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SMART MATERIALITY IN ARCHITECTURAL ASSEMBLIES

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ABSTRACT

Digital Materiality paradigme enhances the architecture products fabrication for construction. It develops the communication between Materials, data, design, construction, structure and fabrication. The integration of advanced digital computationnel Tools into architecture materialization results in enhanced performance systems. The produced system from this paradigm reduce waste, reduce energy consumption and increase the sustainability of construction aspect which all coincides with sustainable development goals SDGs. Digital materiality led to production of complex 3D configurations and deployable structures by exploiting the material dimension. Smart material systems evolves from the programming of the material properties. Smart materials are programmable materials with engineered performances. The research aims to identify the materialization process of the paradigm in recent architecture projects, as well as identifying and classifying material programming methods. This paper presents an up to date review on Digital Materiality and material programming applications. The research classifies material programming into bending active and interactive stimuli active architecture methods. A digital architecture materialization production framework is deduced which utilizes the material dimensions of the system.

KEYWORDS: Responsive architecture, material programming, smart materials, bending active structure.

المواد الذكية في التكوينات المعمارية

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الملخص

رقمية المادة هي نموذج لتحسين التصنيع للمنتجات المعمارية في مجال التشييد. هي تتطور التواصل بين المادة والمعلومات والتصميم والإنشاء والتصميم الإنشائي والتصنيع. تداخل الوسائل البرمجة الرقمية مع التصميم المعماري أدى إلى أنظمة ذات كفاءات أعلى. تلك الأنظمة المحدثة تقلل من المخلفات وتقلل استهلاك الطاقة بالإضافة إلى تحسين جانب التشييد المستدام، حيث يتفق كل ذلك مع أهداف التطوير المستدام. أدت رقمية المادة إلى تكوين تجميعات ثلاثية الأبعاد معقدة لم يكن يتمكن أحد من تكوينها من قبل باستخدام خواص المواد. تنبثق المواد الذكية من برمجة خواص المادة. فالمواد الذكية هي مواد مُبرمجه لها أداء مُصمم هندسياً. تناقش هذه الدراسة مجالات رقمية المادة الحديثة وتطبيقاتها من خلال مشاريع منفذة. تهدف هذه الدراسة إلى تحديد عملية التجسيد لنموذج رقمية المادة في الاتجاهات الحديثة، بالإضافة إلى تصنيف وسائل برمجة المواد. يُصنف البحث وسائل برمجة المواد إلى هياكل الثني الحية والعمارة التفاعلية من خلال محفزات خارجية. توصل البحث إلى نطاق عمل واضح الأركان للتوصل لمنتج معماري ذا استغلال متميز لشق المادة.

الكلمات المفتاحية: العمارة التفاعلية، برمجة المواد، المواد الذكية، هياكل الثني الحية.

1. INTRODUCTION

Materials selection in architecture has been chosen for the pragmatic aspect without considering all properties of used materials, in recent years the material dimension is explored which resulted in new enhanced products that further use the material properties (Krieg et al., 2015; Li et al., 2018; Velasco et al., 2015). Integrating the digital paradigm into construction and design has led research to further investigate the material dimension for optimized performance (Chang et al., 2019; Dahy, 2019; Decker, 2013; Velasco et al., 2015). The merge between material, design, construction, fabrication and data formed a new paradigm identified as Digital Materiality (Willmann et al., 2013).

Applying advanced digital materials and advanced material performance studies into design complies with Chong et al (Chong et al., 2002) definition of “Multi-scale process”. The Multi scale process is the investigation of the atomic structure and changing its structure to define new macro scale material systems. Thus, tailored behaviors and properties can be achieved for enhanced performance. Digital materiality generates smart systems as the material becomes informed with data due to different disciplines integration and interdisciplinarity (Correa et al., 2019; Sachs, n.d.). Smart materials integration in this paradigm produce stimuli responsive systems, which help generate static and interactive architecture features/systems. Smart materials are materials with self/programmed properties that respond to energy input with an output behavior (Bohnenberger, 2013). They can be considered a system as they have their sensors, actuators and motion mechanism. Smart materials are classified into active and passive smart materials; active smart materials are those that show mechanical shape shift upon stimuli application while passive smart materials are those that do not change their properties but produce and output (Rowley, 1994).

This paper investigates the recent applications of digital materiality in architecture. Exploiting the material properties for shape iterations is identified as material programming, which this research classifies such programming into two major research fields; bending active and interactive stimuli active architectural components as shown in **Fig.1**. Bending active is referred to manipulating the material properties to acquire a unique fixed shape (Agkathidis et al., 2019; Kycia et al., 2020; Schleicher et al., 2016; Schmelzeisen et al., 2017), while the latter is identified as components which are designed and programmed to show specified shape iterations when a stimulus is applied, subsequently returns to original shape upon stimuli removal. The research will illustrate the concept of the classification and exhibit recent physically produced projects. A digital architecture materialization framework is deduced from the literature discussed.

2. METHODOLOGY

A literature review is conducted to identify recent advances in digital materiality paradigm. The review identifies main repeated process steps for advanced digital architecture projects. The processes steps identified aid in the formulation of a global digital materialization framework for architecture products/features.

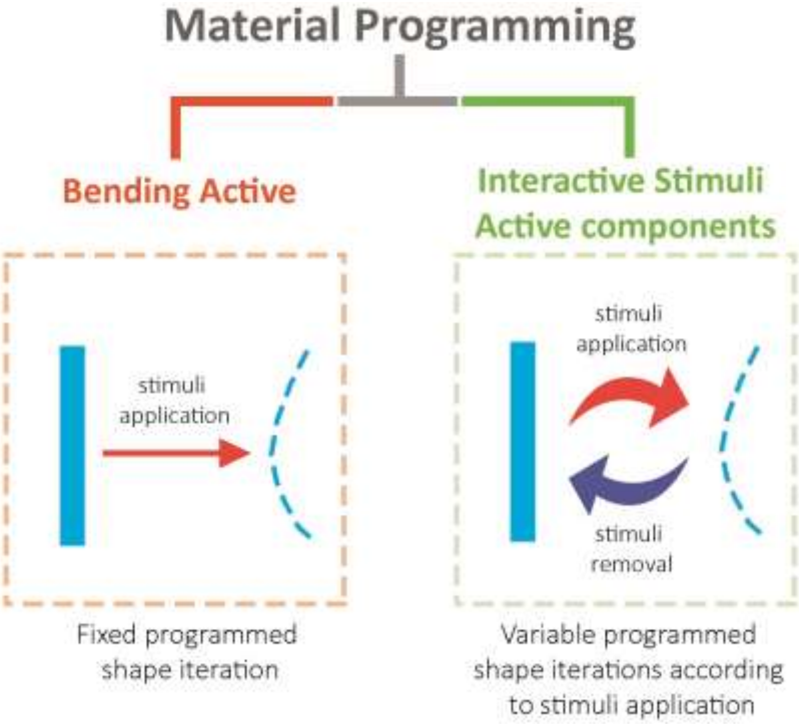

Figure 1: Material Programming classification.

3. BENDING ACTIVE ARCHITECTURE

It is defined as designing the material parameters to drive specified form iteration, while changing any parameter would produce different form iteration. As an example, the Urbach tower in Stuttgart. The tower consists of wooden composite panels which is considered a surface-active timber structure (Urbach et al., 2020). Each panel form is generated due to computational control of the water content inside; when the water content changes the panel takes different forms. Different generated form panels are shown in **Fig.2**.
Another approach by Schmelzeisen et. al (Schmelzeisen et al., 2017) where 3D printed grid is applied on a pre-stretched textile to acquire deployable structures upon tension removal as shown in **Fig. 3**. By comparing the produced 3D deployable structure with 4D printing paradigm definition, the product clearly shows shape/form variation over time (Momeni et al., 2017). Kycia et. al (Kycia et al., 2020) investigated the pretension parameter to generate different form iterations out of Schmelzeisen et. al active bending textile system, while Agkathidis et. al (Agkathidis et al., 2019) managed to investigate the control of motion direction using different patterns.

4. INTERACTIVE STIMULI ACTIVE ARCHITECTURE

It is defined as the architectural products that utilize the material properties variations when subjected to stimuli like heat, humidity, electric current, magnetic field, etc. The acquired systems show enhanced self-shaping systems that help optimize the material use for sustainability purposes. The most researched stimuli are heat, humidity, magnetic field and electrical current. Thus, this paper classifies them into electrically and passively actuated smart materiality as will be furtherly discussed in the following.

Figure 2: Urbach tower panels during installation (Urbach et al., 2020).

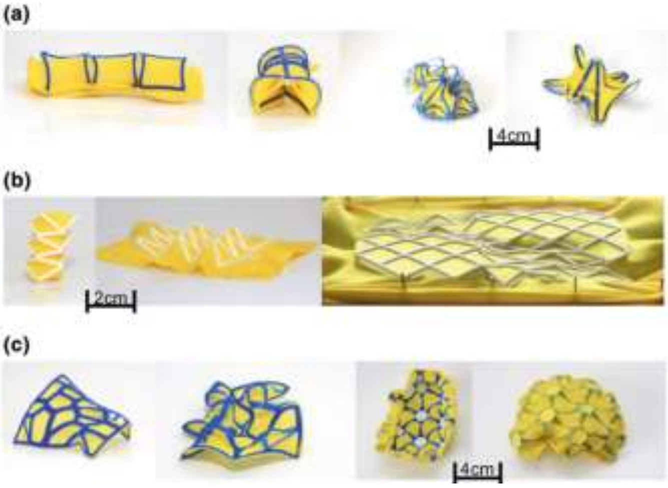

Figure 3: 4D printed textile. A) grid 3D print. B) diagonal print. C) special patterns print (Schmelzeisen et al., 2017).

4.1. Electrically actuated smart materiality

Decker (Decker, 2013) fabricated the Homeostatic Façade System. The system is made of dielectric elastomeric polymer, the material actuates when an electric current is applied as shown in **Fig.4**. The system is structured as a flexible polymer core covered by a dielectric material, where the core expands in response to electric charges. The difference in expansion coefficients of the two materials direct the elastomer motion shown in **Fig.5**.

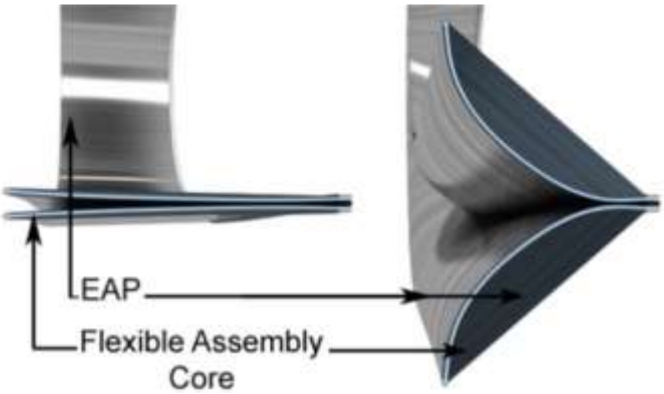

Figure 4: Homeostatic Façade System motion simulation (Decker, 2013).

Figure 5: Homeostatic Façade System (Decker, 2013).

Shimul (Shimul, 2017) investigated the effect of patterning the conductive power inside an elastomer, the amount of conductive powder and elastomeric shape frame which resulted in difference in the motion direction and response as shown in **Fig.6**. The final selected shape trail in **Fig.7.** illustrates the success of achieving active materiality by achieving a smart kinetic system occupying less space.

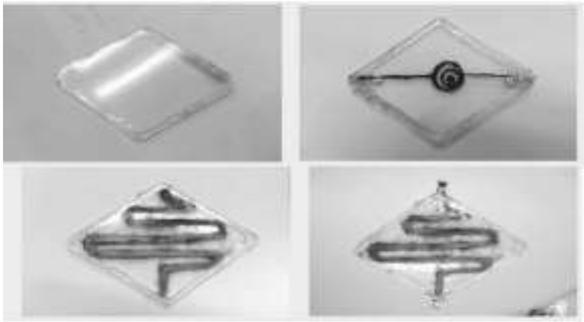

Figure 6: The conductive power powder patterning effect on kinetic motion (Shimul, 2017).

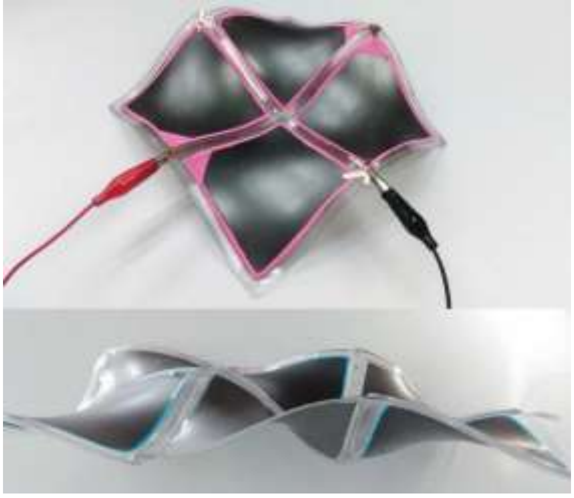

Figure 7: Dielectric shape shifting elastomer (Shimul, 2017).

4.2. Passively actuated smart materiality

Actuation using renewable energy like humidity and heat is classified in this paper as passive actuation. Passively actuated architecture features utilize the built environment surrounding the building, the generated response is programmed to produce new pragmatic functions. They can reduce energy consumption and increase product efficiency.

In literature, Fogged et. al (Foged et al., 2020) presented an interactive thermally actuated louvre in interior space. The louvre is of a composite structure. The laminates are Oak and polyethylene PE, researchers used CES Granta Architectural Edupack for material selection and screening using two parameters; thermal expansion coefficient and Young’s modulus. Subtractive fabrication using laser cutting was used for production. Parts were adhered together by analog assembly. Another material type which is metal composites is investigated by D. Sung et al (Sung, n.d.; Velasco et al., 2015) they fabricated thermal bimetals that senses temperature and deflect in specified direction due to composite programming as shown in **Fig.8**. The difference in thermal expansion coefficient between both metal layers induces stress that directs the motion. As a result of this research, Bloom pavilion was fabricated (Sung, n.d.).

Figure 8: Thermal bimetal installation.

Reichert et al. (Menges et al., 2012) managed to explore the intrinsic properties of wood, where they harnessed wood's hygroscopic property to formulate a responsive composite as shown in **Fig. 9**. The aperture designed so as to self-curl when humidity is low and relax when humidity is high. The design simulation illustrates the geometric assembly of the units to create an opening which is climatically controlled. Their research was further developed into an environmentally responsive fabricated architectural feature that can adapt to context when humidity levels vary, thus it actuates using renewable energy source. They made a pavilion with this designed feature called apertures architectural in HygroSkin project (Correa et al., 2013; *HygroSkin: Meteorosensitive Pavilion | achimmenges.net*, n.d.; Velasco et al., 2015). It was digitally fabricated and digitally assembled as shown in **Fig.10**.

Figure 9: Humidity responsive 3D printed aperture. Low humidity: opened, High humidity: closed (Zuluaga et al., 2015).

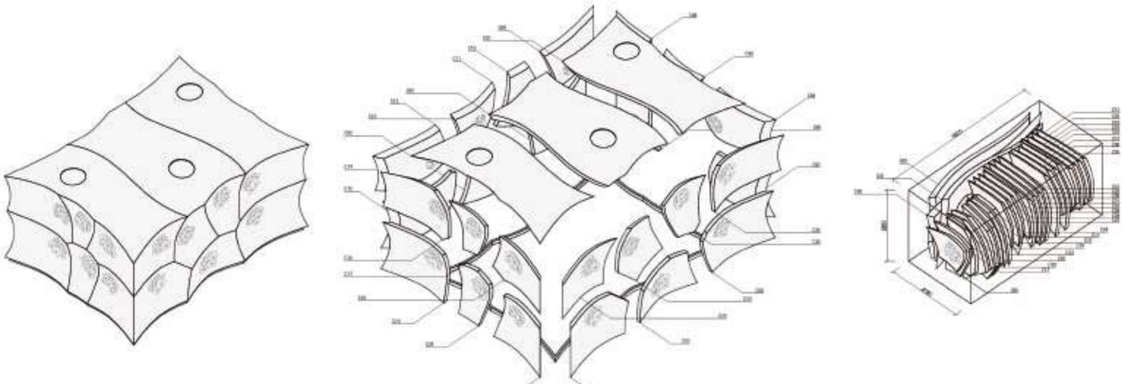

Figure 10: Hygroskin with a climatically adaptive aperture (Correa et al., 2013; *HygroSkin: Meteorosensitive Pavilion* | *achimmenges.net*, n.d.; Velasco et al., 2015).

The climatic aperture is further investigated by implementing 4D printing manufacturing paradigm principles. Correa et al (Zuluaga et al., 2015) 3d printed a humidity responsive architecture feature using co-polyester composite thermoplastic with a high cellulose content from wood fibers; weaving of a Wood Polymer Composite (WPC) composed of fibrous filler from wood-derived fibers (40%) with a co-polyester polymer material as shown in **Fig.11**. They applied different nozzle paths iterations resulting in different patterns of the unit. These different patterns were tested to determine their impact of on shape shift behavior; motion direction and curvature (Correa et al., 2020) as shown in **Fig.12** and **Fig.13**. The tests resulted in that lamination induced least curvatures while weaved composites induced higher curvature and resulted in best mechanical performance.

Another material was investigated for acquiring passive shape shift from material properties is the shape memory polymers (SMPs). Beites (Beites, 2013) produced deployable architectural structures using SMP joints. He used Polyurethane SMP of glass transition (T_g) - 25 degree Celsius as a connection between Polyprolene PP polymer triangular panel units as shown in **Fig.14**. Simulation of the kinetic properties of the folded structure was done using SolidWorks software. The SMP component was thermally actuated, where the T_g was the triggering temperature.

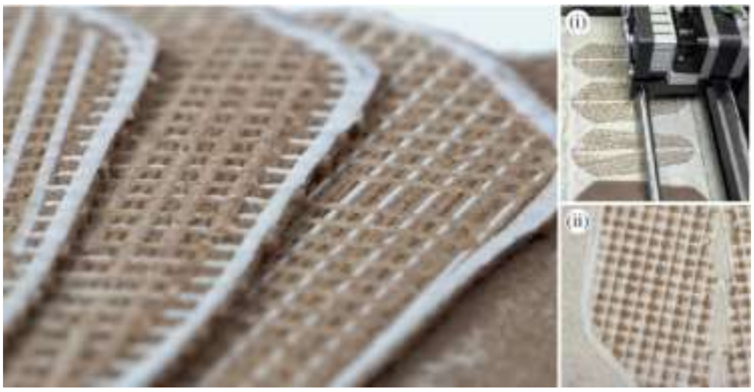

Figure 11: Wood Polymer Composite WPC (Correa et al., 2020)

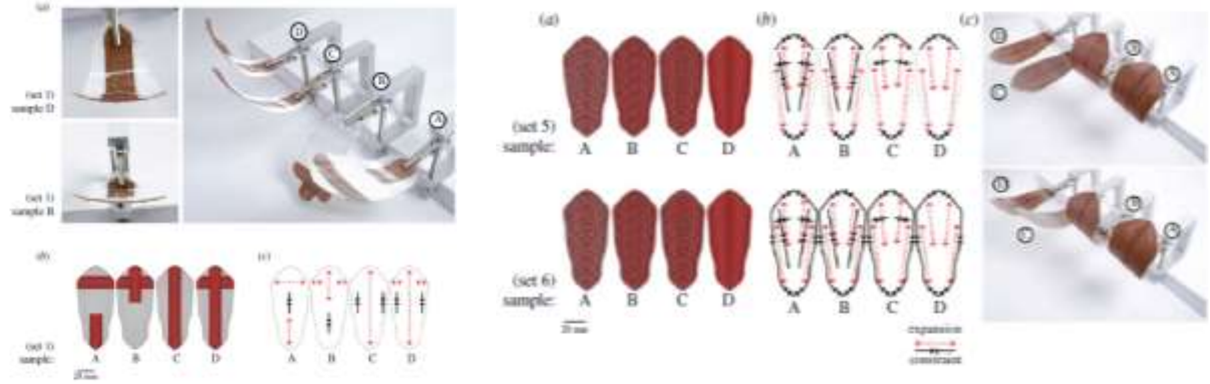

Figure 12: Physical testing of patterning of print paths on the shape shift of parts iterations 1 (Correa et al., 2020)

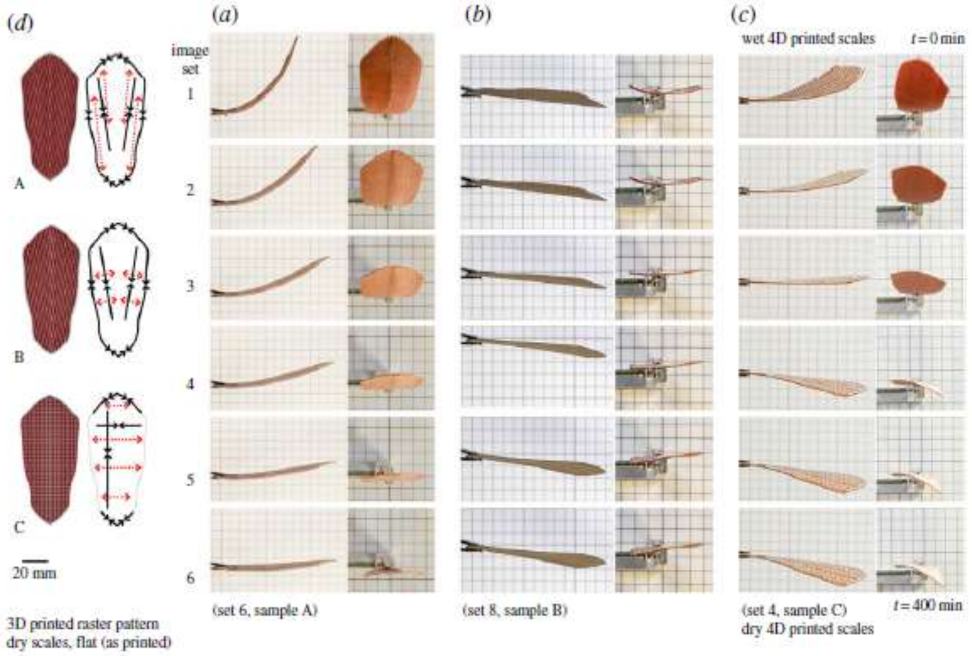

Figure 13: Physical testing of angles of patterning of print paths on the shape shift of parts iterations 2 (Correa et al., 2020)

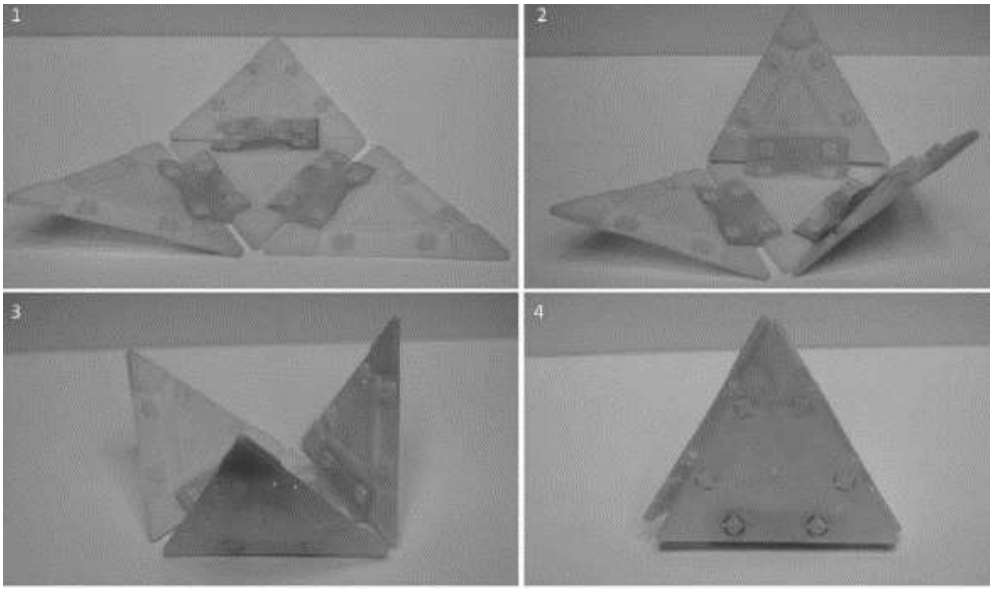

Figure 14: 1-4) Thermally triggered SMP joints for passive shape shift, showing variable form iterations during stimuli application (Beites, 2013)

5. DIGITAL MATERIALIZATION OF ARCHITECTURE FEATURES

This research identifies the material properties study for form iterations design as the initiation of advanced digital materialization process. A Digital materialization (digital product actualization) production framework for advanced architectural features is deduced from literature as shown in **Fig.15**. It starts by material selection. The material dimension is investigated to optimize it's use as well as it has been taken as a form driving force expressed as material programming. The material's properties are investigated and exploited to identify a new stimulus responsive architectural component is expressed as the shape shift analysis in this framework. The shape shift behavior analysis for programming requires identifying the mathematical approach of forward or inverse problem; forward problem is when the final desired shape is known, while inverse problem is when the properties input is investigated to produce unidentified form.

Following is the targeted geometry or geometry exploration using material properties. Upon identifying the form, it is discretized into discrete units for ease of manufacturing and assembly. After, a structural analysis of connections is conducted followed by digital fabrication. Digital fabrication is classified into additive and subtractive manufacturing paradigms. It is observed from literature that additive fabrication produces least waste during material processing. The assembly step of the process is deduced to be digital or analog assembly; digital assembly is achieved using robot arms while analog assembly is done using manual approach.

An evaluation of feature/building performance is conducted after the assembly to validate the process as well as identify any drawback to optimize the production. The evaluation tests durability, performance and user interactivity with the product. It is observed that product/feature produced from this framework shortcomings/drawbacks are either in selected material or a case in between geometry and structural analysis.

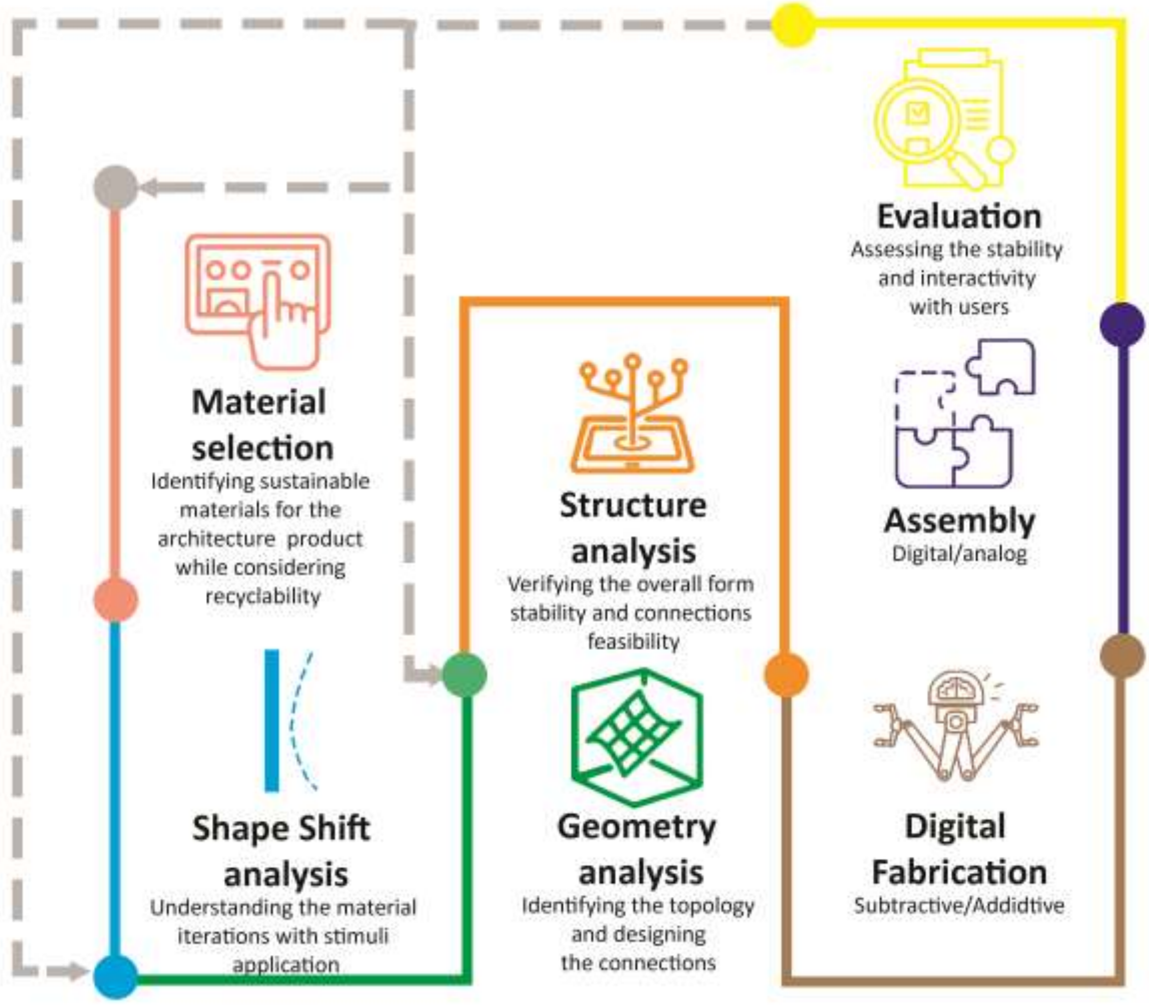

Figure 15: Digital material system materialization production framework

SUMMARY AND CONCLUSIONS

In Digital Materiality paradigm, the usage of material properties as a design method is identified as material programming. Material programming produces smart materials. This research classifies material programming into bending active and interactive stimuli responsive architecture methods. Bending active method produces static form iteration, while the latter produce interactive architecture features. Materials investigated in literature varied from metals, wood-based, textiles to polymers. A Digital architecture materialization (digital product actualization) production framework is deduced from literature. The framework steps are material selection, shape shift analysis, geometry analysis, structure analysis, digital fabrication, assembly and evaluation.

DISCUSSION

This paper classifies material programming methods in Digital Materiality paradigm. Material programming optimize the use of material dimension in the architecture product system which produce smart material system. Advanced interactive stimuli active architecture features use renewable resources of the context of the building feature like heat and humidity as motion stimuli. Thus, there will be a reduction in interactive architecture system energy consumption for motion. Also, varying the stimuli application on studied material to derive static form iterations produce advanced static architecture features that mimic the nature's system. Thus, enhances biomimicry in architecture. The classified material programming methods complies with the sustainable development goals (SDGs) of reduced energy consumption and optimized production. In order to achieve the final product, material programming method selection is considered a step in a deduced digital architecture materialization production framework. It is noted that in some approaches the feature is digitally fabricated then a stimuli application/material programming is done, while in other approaches the programming is considered part of the digital fabrication of unit.

In order to enhance the sustainability of the product fabricated from the presented framework, it is recommended to select biodegradable/recyclable materials like textiles, wooden-based and biodegradable polymers. In addition to selecting renewable energy sources as the stimuli such as heat, solar radiation and humidity. Also, expanding the use of additive manufacturing such as 3D printing in the system to minimize waste during fabrication step.

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