use plastics (like ABS, PLA, or nylon), which are derived from fossil fuels. The environmental impact of these materials includes pollution from the production process and issues related to end-of-life disposal.
- **Energy Use:** Certain industrial-scale 3D printers, especially those that use laser or electron beam melting can consume significant amounts of energy potentially offsetting some of the technology's other environmental benefits.
- **E-Waste:** As 3D printers and their components eventually reach end of life they contribute to e-waste. Proper recycling and disposal become essential to mitigate environmental damage.

Health Impact:

- **Emissions:** Some 3D printers emit ultrafine particles (UFPs) and volatile organic compounds (VOCs) during operation which can be harmful if inhaled. This is particularly a concern in poorly ventilated areas and may pose health risks like respiratory issues and other adverse effects.
- **Chemical Exposure:** The handling of certain materials, particularly in industrial settings can expose workers to potentially harmful chemicals. Proper safety measures, such as gloves, masks and adequate ventilation are necessary to minimize risks.

Opportunities [19] (Figure 2):

Innovative Design Flexibility:

- **Customization:** 3D printing allows for the creation of complex be spoke designs at no additional cost. This can lead to more personalized architecture which adapts to specific environmental or customer needs.
- **Architectural Freedom:** Traditional constraints of manufacturing and construction can be overcome with 3D printing allowing for new forms and shapes that can lead to more aesthetically pleasing and functional structures.

Cost Efficiency:

- **Reduced Labour Costs:** 3D printing can significantly reduce the number of labour hours required to construct buildings. Automated printing processes can decrease the need for large crews especially in dangerous or highly skilled areas.
- **Material Efficiency:** With precise material deposition and reduced material waste costs associated with raw materials can be significantly lowered.

Speed of Construction [W.R-10-18]:

- **Accelerated Building Processes:** Structures can be printed much faster than traditional construction methods can build which is particularly advantageous for urgent housing needs or disaster relief scenarios.

Sustainability Enhancements:

- **Reduction in Waste:** Traditional construction methods are often wasteful whereas 3D printing minimizes excess by using exactly the amount of material needed for each part of the structure.
- **Eco-Friendly Materials:** There is potential to use more sustainable recycled or locally sourced materials in 3D printing processes.

Improved Safety:

- **Safer Construction Environments:** The automation involved in 3D printing reduces human interaction with dangerous construction environments potentially lowering accident rates.

Market Opportunities:

- **New Markets:** 3D printing technology can open up new markets for custom-designed homes and buildings offering construction and design companies new business models and revenue streams.
- **Emerging Economies:** Developing countries could benefit significantly from 3D printing by leapfrogging traditional construction methods thus accelerating infrastructure development.

Technological Integration:

- **Smart Structures:** Integration of IoT (Internet of Things) sensors during the printing process can lead to 'smart' buildings that manage energy efficiency better and adapt to environmental changes.

Environmental Impact:

- **Resource Efficiency:** 3D printing can be more resource-efficient than traditional manufacturing processes. It adds materials layer by layer which minimizes waste compared to subtractive manufacturing processes that cut away large portions of non-recyclable materials.
- **Energy Consumption:** While 3D printing can sometimes use less energy than traditional manufacturing processes, especially in the production of complex or lightweight parts the actual energy efficiency can vary based on the type of 3D printing technology and the scale of production.
- **Logistics:** 3D printing can potentially reduce the environmental impact of shipping and logistics. Products can be printed on-demand at or near their point of use reducing the need for transportation and the associated carbon emissions.

Health Impact:

- Medical Applications: 3D printing has significant positive implications for health through its applications in medicine. This includes the production of customized prosthetics, dental implants and even bioprinting tissues and organs which could lead to ground-breaking advancements in medical treatments.



Figure 1: CHALLENGES OF 3D TECHNOLOGY [W.R -19]



Figure 2: OPPORTUNITIES OF 3D TECHNOLOGY [W.R -20]

Sustainability [20]:

Environmental Sustainability:

- Reduced Waste Production: Unlike traditional construction methods, which often involve cutting large pieces from raw materials and generating considerable waste, 3D printing allows for precise material placement. This additive process significantly reduces the amount of leftover materials as it only uses what is necessary for the structure's formation.
- Use of Recycled Materials: 3D printing technology has the capability to utilize recycled materials as feedstock. This can include recycled plastics metals or composites which not only helps in reducing the waste but also in lowering the environmental footprint associated with new material production.
- Energy Efficiency: Although the energy consumption of 3D printers can be high the overall energy efficiency can be improved through optimized printing processes and the development of more efficient printers. Moreover, reducing material waste and transportation (by printing on-site or using local materials) also contributes to lower energy usage over the lifecycle of a construction project.
- Sustainable Design Implementation: With 3D printing buildings can be designed to optimize energy use, such as better thermal performance and reduced heating and cooling requirements. The design flexibility offered by 3D printing enables the incorporation of natural light and ventilation which enhances the building's environmental efficiency.

Economic Sustainability:

- Cost Efficiency: By reducing material waste and labour costs 3D printing can lower the overall cost of construction projects. The precision and speed of 3D printing also contribute to shorter project timelines, reducing overall expenditure.

- Longevity and Maintenance: 3D printed structures can be designed to be more durable and easier to maintain reducing long-term costs. Innovations in materials can lead to longer-lasting constructions that withstand environmental stressors better than traditional materials.

Social Sustainability:

- Community Involvement and Job Creation: While 3D printing in construction might reduce the need for traditional labour roles it also opens up new opportunities for local communities in terms of jobs in digital design and 3D printer operation. Training programs and educational initiatives can help in skilling the workforce for these new roles.
- Improved Living Conditions: The ability to rapidly construct affordable and resilient housing can significantly improve living conditions, especially in areas affected by disasters or in low-income regions. The customization possibilities of 3D printing allow for culturally and climatically appropriate designs.

Some Cases Study:

- In a significant advancement in construction technology [21] and affordable housing, India witnessed the inauguration of its first 3D printed house. The project spearheaded by a pioneering 3D printing construction company based in Chennai, India, represents a milestone in the utilization of new building methodologies to streamline construction processes and reduce costs. The entire project (500 sq. ft.) was completed in 21 days. Figure 3 IIT-M [W.R-21]
- In an innovative leap for sustainable urban infrastructure, India's first 3D printed bus shelter was constructed for Godrej & Boyce in Mumbai. This pioneering project not only demonstrated the capabilities of 3D printing technology in public infrastructure but also emphasized sustainability through the use of recycled materials. The bus shelter was completed in just one week featuring a design that blends functionality with modern aesthetics. Figure 4 Bus-Shelters [W.R-22]
- This pioneering project marked a significant achievement in the field of Défense infrastructure with the construction of the first 3D printed housing unit for the Indian Defence, specifically designed for the Indian Air Force. Situated in Chiloda, Gujarat, this innovative project utilized advanced offsite construction techniques to deliver twin living quarters for airmen, demonstrating the practical applications and benefits of 3D printing technology in creating robust and efficient military housing. The 1500 sq. Ft. structure was completed in 1 month. Figure 5 Twin-Living-Quarters [W.R-23]
- In a ground-breaking development within India's public infrastructure sector, the first 3D-printed post office was constructed and inaugurated in Bengaluru. This project completed in just 43 days showcases the efficiency and scalability of 3D printing technology in governmental construction projects. The quick turnaround time from conception to completion highlights the potential for this technology to revolutionize public building projects in terms of both speed and cost-efficiency. Figure 6 Post-Office [W.R-24]



Figure 3: IIT-M [W.R-25]



Figure 4: Bus-Shelters [W.R-26]



Figure 5: Twin-Living-Quarters [W.R-27]



Figure 6: Post-Office [W.R-28]

Effects of Weather on 3D-Printed Buildings [22-28]:

Temperature Fluctuations:

- Thermal Expansion and Contraction: Materials expand when heated and contract when cooled. In regions with large temperature swings between day and night or across seasons, this can lead to stress on the structural integrity of 3D printed buildings. The repetitive expansion and contraction can cause fatigue in materials potentially leading to cracks and structural failure over time.

- **Effect on Material Properties:** Extreme temperatures can affect the performance characteristics of materials used in 3D printing. For instance, polymers and certain composites may become brittle in cold weather or overly soft in high temperatures impacting their durability and functionality.

Moisture and Humidity:

- **Water Penetration:** 3D printed structures, especially those made with porous materials like certain forms of concrete or composite are vulnerable to water intrusion. Continuous exposure to rain can lead to water seeping into the material which might cause structural weakening, corrosion and in colder climates freeze-thaw cycles that can enlarge cracks.
- **Humidity Effects:** High humidity can also affect certain materials used in 3D printing by promoting the growth of mold or mildew, especially inside enclosed structures where air circulation may be limited.

Wind:

- **Structural Load:** Wind can impose significant stress on structures particularly tall or slender ones. The layer-by-layer construction technique common in 3D printing must be robust enough to handle these forces. The design of the building must adequately account for wind loads, especially in hurricane-prone or high-wind areas.
- **Aerodynamics:** Buildings with sharp corners or flat surfaces can face higher wind resistance, potentially leading to damage. Aerodynamically efficient designs can help reduce this risk and stabilize the structure.

Sunlight and UV Exposure:

- **Material Degradation:** UV rays from sunlight can degrade many materials used in 3D printing, such as polymers, leading to discoloration, reduced mechanical strength and brittleness over time. Continuous sunlight exposure can accelerate this process.
- **Heat Build-up:** Direct sunlight can also cause heat build-up within structures, especially those with dark-colored or metallic surfaces. This can increase cooling requirements and affect the comfort levels inside the building.

Snow and Ice:

- **Load Bearing:** Accumulated snow and ice can add significant weight to roofs and other structural elements. The design of a 3D printed building must consider these additional loads particularly in areas prone to heavy snowfall.
- **Ice Formation:** Ice formation on edges and overhangs can lead to icicles or ice dams which might cause water damage if not properly managed through design or regular maintenance.

Future Prospects:

Future research will likely focus on refining 3D printing technologies to enhance building efficiency and structural integrity, developing sustainable materials to minimize environmental impacts and creating regulatory frameworks to support widespread adoption. Additionally, exploring the economic implications and potential job market transformations will be crucial to understand the broader impacts of integrating 3D printing into mainstream construction practices.

Conclusion:

The integration of 3D printing technology into the construction sector is heralding a transformative era characterized by increased innovation, efficiency and sustainability. This technology distinguishes itself by enabling greater precision in construction, reducing waste and accelerating building timelines thereby promising to revolutionize traditional building methods. Despite its potential the path to its broad adoption is paved with challenges including overcoming technical barriers, ensuring compliance with evolving regulatory frameworks, developing new materials, and updating the skills of the construction workforce. A collaborative approach involving sustained research, development, and partnership among various stakeholders, including innovators in technology, Sector veterans and government policymakers is essential for overcoming these hurdles.

As we look toward the future, the application of 3D printing in construction not only proposes to redefine Sector norms but also offers significant contributions towards environmental stewardship. This technology enables the construction Sector to deliver buildings that are robust, flexible and cost-effective, aligning well with the needs of modern society.

There is a pressing need for collaboration between governments, private sector players, scientists, engineers and other stakeholders to fully leverage 3D printing in construction. Potential applications are diverse ranging from constructing complex structures in challenging terrains like mountainous areas to developing infrastructure such as military installations, transportation hubs and educational facilities. The demand for this technology is expected to surge in the coming years.

To ensure successful implementation, it is crucial to focus on the selection of superior materials, innovative design approaches and comprehensive planning that takes into account environmental impacts, structural integrity and aesthetics. Involvement of skilled professionals is key to ensuring that the built environment is not only functional but also enduring and visually appealing.

Moreover, the integration of advanced materials such as nanoparticles-including silver, carbon nanotubes, titanium dioxide, silica, copper, clay, aluminium oxide and lithium compounds into polymer, ceramic or metallic matrices could facilitate the use of nanotechnology in further enhancing 3D printing

applications in the construction sector. These enhancements could lead to stronger, more durable and environmentally friendly building practices, propelling the Sector into a new era of architectural innovation and efficiency.

Acknowledgement:

The authors wish to express their profound gratitude to the Honourable Vice Chancellor, Prof. (Dr.) Bimal Prasad Singh, of Sido Kanhu Murmu University, Dumka and the Principal, S.R.I. Rizvi, of Sahibganj College, Sahibganj for their indispensable moral and ethical support.

We also extend our heartfelt thanks to the late beloved Shri Mati Jyoti Kumari, former BLIS Head at Sahibganj College, Sahibganj and to Vinay Kumar, Rishav Kumar, Aiswarya Prakash, Devrath Kumar, Abhisek Anand and Ankit Kumar from the Chemistry Department. Abhisek Kumar a student of B.Tech in Electronics. Their dedicated contributions in literature review, resource gathering, typing, printing, diagramming and sketching were invaluable.

Additionally, the authors acknowledge the support of numerous individuals not explicitly mentioned, whose diverse skills were crucial to this research. The collaborative efforts of the entire research community are deeply appreciated in this expression of thanks.

Conflict of Interests:

Authors declare no conflicts of interests.

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