

Decarbonising Building Construction Using Bio-Digital Fabrication: An ISM Approach

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Abstract. To embark on a truly sustainable path to have a greener environment, instead of putting electric motors on the building facades, an inherently natural resource should be opted for. Decarbonising the building construction, which is an energy-intensive process, needs a shift toward biomanufacturing integrated with innovative genetic engineering technology. This paper aims to examine the potential role of living microorganisms in making building materials through bio-digital fabrication. These bio-manufactured materials are bio-degradable and self-healing living spaces. The present study identified eight key success factors of bio-digital fabrication in the Indian context. From government policies to public awareness and technological advancements in bio-digital manufacturing, cost and scalability-related factors were among the identified factors. Further, an Interpretive Structural Modelling (ISM) based approach was used to evaluate the success factors that are interrelated and are part of a complex system. The results reveal that government policies and technological innovation are the root factors and independent factors.. Further, collaboration and education & training are the strongest strategic enablers on which all the structural and operational enablers depend. Reduced waste from construction demolition appeared to be a dependent variable, i.e., outcome variable. Overall, bio-digital fabrication is a promising solution toward decarbonising the Indian building construction industry.

1 Introduction

Building construction is an energy-intensive field with a significantly high carbon footprint. With rapid urbanisation and increasing demand for infrastructural development, over-consumption of resources and waste generation have increased manifold. Hence, sustainable alternatives to construction and building materials are imperative. Living building materials in this area are a breakthrough.

Living building materials are bio-manufactured building construction materials made from living organisms such as bacteria, fungi and algae. Unlike concrete and steel, these living organisms offer bio-degradable, self-healing and self-heating building materials, promising to be highly sustainable options. Bio-manufacturing refers to farming,

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constructing and improving the derived biomaterials for making building materials. Along with their mechanical robustness for constructing bio-buildings, these living bio-materials can also help save energy through their bioluminescence properties and by generating bioheat for residential heating purposes. Overall, these bio-construction materials can save on electric energy consumption, leading to low carbon emissions.

Using genetics in Architecture to create bio-building materials while controlling the growth of living cells can open up unlimited opportunities to become dependent on renewable resources and push India toward greater sustainability[1]. The Sporopollanin house in Barcelona is an example of one such building made from a living organism. Sporopollanin is a biopolymer with a robust outer skin made up of pollens and plant spores. Structurally, it is a chemically inert and mechanically resilient biopolymer. This is possible by integrating digital tools into bio-manufacturing[2].

Bio-digital architecture and genetics together can harness the potential of living organisms in making sustainable buildings[1]. Genetics represents an intersection between technology and nature. DNA, fundamentally, is a chain of biological information, whereas artificial software is a chain consisting of digital information. Natural DNA has four letters in its transcription, whereas the latter has binary transcription as zeros and ones. The bio-digital fabrication refers to DNA and software, together making a new building material for new architecture.

This research aims to identify the key success factors for developing Bio-digital fabrication in India. To address this issue, an ISM-based approach is utilised to identify and evaluate the interconnected factors, which are part of a complex system. This, eventually, will assist policymakers in having a clear pathway to bio-digital fabrication in the Indian construction industry.

The paper is divided into the following sections: The review of literature is presented under section 2, where specific details about the factors will be presented. The methodology, steps, analysis, and discussion is presented under section 3, followed by section 4, while section 5 reports the conclusion.

2 Literature Background

2.1 Government Policies (GOVT)

Government support in the form of subsidies, tax structures and regulations is an assured way to promote trust among architects and developers. The government can also align their housing-related projects, such as smart cities, with incentives for adopting bio-materials or bio-manufacturing fabrications to promote sustainable living spaces.

2.2 Technological Innovation (TECH)

Bio-fabrication is an emerging field with a promising future. Productive collaboration among Manufacturing corporations and biotechnology firms can create a pathway for advancement in genetics and bio-fabrications. Investing in research and development to utilise robotics, artificial intelligence and computation design tools for bio-digital fabrication and 3D printing would promote its development in India. Smart building systems can ensure monitoring of the performance of these biomaterials when integrated into a system.

2.3 Cost (COST)

When fully developed in terms of technology, bio-digital fabrication will be a cost-effective solution for constructing homes and buildings. With just a seed of sporopollenin, it is likely to be converted into a habitable space, such as sporopollenin houses in Barcelona (Barcelona, 2009-10)[3]. Genetically engineered bio-materials would have their growing capacities while being genetically controlled.

2.4 Scalability (SCAL)

Bio-composites from living organisms can be a solution to bio-fabrication. Its mass production, to achieve economies of scale, largely depends on technological advancements and supporting government policies. Biologically, the growth of microbial composites can be controlled through genetics and computational techniques.

2.5 Collaboration (COLL)

Bio-manufacturing, Bio-materials, and bio-fabrication are a few nomenclatures that indicate the need for a team of experts from the fields of biotechnology, construction, architecture and genetics[4].

As it is still in its nascent stage of development, its feasibility and scalability in each environmental condition are subject to further research and development.

2.6 The potential of the localised supply chain for bio-materials (SUPP)

Dependence on locally available micro-organisms, such as algae and fungi, would help in additional cost savings on operational heads. Simultaneously, this would be an attractive employment opportunity for locals with knowledge and expertise in the field

2.7 Reduced Waste due to Construction and Demolition (CNDW)

The property of being self-healing and naturally biodegradable would lead to reduced waste from construction and demolition, eventually contributing to the goal of becoming carbon-neutral in the production process [5]

2.8 Education and formal Training (EDU)

UIC Barcelona- Institute for Biodigital Architecture & Genetics offers a Master's programme in Biodigital Architecture[3], [4]. The course puts emphasis on educating about combining techniques from biology and digital fabrication. Courses designed to train the students to understand the nuances of construction, designing, architecture, genetic engineering, biomaterial sciences, ecology and environmental science are expected to equip them to fight the challenges of the 21st century.

2.9 Promoting the Prototypes (PROT)

Several academic and research-related events, such as the International Conference (BIODIG), ESARQ (UIC), organised in Barcelona every third year since 2008, have been helpful in spreading awareness among the academia and research community[3]. Several exhibitions held in various places such as Venezia (2018), Serbia (2018), Florencia (2009),

Valencia (2009) and in Barcelona itself many times (2003, 2004, 2010, 2013, 2014, 2022) have also played a crucial role in promoting the idea[3].

3 Methodology

When the factors are interrelated and make the system complex to understand, the Interpretive Structural Modelling (ISM) technique can be helpful. It systematically analyses the complex association of these multi-dimensional key factors. Warfield proposed the ISM approach [6]. ISM enables the evaluation of factors and gives a hierarchical arrangement and impact among each of the factors. ISM is a useful method when the factors of a complex system are required to be analysed [7]. ISM has been widely applied in various fields of study, including e-commerce, sustainable transportation such as inland waterways, sustainable energy sources such as ocean energy, circular economy and brand experience in retailing [8], [9]. The ISM procedure is explained below:

Step 1: Experts' judgments are used to obtain a structural self-interaction matrix (SSIM).

Step 2: SSIM is followed by the creation of the Reachability Matrix by considering '1' for an influential relationship and '0' for the otherwise relationship.

Step 3: The third and final step involves the process of Level partitioning. The rules that are applied while conducting the level partitioning are as follows. For each variable, reachability and antecedent sets are derived from the reachability matrix. Analyzing the two sets yields an intersection set that represents the elements that are common to both. When, in a certain circumstance, a variable's intersection set ties with its reachability set, that variable is considered as a high level variable within the relationship hierarchy. Sequentially, the variables is separated from the others, and the level partitioning is repeated. These repetitions remain until we reach a juncture where all the variables ultimately attain their certain levels within the hierarchy.

4 Results and Analysis

A sample of fifteen domain experts from the industry and academia both was recruited. Participants contained of experts with at least ten years of domain specific expertise in research and practice to whom the questionnaire was administered. The responses were warily acquired and taken to step 1, which formed the SSIM. Then reachability matrix is developed, which is given in Table 1. Further level partitioning is done, which is shown in Table 2-5 up to stage five. Level partitioning resulted in the finally desired outcome: an interpretive structural model (ISM) that represents the hierarchical relationships among variables. ISM is provided in Figure 1.

Table 1. The Reachability Matrix

	Reachability Set	Antecedent Set	Intersection Set	Level
GOVT(1)	1,2,3,4,5,6,7,8,9	1,2,6,7	1,2,6,7	
TECH(2)	1,2,3,4,5,6,7,8,9	2,5,8	2,5,8	
COST(3)	3,4,5,6,7,8,9	1,2,3,5,6,7,8,	3,5,6,7,8	
SCAL(4)	4,5,6,9	1,2,3,4,5,6,8	4,5,6	
COLL(5)	2,3,4,5,6,7,8,9	1,2,3,4,5,6,7,8	3,4,5,6,8,9	
SUPP(6)	1,3,5,6,7	1,2,3,4,5,6,7,8	1,3,5,6,7	I
CNDW(7)	1,3,5,6,7	1,2,3,5,6,7,8	1,3,5,6,7	I
EDU (8)	2,4,5,7,8,9	1,2,3,4,5,6,7,8	2,4,5,7,8	
PROT (9)	9	1,2,3,4,5,8,9	9	I

The reachability matrix results in the level partitioning, as explained in Step 3. Tables 2, 3, 4 and 5 represent the resulting five levels, which were later utilized to produce the interpretive model shown in Figure 1.

Table 2. Level Partitioning- Stage I

	Reachability Set	Antecedent Set	Intersection Set	Level
GOVT(1)	1,2,3,4,5,8	1,2	1,2	
TECH(2)	1,2,3,4,5,8	2,5,8	2,5,8	
COST(3)	3,4,5,8	1,2,3,5,8	3,5,8	
SCAL(4)	4,5	1,2,3,4,5,8	4,5	II
COLL(5)	2,3,4,5,8	1,2,3,4,5,8	3,4,5,8	
EDU (8)	2,4,5,8	1,2,3,4,5,8	2,4,5,8	II

Table 3. Level Partitioning- Stage II

	Reachability Set	Antecedent Set	Intersection Set	Level
GOVT(1)	1,2,3,5	1,2	1,2	
TECH(2)	1,2,3,5	2,5	2,5	
COST(3)	3,5	1,2,3,5	3,5	III
COLL(5)	2,3,5	1,2,3,5	3,5	

Table 4. Level Partitioning- Stages III

	Reachability Set	Antecedent Set	Intersection Set	Level
GOVT(1)	1,2,5	1,2	1,2	
TECH(2)	1,2,5	2,5	2,5	
COLL(5)	2,5	1,2,5	2,5	IV

Table 5. Level Partitioning- Stages IV & V

	Reachability Set	Antecedent Set	Intersection Set	Level
GOVT(1)	1,2	1,2	1,2	V
TECH(2)	1,2	2	2	VI

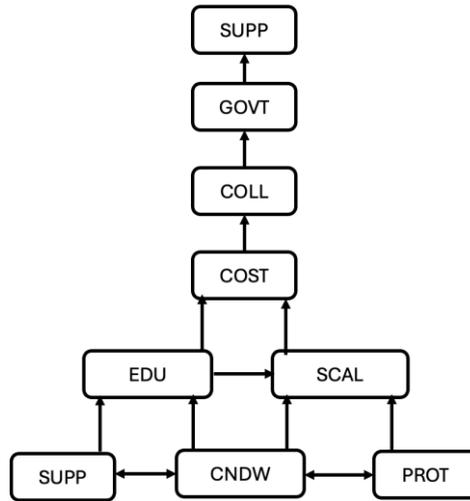


Fig.1. Interpretive Structural Model

The analysis of the interpretive structural model presents that the technological innovation (TECH) is the most influential enabler in the adoption of biodigital fabrication, closely followed by government policies (GOVT). TECH functions as an independent factor with high driving power, while government support emerges as the strategic enabler, which channels government policies around subsidies, incentives under initiatives such as Smart City. GOVT and TECH together can encourage genetically engineered construction and AI-based designs for significant growth of the domain. Moreover, collaboration and cost are structural enablers that would have a great deal of impact on shaping the body-digital fabrication system. Collaboration among policy makers, researchers, training organisations and architects would act as a catalyst for mainstreaming the novel bio-building materials for sustainable constructions and fuelling the innovation. Further, scalability and Training & education (second lowest in the hierarchy) are operational variables. They largely depend on the cost, potential collaborations, and supporting ecosystem provided by government policies and technological innovation. Eventually, localised supply chain, construction and demolition waste reduction and prototype promotion are the most dependent variables, which are also known as outcome variables. These are the tangible sustainability benefits that materialise when fundamentally driving enablers are in place.

The present study offers several practical implications for policymakers. Prioritising technological advancements and fostering collaboration between manufacturers and biotechnologists will be essential to reducing costs and achieving economies of scale. Integrating skill development and training modules into formal education systems can further support scalability by preparing a skilled workforce. Localised production and supply chains not only reduce operational costs but also create income opportunities for smallholder farmers and semi-skilled workers. The growth of bio-digital fabrication is therefore expected to contribute to socio-economic development through education, training, and diversified sources of livelihood. Ultimately, the adoption of self-healing and biodegradable construction materials will drive decarbonization and environmental sustainability by reducing waste management burdens and minimising maintenance requirements.

5 Concluding Remarks

The ISM results from the present study highlight that bio-digital fabrication in India heavily depends on Technological innovation and government policies. Hence, the goal is to raise

awareness among policymakers, architects, builders, researchers and other stakeholders of the climate crisis caused by harmful building materials & construction practices. This research study emphasises identifying the key enablers of bio-digital fabrication by employing an Interpretive Structural Modelling (ISM). The foremost goal of this research is to examine the hierarchical relationships among the key enablers that would foster the development and widespread adoption of MF in India.

The study underscores the critical role of technological innovation as an independent driver, facilitating advancements such as robotics and AI-based bio-digital designs for sustainable building systems. In parallel, supportive government policies—through tax incentives, subsidies, and regulatory frameworks—are essential for achieving the UN Sustainable Development Goals. Together, these enablers can accelerate the promotion of bio-digital fabrication for sustainable building materials, 3D bio-printing, and smart monitoring systems, thereby laying the foundation for mainstreaming this field while contributing to sustainable living environments, reduced maintenance needs, and long-term environmental sustainability.

Collaboration and cost emerge as critical structural enablers. Effective collaboration among policymakers, researchers, architects, biotechnologists, and manufacturers can facilitate knowledge exchange, enhance research and development capacity, and address feasibility challenges. At the same time, advancements in technology are expected to drive cost reductions, thereby promoting wider adoption of biodigital fabrication and enhancing its competitiveness with conventional construction methods.

Large-scale adoption of bio-digital fabrication is expected to contribute to environmental preservation by lowering energy use and reducing carbon emissions associated with repairs and maintenance. Its scalability, however, depends on sustained investments in training and education. Emphasising skill development, modular training, and integration into academic programs will be critical to accelerating broader acceptance. Finally, localised supply chains, reduced construction and demolition waste, and prototype promotion emerge as highly dependent factors, representing the tangible outcomes that can realise the full sustainability potential of this approach. Genetically engineered building blocks and materials are a promising solution at several fronts, including the reduction of construction and demolition waste, leading to a reduction in the management load through the self-repair mechanism of genetically engineered microorganisms used in building materials. Further, a localised supply chain will have dual benefits of creating a diversified source of income for local producers and sustainable transportation, warehousing and other related logistical functions, resulting in lower carbon emissions.

The present research opens avenues for several future works in the domain. Future researchers might wish to develop experimental designs to test the system's effectiveness. Additionally, longitudinal data can be analysed to identify and examine other potential enablers and barriers. As the domain is at its inception stage, experts' opinion is also expected to evolve over time with practical experience of users.

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