***Ar. Gunjan Jain** completed her B.Arch from G.G.S.I.P.U New Delhi in 2003 and Masters in Planning with specialization in Environment from School of Planning and Architecture,New Delhi in 2005.*

She has 16 years of experience, wherein she has worked on projects in association with CPCB, GTZ, MoEF, HUDCO, DDA, SPA Delhi (institutional projects) and well known private firms in Delhi. She has also been actively involved in teaching since 2010 as a visiting faculty at SPA Delhi and architectural colleges under IP University.

She is presently working as an Assistant Professor(on contract) in the Department of Architecture, SPA New Delhi and is also pursuing her PhD research in the field of energy efficiency in the built environment from the same department.

Dr. Shuvojit Sarkar ***completed his graduation in architecture from TVB,School of Habitat Studies,G.G.S.I.P.U New Delhi in 2002 and Post Graduation in Planning with specialization in Environment from School of Planning and Architecture,New Delhi in 2005. He completed his Doctoral Research in the year 2019 from Jadavpur University.***

He has almost 17 years of experience in research and academics.He has worked on various funded research projects in SPA,Delhi apart from institutional consultancy projects.

He is presently engaged as an Associate Professor in the Department of Architecture, SPA New Delhi. His fields of research and interest include Sustainability, Environmantal Stewardship and AI.

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Material Oriented Design Approach
A Paradigm shift in Form Generation

Ar. Gunjan Jain[1]*
[1]*Assistant Professor,
School of Planning and Architecture, New Delhi

Dr. Shuvojit Sarkar[2]*
[2]*Associate Professor,
School of Planning and Architecture, New Delhi

Abstract

The study investigates futuristic material-oriented design approach in generating forms, wherein the form generating process is informed by the combination of material properties and its behaviour, keeping in mind its impact on the environment. It is an alternative to the present-day form oriented design approach, wherein the material aspect is often taken up after the form generation, within the limitations of the known traditional construction techniques. The need of the study originates from the fact that the nature inspired material-oriented design approach could be the potential need of the hour for a more holistic sustainable architecture and to address the global emergency of climate change.

The current experimental practices involving the concepts of 'material ecology' and 'material morphology' along with their design process and implementation have been explored by reviewing and critically analysing the works of Ar. Neri Oxman and Ar. Achim Menges. An effort has been made in the study to evaluate the pros and cons of implementation of both the concepts in the form generation process, so that the architects and designers can take a more informed decision. The study relies on secondary case examples as very few works have been attempted globally on this

emerging concept.

The detail study of the works on this concept reiterates that built form generation through this approach addresses the complex interrelation between materiality, form, structure and space, the related processes of production and assembly, and; the varying degree of performance effects that emanate from the interaction with environmental influences and social/cultural forces. The construction of built forms is no longer limited to collections of discrete parts with homogeneous properties. They rather resemble organs that can be computationally 'grown', additively 'manufactured' and biologically 'augmented' to create heterogeneous and multifunctional objects.

The potential and challenges of the material-oriented design approach along with the possibility of taking it up on a large scale in the near future has also been discussed.

Keywords: ***Material Informed Design, Material Ecology, Material Morphology, Sustainable Architecture.***

Introduction

The rapid growth of the building and construction sector is contributing significantly to human induced climate change. Buildings and construction together account for 36% of global final energy use and 39% of energy-related CO_2 emissions. The energy intensity per square meter of the global buildings sector needs to improve on an average by 30% by 2030 (compared to 2015) to be on track to meet global climate ambitions set forth in the Paris Agreement (UNEP Global Status Report,2017). Countries, party to the Paris agreement, are making every possible effort for reducing the carbon footprint of the building and construction sector. Lot of

efforts have been made in reducing the operational energy through building envelope optimization and regulatory measures such as introduction of energy codes. Improvements in technology of processing, manufacturing and assembly of building materials are also being undertaken. However, the ecological soundness of modern day design approach in form generation, especially inspired and governed by the chronicles of industrial revolution, needs to be relooked into, which is often neglected in literature and currently seen architectural practices.

In this paper, emerging concept of nature responsive and nature inspired material oriented design approach has been reviewed and critically analyzed to see its potential as a possible alternate way to make the modern design approach more environment sensitive and sustainable along with respecting both human and functional value of architecture (Asefi et.al,2016). The short comings of the current methodsare evaluated according to ever-changing userrequirements and with respect to the environment.The available technology in terms of material andfabrication techniques has been taken into consideration as an invaluable opportunity in the development of theproposedstrategy.

Design approach with materials and methods-a historical perspective

The foundation ofbasic frameworkfortheemergence and initial establishmentofdifferent architectural theories was laid during 'TheRenaissance'andflourished especially after the advent of industrial revolution. The attention towards the incorporation and adaptation of the industrialization processes and methods in building construction industry led to amajor paradigm shiftinarchitecturaldesign.Thediscovery and inventions of new

materials, construction methods and large number of industrial products and production technology, coupled with the population explosion, propelled the progress of modern architecture to a whole new league. Progresses in science and advent of new possibilities; overwhelmed the architectural fraternity so much, that they started to deviate from the classical architectural principles and adapted to the new 'trends' in design which were often results of various experiments. These new and rapid developments led into separation of architectural and engineering processes. Development in engineering and technology, especially propelled by advancement in computer science related to design and analysis of form and structure, opened new avenues towards free form architecture and gave a whole new dimension to construction of complex geometry forms.

With the unprecedented scale of urbanization and tremendous building growth across the world, in the modern architecture, design processes are based on the principles of industrial revolution imbibing values of mass production which has led into separation of form, analysis and fabrication.

However, in vernacular architecture it's the holistic understanding of the traditional materials, their behavior and assembly difficulties that led architects into design and fabrication which helped it to further evolve as an integrated process (Asefi, 2016).

The need for anewenvironmental-sensitive designapproach- material oriented design

"Climate change is not a problem of the future, it's here and now and affecting very region in the world" said Dr. Friederike Otto from the University of Oxford, and one of the many authors on the

UN's Intergovernmental Panel on Climate Change (IPCC) report.

The most recent IPCC report, August, 2021, underlies the urgency of taking action at global level to halt climate change and deal with its unstoppable effects. The report warns that without immediate rapid and large scale reductions in greenhouse gas emissions, it will be impossible to limit warming close to 1.5^{o} C or even 2^{o}C.

The global climate emergency is prompting architects to embrace new sustainable design and construction strategies to counteract the effect of widespread building activity on the environment. This is paving way for a pressing need of an imminent change in architectural design approaches too. It is leading to emergence of approaches like Bionics or Biomimetics, Biomimcry, Biophillia etc. in the domain of architecture. Though at present, they are often dealt in a superficial and cosmetic manner.

The ecological failure of the modern design, is leading to a shift to materiality in the design culture (Oxman et.al, 2014). Material-based design approach is in general trusted upon to achieve a more sustainable design approach. In this approach the processes of form-generation are informed by the combination of material properties and environmental constraints (Oxman, 2012). Advancements in technology has provided new possibilities for material experimentation and exploration in various stages of architectural design processes.

Material-oriented design approach explores the way in which material behavior and properties can be utilized to its full potential from the very inception of the design processes to make resulting architecture more sustainable, truly holistic and

encompassing. Unlike prevalent design practices of architectural form generation, material-based design emphasizes the integration of design and fabrication processes inspired from various phenomena existing in nature. Nature's way of design shows that infinite iterations in forms are possible through optimal resource utilization. Figure 1a and b. illustrates the process of design in the material-based approach in comparison with the current design practices in architecture.

In current design practices, architects design forms and then seek help of engineers and various consultants for environmental, structural, services analysis and; when the form is finalized, the construction experts start the fabrication processes. This approach to design is often quite inefficient as it results in consumption of a lot of resources to achieve the desired architectural form.

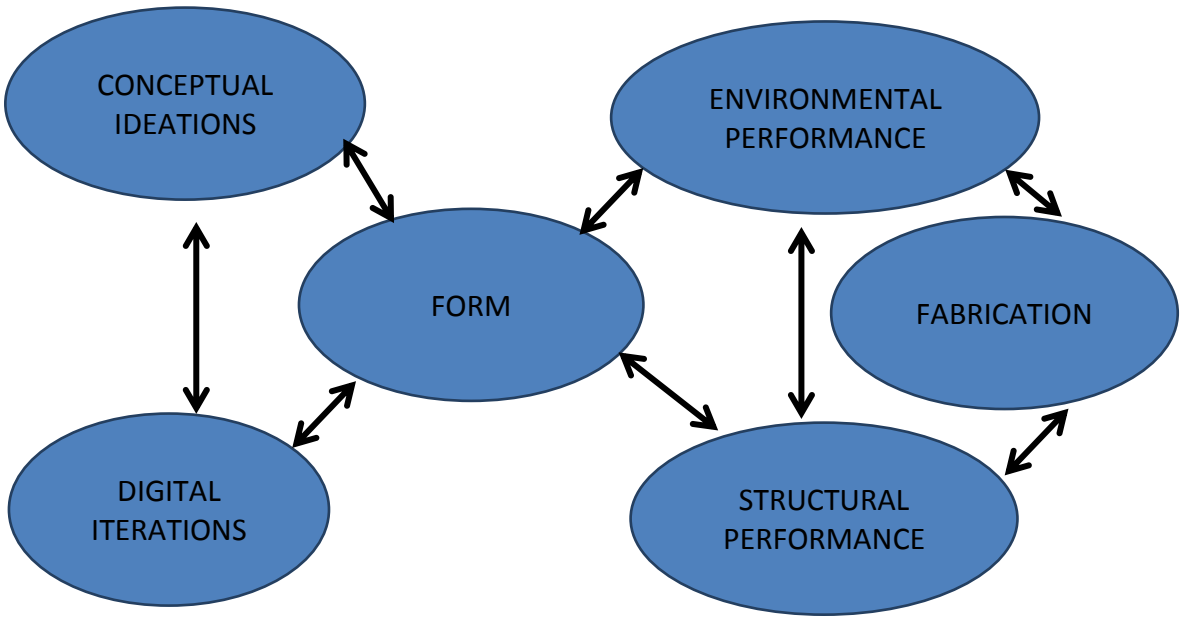

Fig1a.Present Prevalent Practice
Source: Author

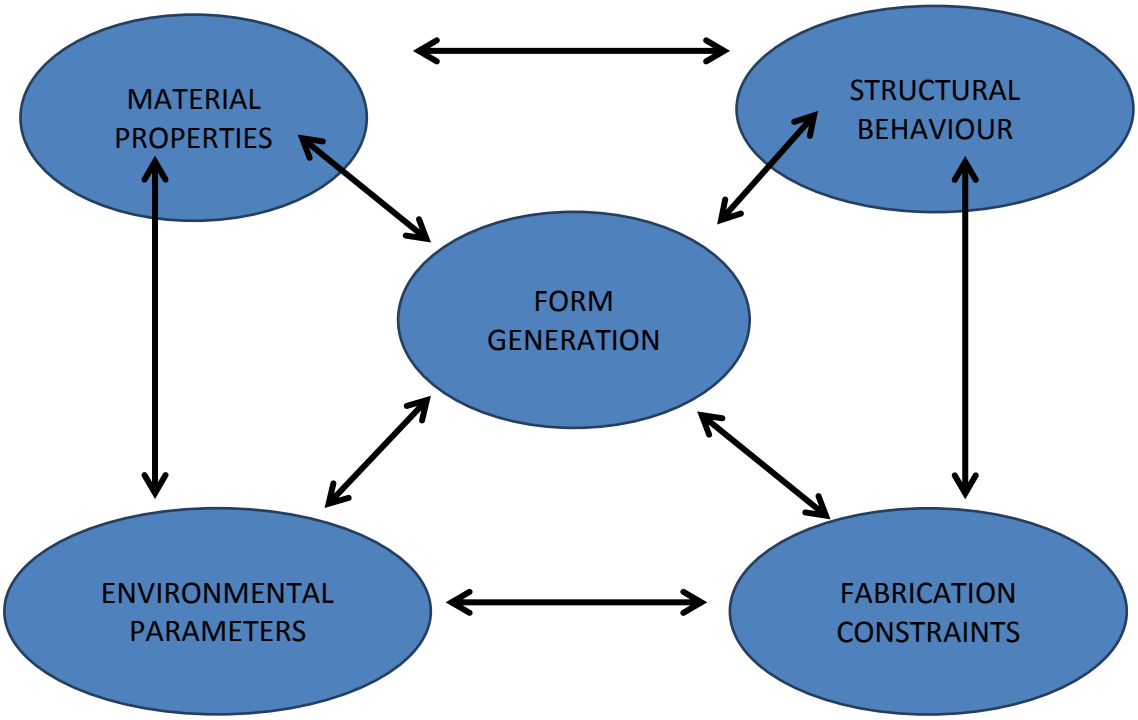

Fig1b.Material Oriented Design Practices
Source: Author

In material-oriented design approach inspired by nature, form generation is driven by primarily with the motive of maximizing performances with minimal resources (Oxman, 2012). In this method, analysis and computation of material behavior and properties is done at an early stage of the design to tap the potential of the material in terms of structural and morphological properties, increasing efficiency and reinforcing performances of the form and the resultant design. Analysis plays a vital role during the entire morphogenetic process, not only in firmly establishing and assessing the suitability criteria related to the structural and environmental capacity, but also in revealing the system's material and geometric behavioral tendencies (Menges 2007).

Material oriented design practice is characterized by the dominance of material over shape and incorporation of material

properties, structural behavior and environmental parameters to inform the distribution of matter to generate form. In current design practices, virtual shape- defining parameters are typically prioritized over physical material and fabrication constraints, which are often considered only in hindsight, following a geometric-centric design approach (Oxman,2011; Menges,2011).

Recent advances particularly in the upcoming field of direct digital production are enabling a shift from the popular geometric-centric design practice (Oxman, 2011). Such approach to design is an outcome of the easy availability of computational design, digital fabrication, additive manufacturing and also progresses in material engineering. Computing the distribution of matter as a function of structural and environmental performance, is not only to control substance variation defined as per a given boundary, but better still, utilizing such method for generation of form itself (Oxman, 2010). Thus material computation does open up endless form generation possibilities inspired by nature. Figure 2 illustrates the main goals of material based design.

Most designers employ bio-mimicryas a method to incorporate the aspect of sustainability in whattheyhavedesigned (Baumeister, 2007). Despite The availability of nature as an inspirational source to design, translation of biological knowledge to a human design setting has stayed at a very superficial levels inceit is mostly done by mimicking formor certain mechanical aspects of an organism (Zari, 2007). Material-oriented design approach takes bio-inspiration and bio-mimicry to the next level where it seeks to mimic nature's way of not only to build but also design.

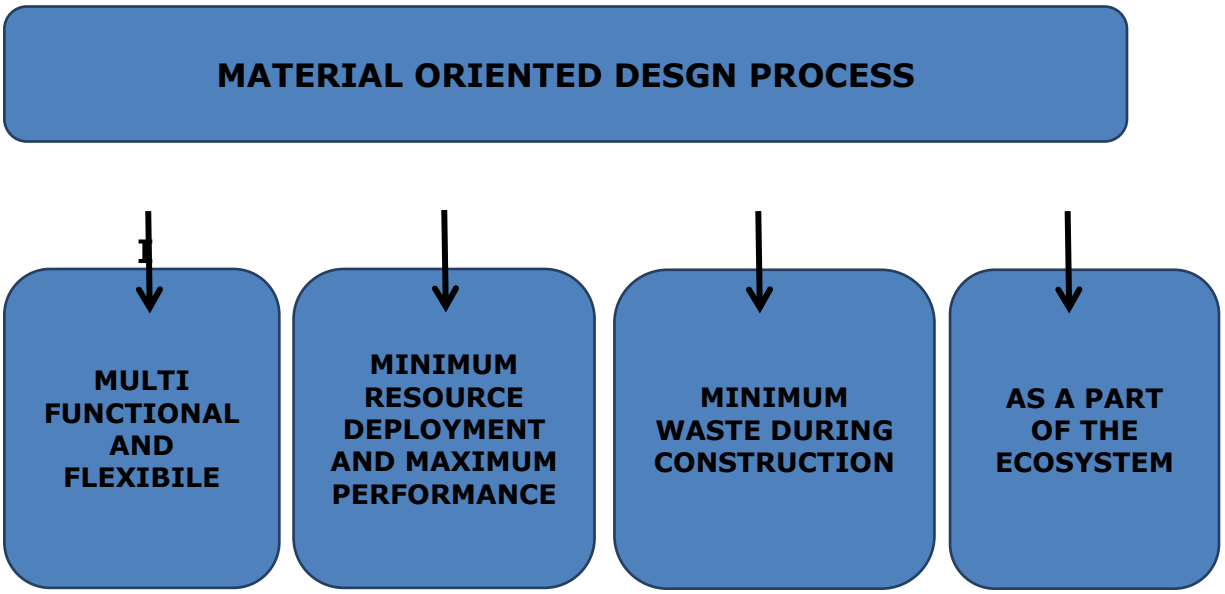

Fig2.Material Oriented Design Outcomes

Source: Author (Adapted from Asefi et.al, 2016)

Although many other forms ofbio-inspired designs have also been explored and widely used by researchers and professionals in the field of sustainable architecture (Reed,2006;Royo et.al,2015),material-baseddesignapproachis more likely to accomplish sustainability through fundamental changes in design strategies as it is more holistic and starts from the inception. Thisapproach holds promise as a true shift from conventional design methods to an approach in which form generation is based on natural principles that allow it to successfully function. However the widespread and practical application of material-oriented designapproach to design architectural form as a design method remains experimental till date.

Evaluating existing material oriented designstrategies - a comparative analysis

In this section, the researches in the field of material-oriented design in architectural domain by Prof. Neri Oxman and Prof.

Achim Menges have been critically examined and the similarities and differences between their design approaches are highlighted.

Prof.Neri Oxman conducts research at the intersection of computational design, digital fabrication, material science and synthetic biology. She frequently uses the term 'material ecology' to best define her research work. On the other hand, Prof. Achim Menges research primarily focuses on the development of integral design processes at the intersection of morphogenetic design computation, biomimetic engineering and computer aided manufacturing. His research aims to demystify the morphological complexity of material constituents used in design of architectural forms. In this paper his work in the field of material-based design will be referred as 'material morphology' to be categorically distinguished from 'material ecology'. The comparison of the set wo design practices is based on the strategies that they implement in the development of their design and research projects.

Some of the similarities in the design practices followed by architects Oxman and Megnes are that they seek the integration of material behavior and design computation. They are inspired by the inherent guiding principles behind nature as active agents of form-generation. Both the design practices aim to study, understand and compute material behavior at microscopic and macroscopic level to be able to generate forms. The difference being that material morphology practiced by Menges unfolds performative complexity through morphology, the assembling method is through the process of construction and the forms may or may not be multifunctional. Whereas the material ecology practiced by Oxman tend to create new material and behaviour

through assembling method and seamless design by use of anisotropic materials.

The piece-of-art displayed in CentrePompidou Paris, 2012 (Plate 1) is an example in which Achim Megnes uses wood as responsive skin material by rediscovering new performances in wood structure by means of computational design. In this project inherent hygroscopic properties of wood as well as differentiation of wood structure in radial and tangential sections are employed to design an innate climate responsive piece of art with no need for any technical equipment or energy. This hygroscopic skin reacts to different levels of humidity and canbe employed as passive solution for ventilation inbuildingskin.

Plate.1 : Hygroscope – Meteorosensitive Morphology Morphogenetic Design Experiment, Permanent Collection, Centre Pompidou, Paris, 2012.
(Source: http://www.achimmenges. net)

Monocoque project (Plate 2) undertaken by Neri Oxman entails experimenting with a structural skin that combines structural, environmental and physical performances of the skin by adjustingits various physical performances like thickness, pattern density, stiffness, flexibility and translucency to load,curvature and skin pressured are as respectively

(Oxman,2012). In this project by understanding and exploiting material properties creatively, the skin is able to perform multiple functions. The white soft material by letting light through thereby addresses the transparency and luminosity aspect, while the black stiffmaterial lends the required structural strength to the skin in question. It should be noted that multi functionality which is the primary aim of the project, draws its inspiration from nature and is one of the main principles that Prof. Oxman follows in herdesignprojects.

Plate 2: Monocoque – Structural Skin, 3D Print Museum of Modern Art, NY, 2007,
(Source: https://mediatedmatter.com)

Functional anisotropic materials displaying their gradients on multiple length scales and locations are ever present in natural systems (Oxman et. al, 2012).Prof. Oxman's desire to design heterogeneous forms into one single part in orderto accomplish multi functionality within the structure and also moving away from assembly of parts by means of digital anisotropy is clearly reflected through her designs.

In one of the Prof. Oxman's experimental projects; a large scale continuous and multi-dimensional structure- 'The Aguahoja' (Plate 3 and 4), the structural pattern that unfolds is inspired by nature, an insect wing or leaf venation structure as one may like to interpret, and its final shape outcome demonstrates

controlled folding into arobust and light weight cantilever beam configuration (Berkebile,2007).Through the application of additive manufacturing techniques, the different material properties created out of carrying chemical concentration of materials was employed to generate a structure that surprisingly and seamlessly transmitted from beam to mesh at such a large scale.

Plate 3: The Aguahoja-Project, Hierarchically structured Chitosan made – Structural Skin on display, MIT, Mediated Matter Lab, Media Lobby2018 (Source: https://www.creativeapplications.net, https://mediatedmattergroup.com/)

Plate 4: Hierarchically structured Chitosan properties – Structural Skin (Source: https://www.creativeapplications.net)

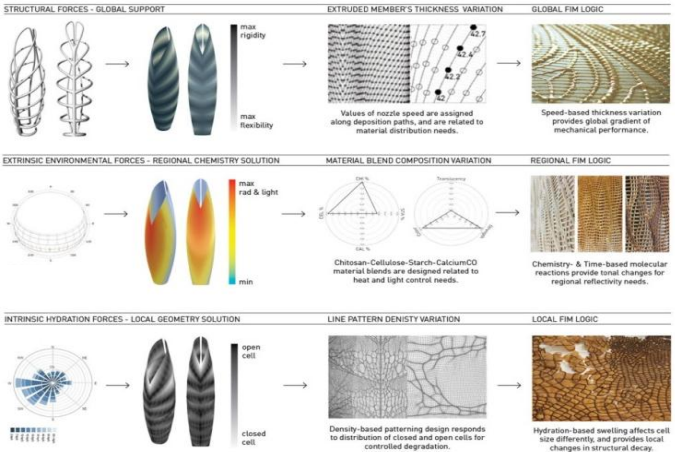

Plate 4: The Aguahoja-Project, Property of the structural skin and its performance under various forces

(Source: https://mediatedmatter.com)

In comparison to Oxman's projects, that are primarily additive processes and with incremental growth idea majority of the times, Megnes's is mostly assembly in fabrication while benefiting from digital fabrication in his projects that he employs. The structure of a temporary research pavilion designed and constructed in 2010 in the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE), is made out of plain plywood (Plate 5). In this project the elasticity characteristics of timber in its equilibrium state is engaged to derive the complex physical form of the structure.

Plate 5: The Pavilion (various views) – Stuttgart University, 2010

(Source: http://www.achimmenges. net)

One of the salient features of this pavilion is the implementation of architectural aesthetic features integrated with material behavior and environmental constraints to achieve a highly

efficient architectural form with one single material. Even though the design process was an extremely challenging, complicated and intricate task, the result was a form which was quite simple and efficient. Integrating architectural forms with material and structural behavior as well as environmental constraints as a fundamental principle in material-based design approach is an intricate and complex task that has been successfully achieved in this project. The torus shape of the pavilion as well as the light penetration through the skin of the pavilion is combined with the curved entrance of the pavilion to create a dynamic and an exciting architectural space.

Prof. Oxman seeks to design forms which change not only the design processes but also fabrication processes in order to achieve forms that are highly efficient both structurally and unctionally. In this approach, she also seeks to construct forms that are not only fabricated but also grow. Prof. Oxman's desire to explore a non-assembly method of construction, primarily geared towards seeking growth in form-generation, becomes apparent in the project of Silk Pavilion (Plate 6 and 7). In this project digital fabrication was used to set up the main structure of the pavilion while silk worms filled inthe gaps over a period of time. The process of form generation in whichdigital technologies and nature are employed to create a desired form is called by Prof. Oxman anature inspired-design.

Plate 6: Silk pavilion-MIT Media Lab, 2012-2018
(Source: https://mediatedmatter.com)

Plate 7: Silk pavilion-MIT Media Lab, 2012-2018
(Source: https://mediatedmatter.com)

Comparing two design practices highlights that materiality as a driving agent of form-generation process opensup endless design possibilities just like the way nature provides diverse, efficient, adaptable forms out of limited number of fibers and cells. As a whole, Megnes's design practice ismost likely to be easily assimilated in current architectural practices due to its eco-friendliness, the similarity of forms to current architecture which makes it more relatable. On theother hand, Oxman's design practice might leadto fundamental changes in the future

of not just design processes but also the form of architectural buildings and inherent quality of material as a driver of form. This has been clearly shown through the material-based design approach examples discussed here.

The implementation of material-oriented designapproach- the potential

Many designers and architects select bio mimicry or other bio-inspired design approachesto enhance the sustainability of what they have created (Zari,2007)and the outcomes do witness small yet significant improvements. On the other hand, material-oriented design approach seeks to pick up particular characteristics both in micro and macro scales through the larger understanding of the materiality in nature and strive to translate it into a usable human design options in addition to possible implication of analysis right from the inception of the project and carries it through.

The other bio-inspired design approaches might just simply entail replicating nature's ecosystem and not just forms and organisms. In this strategy, architects may not be able to produce a satisfactory design addressing all the important issues unless they have a sound scientific understanding and collaboration of the entire process of design. With the limited understanding of materials in design computation and digital fabrication, itis quite possible that the translation of such knowledge into a human design setting may lead to unsuccessful designs. On the other hand, the material-oriented design approach can result in innovative building technologies and materials since itnot just studies materials superficially but also

explores the properties of materials.

While other bio-inspired design approaches mainly aim to respond to particular predetermined built environment and design problems, material-based design outcome can lead into thoughtful design solutions through studying material behavior and properties in both micro and macro scale and accordingly manipulating its properties. Ecosystem mimicry means that a far more in-depth understanding of ecology guides the design of a built mass that is able to participate in the major biogeochemical material cycles of the planet (hydrological, carbon, nitrogen etc.)in are inforcing rather than damaging way(Charest,2007).

Material-based design approach can be seen as a sourcefor possible innovation and even a regenerative and uniquebuilt environment. This approach if imbibed can go way beyondsustainingcurrentconditionstoarestorativeonetoguidethrou ghintegrationwithsurroundingenvironment andbecoming part ofnature'secosystem. In fact, the greatest advantage of thisapproachisthepotentialpositiveeffectitcanhaveonthesurroundin genvironmentandevencounteracting the current drawbacks of modern design to a great extent.

While modern design was primarily based on the basic premise and values of mass production, whereas material based design approach is promoted basedon primarily the values of sustainability raised by the ecological failure of modern architecture. Inspite of modern architecture in which form follows function, in this approach form follows material behavior and properties.

Material-based design may be sought to attain and address ecological, social, cultural, aesthetical aspects successfully so that the new built forms don't fall into the same trap of modern architecture. It is often argued that studying natural systems and the way nature designs may open away towards strengthening architectural design strategies by addressing human values while the form is generated. Studying nature's design strategies shows that each form is representative of unique and very special needs. For example body structure and behavior of Namib Desert beetles known as Fog stand beetles is a highly efficient response to the harsh arid climate of the desert as a water vapor harvesting technique (Guadaremma et.al,2014) while protecting the beetles from surrounding environment. By studying nature, it becomes clear that different forms generated by nature are responsive to unique needs and the irresponsive is highly effective and efficient.

Architecture is a response to various needs and values of human beings,therefore it is only natural and obvious to implicate human criteria in conjunction with material and structural behavior and also environmental constraints at the early stage of design processes. This design strategy which considers both material properties and function and the form of the building in a mutual interaction is able to respond to many human and environmental needs and values while embracing the nuances of technologies.

It allows the architect the quintessential freedom to manipulate the design not just supported by technical, material, structural and environmental aspects but mainly through a close reference with aesthetical, social, cultural necessities. The recommended material-based designstrategy in Figure 3 begins by an emphasis

on how human needs, expectations andvalues (social and culture) can be implicated in the design process along with existing project constraints while achieving a sustainable architectural design while emphasizing the domain of materiality. The variables of structure, environment, social and fabrication constraints are also considered while form generation in this design process. Hence, it is the architect who finally guides form generation and develops it till finding an efficient response to architectural and environmental values and requirements. Additive manufacturing does hold good promise for large scale design and building fabrication especially in this era of globalization.

The implementation of material-oriented designapproach- the challenges

It needs to be mentioned that it is hardly expected that the material-oriented design approach becomes popular any time soon in near future due to the fact that the form generation during this approach employs highly advanced and complicated knowledge and sophisticated technologies. Nevertheless, the ever-changing architectural requirements, evolving technologies and world's emerging environmental problems may make this design strategy a necessity and even an indispensible part in the future of architectural design and construction.

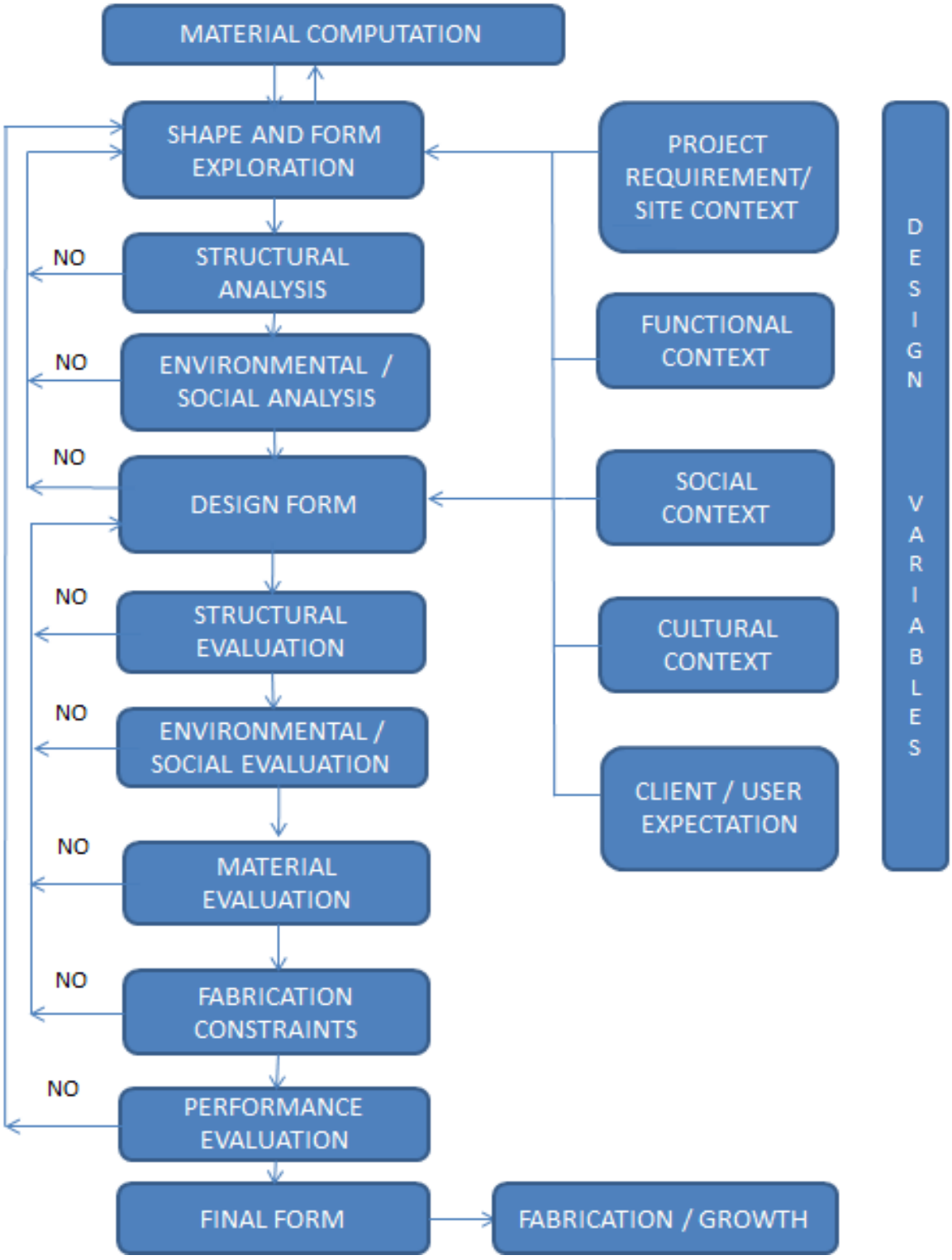

Fig3.Recommended Material Oriented Design Approach to overcome the Challenges in Form Generation

Source: Author (adapted from Asefi et.al,2016)

The complexity of this approach is primarily due to the involvement of many parameters that are barely considered in any simple architectural design strategies such as material morphology and material ecology. It is quite clear that it will not be possible to design and construct entire building through material-based design approach in the immediate future, due to many undefined parameters and technical issues that need to be addressed, including the way different parts of building such as electrical and mechanical equipment are incorporated in the design. However, one does hope for implementation of this approach, as the various technical issues are addressed in due course of time.

Conclusion & way forward

Material-based design approach has the potential to become an inherent part of the eco-system and revolutionize the approach and generation of architectural forms. The proposed approach can be considered as an efficient strategy for the design of kinetic architecture. It eliminates the need for joint connections to a large extent and helps in accomplishing energy efficient design with little need to rely on external energy and technology during manufacturing phase. Another great potential of material-based design approach is generating passive multi-functional building skins which makes it a part of the surrounding eco-system and thereby reducing the energy consumption during the operational phase. As a whole, material-based design approach holds immense promise as the initial step towards the future sustainable architectural design practices. However, how it addresses the issue of social acceptability, technology adaptability and economic viability on a mass scale in the near future would be interesting to see. But one may argue that in this

era of globalization this may not be such an issue considering the immense environmental benefits it has and with the present level of awareness.

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