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Towards a transformational eco-metabolistic bio-based design framework in architecture

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Abstract

This paper discusses the foundations of a bio-based material paradigm for architecture. It argues that moving from a current reliance on the non-renewable materials of the geosphere, to the renewable and fundamentally cyclical materials of the biosphere can establish alternate foundations for thinking alternative sustainable building practices. By positioning architecture and the built environment as a particular case for bio-based materials, where the longer life spans of buildings support better carbon storage, this paper identifies the bottlenecks that limit their adaptation into the way architecture is thought, designed and built. If architectural ideation and design is traditionally understood through the durable and the permanent, our aim here is to challenge this foundation and bring forth the fundamental differences that bio-based materials engender. With focus on the embedded lifespans of living materials, the fundamental circularity and degradability of biomass and resulting transformative life cycles of the artefacts that they embody, this paper asks how a new representational framework for bio-based material paradigm can be conceptualised, instrumentalised and in turn materialised. The paper supports this positioning through a presentation of a series of methodological probes. The probes outline strategies for new methodologies by which we can capture, predict and steer the transformations of living materials and funcationalise them as part of an architectural performance.

Keywords: architecture, bio-based materials, computational design

1. Introduction

Architecture, the way it is designed and produced, is under pressure to rethink its practices in order to address its responsibility and agency in an era of climate crises. A particular aspect of this crisis, and in which architecture holds a very direct accountability, lies with the current rampant overconsumption of resources. As we enter a new age of resource scarcity, it is clear that real innovation in the way we build and occupy our communities is needed. A particular part of this crisis is its coupling with the actuality of material depletion [1,2]. The built environment is notoriously intense in its use of materials. Industrialisation has focussed building fabrication around particular material processes that are suitable for mass-production and allow standardisation. In Europe alone, 30-50 percent of total material use goes into construction with 65 percent of these being aggregates and 20 percent metals [9]. Today, we are aware that many of our primary materials such as copper, zink and lead are under threat of depletion [1–3], but also broader used materials such as sand and gravel, fundamental for concrete, are projected to be exhausted over the next 15-20 years [4]. By predominantly depending on a small subset of materials extracted from the geosphere, we have contributed to a global material crisis with severe socio-political, economic and environmental repercussions [5, 6].

In response, the call for augmenting, optimising and informing design and construction practice has led to new paradigms that seek to innovate structural thinking by enabling us to augment material fabrication processes in order to minimise material deployment and engage material performance [7,8]. Biomimetics is part of this effort. Where biomimicry has incorporated ideas of circularity, regeneration and the exploitation of passive energy systems, it is still founded on an idea of technology transfer by which systems found in nature can be translated and transformed into existing building design-, fabrication- and operation frameworks and their associated material practices. This position paper argues that we need to move the mileposts further: to truly challenge the linear models of resource usage and enter a new paradigm of renewable and circular resource, we need to challenge the boundaries of how we consider the solution space of sustainable design. Our position is that the compound problems of the climate crisis, resource depletion and increasing global economic inequality can not be solved by optimisation alone, instead we call for the entry into a bio-based material paradigm in which resources are understood as truly regenerative and strong links can be cemented into dimensions of localisation and waste-less fabrication. However, this new engagement should be undertaken with some humility. Where bio-based materials are sometimes described as abundant, other materials which have received similar descriptions in the past, such as sand or gravel, are dwindling due to the building sector's sheer global size. The simple replacement of a current geosphere-oriented material practice with one favouring bio-based materials requires careful consideration of the global environmental, ecological and social contexts of resource production and procurement. Like all planetary resources, bio-based materials are limited. The fundamental boundary of the photosynthetic ceiling means that we, as a global society, can not grow more crops, trees or marine based bio-materials but only substitute one kind of organic growth for another (). These land use changes have direct impact on the breadth of performance embodied by our shared natural capital. Building a bio-based design framework must therefore include considerations for the environmental as well as social implications of this material paradigm.As such, the Eco-Metabolistic Architectures framework is tied to material optimisation, albeit with a broader orientation. Rather than positioning optimisation solely around material conservation, *building smarter with less*, then optimisation in this framework also addresses moving the value chain and using a larger part of the resources. In order to do so it examines how to characterise the heterogeneous and transformative properties of bio-based materials understanding material weakness and embedded dynamisism as positive attributes for a more resilient material practice. The central argument of this paper is that in order to do so, we need rethink our ways of conceiving, representing and designing architecture, leaving the current anthropocentric perspective. It defines three different classes of bio-based materials; the harvested, the designed and the living and associates these to three central characteristics; the heterogeneous, the behaving and the living performance and asks how these challenge our ways of understanding design, specification and fabrication in architecture. The aim is to offer a holistic conceptualisation of a bio-based architecture in order to empower the instrumentation of these otherwise suppressed properties of bio-based materials and develop a constitutional re-address of the drivers of a sustainable material building practice.

2. The challenge to representation

The new narratives of circular bioeconomy and bio-design present alternate pathways to a sustainable future [9–13]. While both are invested in the overall vision of building the foundations of more sustainable design practices, they can also be described as representing two different methods; the former seeking to devise a new class of materials with *comparable performances* that can replace existing materials (9, 10). By advancing the fabrication of products and energy made from the biosphere, they present a material paradigm of carbon neutrality, renewability, and circularity [11,12]. However, despite well-organised calls for action maturing into local legislation and an attentive profession, architecture is proving hesitant in this transition [13-17]. The latter understanding bio-design as fully innovating new ways of understanding what design can be and how performance can be driven [18-19]. Bio-based materials are fundamentally different to current building materials. If industrialised materials are designed to be homogeneous, static and stable, enabling certification and ensuring durability, bio-based materials are essentially transformational evolving in time and across process. Shaped by growth cycles and formed by their environment, bio-based materials are characterised by their complex heterogeneity, unpredictable behaviours and the high degree of interdependence their life-cycles embody. As instantiations of biomass, bio-based materials are part of a global steady-state system in which inflow is exactly balanced with outflow [20]. As such, their primary characteristic is their embedded temporality and inevitable decay. Present agendas share the ambition to produce materials that replicate existing in performance and durability. However, this endeavour to facilitate continuity in our perception of what materials do, how they are employed and what their performances are, creates a false premise that limits our understanding of their design, fabrication and deployment.

The major contribution of the eco-metabolistic framework is to build new representations by which a bio-based material paradigm for a future sustainable architecture can be examined. Unlike the 20th century architectural theory of metabolism, in which the metaphor of organism was interpreted mechanistically [21], this eco-metabolistic modelling framework provides a literal conceptualisation of materials through and with the living. The focus on building new representations is seen as part of a larger architectural tradition by which the agency and remit of design is continually evolved. Architectural design is a prescriptive practice. The ability to project spatial intent and instruct material address depends upon architecture's capacity for capturing and describing the material processes it embodies.

The traditions of architectural representation are predicated on an idealisation of absolute permanence and durability [22]. Current methods of architectural representation are not able to represent and therefore fully conceptualise and in turn operationalise the complexity, behaviours and lifespans of bio-based materials. The conventions of architectural representation limit our ability to account for the impact of design choices, instead cementing the autonomy of the design space and asserting building completion as a cut-off point to design agency. Current architectural representations, such as Building Information Modelling, aim to mitigate this fixity by incorporating ideas of transformation but firmly consign these to mechanistic simulations of assembly and facility operation [23,24]. Dimensions of circularity and feedback are afforded through the integration of life-cycle assessment evaluating the environmental impact of production [25,26]. However, these methods focus on external environmental impacts such as global warming potential (CO2-eq), ozone depletion, human toxicity, eutrophication or acidification [27] and disregard the internal changes to the materials themselves and the changing performances within the architecture they embody across their life-spans. In order to simulate complex interactions of buildings, occupants and environment over time, modelling paradigms from other disciplines, such as Discreet Event Simulation, have been introduced in the field of architecture [28]. These provide ways to integrate temporal phenomena into design evolution, when these multi scalar simulations are connected with generative design processes [29] . A multi scalar approach allows to interface very different types of analysis of for instance, environmental, geometrical and Material level [30]. Parallel efforts in academia and industry examine a new performative perception of materials [31–34]. Fuelled by the creation of advanced computational design methods that connect otherwise discrete design phases of design, simulation, specification and fabrication [35], the field is defined by the theorem that by formalising the properties and behaviours of materials and devising means of representing their composition, we can access their underlying compositional logics and gain access to their steering [36]. Large scale research efforts into concrete [37,38], masonry [39], timber [40–42], steel panelling [43], textile membranes [44,45] and fibrous shell structures [46] investigate the steering of material performance in the expanded digital chain.

However, despite enabling the interfacing of manifold data supported design concerns into holistic information models, these continue to treat materiality as continuous and stable. Where parallel fields are able to model material behaviour such as creep, fatigue or decay in e.g. timber [47-49], these properties are not integrated in architectural design models. These models operate on the premise of a virgin state, which needs to be conserved. The transformation of materials is usually neither conceptualised nor represented and simplified into maintenance cycles of objects in Facility Management models [50].

Similarly, fabrication conceptualises in its models the matter it is shaping as static and homogenous. Adaption of fabrication processes to the heterogeneities of material are in practice a manual task relying on the experience of the machine operator [51]. Adaptive fabrication strategies, which take material heterogeneities into account are only developing [52-55] for architectural production. Measurement and modelling practices, which take into account the transformation of materials after fabrication are only emerging in our field [56].

3) Entering a bio based material paradigm

The transformational metabolisms of a bio-based material paradigm fundamentally challenge these strategies. In architecture, the field can be described across three material perspectives:

The harvested: Harvested materials; timber, bamboo, reeds or straw, are cemented parts of building culture. Timber is a central example, currently undergoing a radical rethinking as one of the few ecologically sound building materials [57]. Timber is renewable, recyclable, energy-efficient and acts like a carbon sink [58]. Where current timber practice is informed by high-end simulations of material behaviour [59,60] and advanced robotic fabrication [61], these are predicated on highly wasteful systems of standardisation. Timber is characterised by its inherent heterogeneous material structure leading to anisotropic and visco-elastic behaviours. Capturing and harnessing this material variance is highly complex [62]. Where high-end industries of forestry and timber milling are maturing methods of advanced sensing (satellite imagery, 3D scanning and computed tomography [63,64] to optimise felling, cutting and grading, the data is not interfaced with design and the potential of information transfer across the digital chain is broken. *To truly harness the inherent properties of timber, we need to develop the ability to capture the heterogeneity of the single timber section, represent its inherent complexity, predict its structural performance and behaviours and interface these with novel models of design and fabrication for the optimisation of material deployment in bespoke timber elements.*

The designed: Bio-polymers, made from biomass such as starch, cellulose, gums or microorganisms, are currently attracting attention as ecologically sound alternatives to petroleum-based polymers [65]. Despite having preceded their oil-based counterparts in the 1940's and 50's, bio-polymers are not readily appropriated in architecture. Bio-polymers have low mechanical strength, shorter durability, less chemical inertness and demonstrate complex behaviours during fabrication [66,67]. A central problem is the high volatility that especially water-based bio-polymers demonstrate. Here, processes of curing entail large-scale anisotropic structural and dimensional transformations. Recent research examines how advanced computation and 3D printing can introduce new methods for localised steering of deposition through the grading of geometry and material composition [68,69] and propose methods of characterising material behaviour for multi-objective optimisation of process setting. However, these methods remain unintegrated, not linked to online processes of fabrication and do not address material lifespan. *To truly exploit the potential of bio-based polymers, we need new models that harness the limited duration and volatility of bio-polymers not as failures but as active design parameters. We need to interface material characterisation with fabrication to understand material performance and develop means of conceptualising how parameters affect and change material lifespan.*

The living: The emergence of new bio-technology platforms is allowing novel explorations of an architecture embodying the living [70,71]. New perspectives are aspiring to position architecture as the host of functionalised biological organisms that metabolise and transform materials or produce energy, creating living microbial fuel cells using human waste for distributed energy production [72], dedicated bio-factories producing heat or nutrition [73,74], employ hygromorphic bacterial spores to allow environmentally triggered shape change [75,76] and genetically engineered pressure sensing bacteria to rethink building foundations [77]. Living materials are manifestly different to produce, manipulate and administer. At present, this highly emergent field remains unintegrated with architectural design tools and advanced computational design. As such, present studies have difficulty in assessing the impact of architectural form and how the topology and arrangement of such systems within an architectural framework impact the performance, propagation and life-spans of living systems. *To truly enable the integration of living systems into design, new models are needed for design-integrating the capturing, characterising and predicting of the living performances of organisms and their functionalised interaction with their environment. We need to develop new practices of temporalised representation to understand how design can impact propagation and lifespan.*

4) Developing the foundations of a new representational design framework

In our current work we are examining the foundational infrastructures of a holistic eco-metabolistic model for a bio-based material design framework. This model proposes a novel architectural design representation to capture, design and steer the properties of bio-based materials; their heterogeneity, temporal plasticity and living performances, interface their fabrication and track a situated understanding of their behaviour over their lifespans. The model is developed across three levels that address the three classes of bio-based materials identified above. The foundational technological concepts are working across these levels, however each of these requires adaptations in technologies.

Harvested materials are characterised by heterogeneity - how do we capture and instrumentalise the individual properties and how do we understand and instrumentalise this variety? In our work we have been investigating methods to capture data from harvested materials. In CITA, have developed computational methods to analyse, classify, represent and set this data in use for design. 3D registration is used to capture the geometry of full trees even before harvesting. Algorithms are able to automatically classify and sort this data in digital libraries (Fig. 1). These digital stockyards are then accessed by digital design tools, which choose the best fitting elements for a certain location and its specific requirements [78–80]. Natural materials differ as well in their internal material composition. A three dimensional understanding of this is today established within seconds by means of Industrial CT scanners and can be used to predict its structural performance and behaviours can be expected from different areas of a log [81].

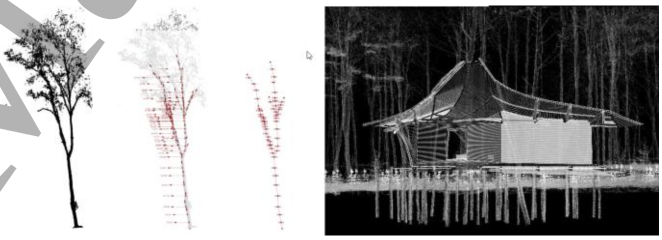

Fig 1) Serial Branches - Processing of 3d Point Cloud data of trees into a computational vector model describing length, thickness and branching and subsequent use in architectural design.

In RawLam [82] we are using CT scans of logs to represent the inner structure of trees (Fig. 2). Created by Computervision tools and Machine Learning [83] these three dimensional views onto different material properties e.g. densities, branches or areas with sap informs a global mapping of wood qualities in the logs. In RawLam we develop models, which correlate the detected wood qualities to the required timber qualities in different areas of glulam elements. The model specifies furthermore the cutting and assembly process of the single lamellas into structural beams (Fig. 3). Our bespoke approach uses a far greater amount of wood qualities from logs, than current techniques and provides a sustainable outlook for a future timber building practice. The CT scan based maps of internal timber qualities provide as well means for the logistics of this practice, as these patterns can be identified by computer vision system in cut boards and provide a "Digital Fingerprint" allowing to track and trace each log in every step of its transformation into lumber [84].

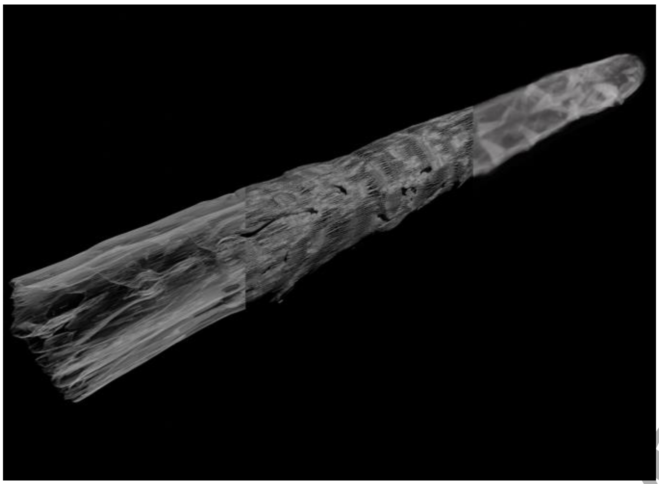

Fig 2) RawLam - Data from CT Scans is used to provide multiple model representations of a timber logs geometry and material constitution. In the picture here from left: density, meshed outer geometry, internal branches (knots).

This traceability bears the potential to inform future automated assembly of individualised timber elements and close the current information gap between forestry and building construction. However these data heavy and information rich practices are computational demanding.

Fig 3) RawLam: Detail of a fabricated GluLam beam with low quality wood (Wane) in areas of low requirements of structural performance. The performative needs of areas in a timber element are analysed and associated with wood qualities found in the data of CT scanned logged. This informs the fabrication of elements.

New design representations and computational methods are required, when architects want to engage with volumetric datasets or design and fabrication is based on the identification of material qualities within forest inventories or data representation of the CT scanned logs in stockyards of sawmills. This has led to further investigations and developments towards an integrated adaptable computational framework, which integrates the necessary methods of data acquisition, dataset alignment; pre-processing, segmentation and visualisation and manipulation of volumetric data for design purposes [85].

Designed bio materials are highly transformational during all states of their lifetime. In order to design with these materials it is necessary to position this inherent temporality as a core concern in architectural design concepts and tools. In recent work, we have developed frameworks, which are able to capture data of the transformation, make sense of this and integrate it into design and fabrication processes. In the project Predicting Response we are investigating methods to sense and predict with Machine Learning methods the large geometrical and performative transformation of 3d printed cellulose based bio polymers during and after production [86] (Fig. 4).

Fig 4) Predicting Response - Robotic 3d Printing of Cellulose Biopolymers with a printing system developed for slurry based materials.

We have developed a Material Monitoring Rig, which integrates data from sensors in a cloud based time series database. In order to capture the spectrum of changes in the material we need to use an array of sensors. We sense visual appearance and texture (image sensor), geometry (Lidar and motion capture), weight (electronic scale), evaporation induced changes in material humidity (humidity sensor probes) and temperature (thermal camera) and monitor the environment the artefact is positioned taking place (humidity and temperature sensors). This interrelation of many different parameters is in our understanding a typical feature of biomaterials and challenges the mechanistic models, which serve currently as backbone for the simulation of material behaviour [87]. We find that predictive models, using Machine Learning, are better equipped to make sense of the monitored behaviour of materials and trained ML models are able to provide the necessary fast feedback and agency for design and fabrication [88]. In our projects we investigate to which extent these models might predict the long term behaviour of bio-materials specific to design and location. In our practice with predictive models we have already proven that they are able to foresee a materials transformation during fabrication [89]. In the project Predictive Response we are investigating how these models allow for an adaptive robotic fabrication of bio-plastics, taking into account the changing behaviour of materials due to the material heterogeneity characteristic to bio and recycled materials.

Fig 5) Restless Labyrinth (*Claudia Colmo*) - *Details of emerging dense clusters of fruiting bodies developing from the mycelium network which has enveloped the 3d print.*

The integration of *living materials* into architectural design and spaces demands the development of *new practices of temporalised representation*. Our current computational tools for design, simulation, fabrication and monitoring of architectural structures have an almost complete anthropocentric focus. Working with living materials means though that we need to design an environment which provides good living conditions for all housed species. This requires a thorough understanding of the needs of these species and the means to establish and maintain them. In a series of projects we have been developing protocols and tools to capture, characterise and predict the living performances of organisms. Flora Robotica investigates symbiotic relations of plants and robots. The interaction of the latter with plants is here triggered by data captured via electrodes from the plants - the plants become the actual sensors for environmental conditions [90]. The project Fungar - extends this functionalisation of plants and investigates living mycelium as part of building elements, which both senses conditions and computes this data [91]. Fungar exemplifies the challenge to design relationships between several living species occupying a space: where mycelium needs damp environments for survival this is neither favourable for human occupants nor for most of our current building materials. These concerns lead in the past to a separation of species and the reliance on electromechanical appliances, as seen in the intricate tube work of algae facades [73]. An alternative approach investigates co-inhabitation and mutual benefit in the sense of nature based solutions. In Fungar this results in an intelligent nesting of living and dead matter. In the project Restless Labyrinth [92],we are investigating mycelium for remediation of contaminated soil and propose an spatial, geometric and material deployment strategy based on 3d printing earthen bio plastics, reacting to the changing contamination level and offering alternating outdoor spaces to humans [93] (Fig. 5). A further project, BioLum [94] investigates how bioluminescent organisms can become a part of architecture through a functionalised interaction with their environment (Fig. 6).

Fig 6) BioLum - Hydrogel printing with living bacteria using a robotic arm with a dispenser

For this we investigate modes to establish empathic relations between humans and the organisms. In BioLum bioluminescent algae provide visual feedback and attraction for tactile interaction of humans with algae in softrobitc encasements, providing them in return With the necessary flow for delivery of nutrition and cleansing. The bioluminescent bacteria strand develops models and protocols to design and 3d print the moist hydrogel topologies, which bioluminescent protobacteria require to live. Based on observations we develop computational models, which simulate the relation between the bacteria and the designed environment over time with the aim to choreograph the propagation of light emitting bacteria through the structure over time [93] (Fig. 7).

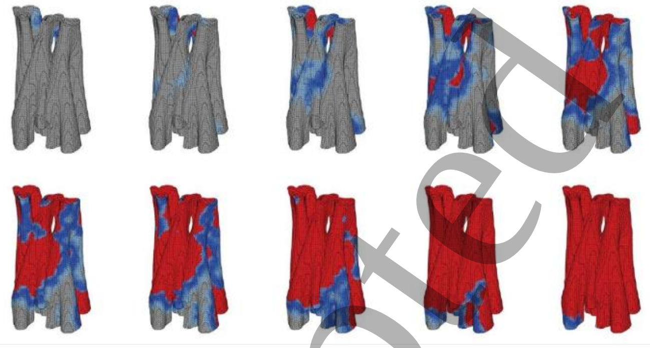

Fig 7) BioLum - Particle system simulating the progress of bacteria propagation through the medium.

5) Conclusion

The proposal of an eco-metabolistic bio-based design framework enforces circular thinking and supports the engagement of complex heterogeneous and temporally behaving material properties in bio-based materials. In doing so, it challenges the boundaries of architectural representation, building a new reliance on the understanding and monitoring of the origins, genesis, use and finally decomposition and transformation of bio-based materials into new elements.

In our probes, we examine how the entering of a bio-based material paradigm is associated with novel computational design methods for retrieving and processing data to inform the model runningly. The prototyping of methods for registering, modelling and functionalising material heterogeneity, time based monitoring regimes and designing and fabricating with living organisms question the underlying representational framework needed to fully design with and for a bio-based material paradigm. The central differences in this emergent eco-metabolistic modelling framework lies with the idea of building a persistent correlation between the artefact and its representation [94] in which the life span, transformation and even life state of the designed is continuously interfaced and updated with its representation. This challenges the idea of design as an act taking place before completion, hand-over and inhabitation instead building new bridges to what it means to inhabit and live in a living architecture.

The further development and prototyping of an eco-metabolistic bio-based design framework is challenging current practices and demands a step change. -

We see that the practical use of models for eco-metabolistic practices can currently seem challenging, as they have a tendency to be unbounded. They share this challenge with other simulations, such as LCA or CO2 impact calculation, which need to span from the very origin of a material to its reuse and further life. This wide span comes with an at least partial inability to evaluate the quality of many of the included parameters. It contrasts as well with the current modelling practice for the building profession, which favours clear model boundaries and mitigate insecurities and material inhomogeneities with practices of certification and standardisation. While this reduces complexity for the simulation, it narrows down the range of materials and qualities for design consideration, promoting an unsustainable material practice. In our work we show that more holistic approaches are possible, where individual behaviour and performance of biological matter can become driver for design and explore how this can be scaled up in a practice oriented way.

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