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Title.

Material-based Computational Design (MCD) in Sustainable Architecture

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Material-based Computational Design (MCD) in Sustainable Architecture

Abstract:

Today material is the driving force in architectural design processes run by Computational Design (CD). The architect may lead the design process and its outputs by analysing material type and properties, as well as constraints, at the beginning of the process. This article reviews the state of the art in Material-based Computational Design (MCD) and aims to analyse the role of materials in efficient and sustainable MCD processes. A set of critical projects developed over the past decade have been selected and grouped based on how material is incorporated into the process. In the process, three main categories are identified—namely, Material Performance, Informed Materials and Programming Materials. Based on predefined criteria on efficiency (E) and sustainability (S) in architectural design processes, the projects are analysed to calculate their E+S ratings. The analysis identifies two principal approaches implemented in MCD. One focuses on integrating material properties with other critical parameters—including form, performance and fabrication. The other concerns enhancing material properties by designing new materials. The analysis verifies that MCD generates both efficient and sustainable design solutions. By using CD in architectural design processes, existing materials can be re-interpreted and innovative materials can be produced to achieve new spatial experiences and meanings.

Keywords: Material-based design, computational design, architectural design, efficiency, sustainability.

1. Introduction

The increasing influence of information technologies in the field of architecture over the last decade has defined a new relationship between material and architectural design in which material has become the principal driver. Parameters, rules and relationships related to the various material types and properties can be integrated into Computational Design (CD) models. In those models, parameters are expressed with variable properties, which relate to each other by predefined rules. Problem-solving in the design process must reckon with both *ill-defined* and *well-defined* problems (Reitman, 1964; Cross, 1984, 2000; Coyne, 2005; Casakin, 2010). Here, well-defined problems define rational processes for specific goals, unlike ill-defined problems, which involve uncertainty (Suwa et al. 1999). Using CD, critical parameters affecting architectural design become well-defined and can be identified at an early stage of the design process.

Pioneers such as Gaudi, Fuller and Otto used physical modelling for the purpose of form-finding at the beginning of the design process. Material systems, such as chain and weights, were able to interact with environmental forces integrally to provide optimal form. Today, architectural design has been transformed into a tectonic integrity, such that material is now evaluated along with form, performance and fabrication (Kolarevich and Klinger 2008; Oxman 2010; Menges 2016; Yazici and Tanacan 2018). The term 'digital materiality', which was first conceptualized in 2008, incorporates two key words—'digital' and 'material'—to create new realities in architecture (Gramazio and Kohler, 2008). The use of CD in architectural design processes has extended the meaning of digital materiality as identified almost a decade ago, thus making the role of materials even more important today. There were previous attempts to evaluate material-based design in computational design processes, including informed tectonics concept that investigates integration of structure, material, and form within the logic of fabrication technologies (Oxman, 2012) and form-generation and materialization processes in computation through series of built projects that underline new experimental areas in architecture (Menges, 2016).

It is crucial to evaluate materials in CD processes from the perspectives of efficiency (E) and sustainability (S), both of which bear heavily on the decision-making processes of architects and engineers today. Since building materials are responsible for about 5 to 10% of the overall CO_2 emissions in the world (Habert et. al. 2012), integrating digital fabrication into the design process allows optimization of material use and reductions in environmental impacts (Agustí-Juan and Habert, 2017). This article aims to address the role of materials in MCD processes that provide both efficient and sustainable solutions. The findings offer benefits to architects, designers, engineers, as well as students, by identifying and shedding much-needed light on the different roles that materials can play in the design process and how material properties can inform design at different scales.

2. Research Methodology

The methodology of this study builds on existing research and also undertakes new experimental work by identifying the role of materials in the CD process, consisting of four stages including (1) describing the general workflow of the MCD system, (2) identifying the material, generation method and output, (3) specifying the geometric features, the type of digital fabrication (DF) and constraints, and (4) applying efficiency and sustainability criteria.

2.1 Describing the general workflow of the MCD system

The role of materials in the process should be described in the workflow of the MCD at the outset by introducing the input and output data along with the relationships among them. A flowchart diagram should represent how the material type and properties are linked to the form, analysis, optimization and generation methods.

2.2 Identifying the material, generation method and output

The material type should be specified through a unique material identification (ID) and the form-generation method needs to be identified—namely, as either 'construction', 'digital fabrication' (DF) or 'self-generation' (SG). These methods differ according to the selected materials, the scale of the output and the tasks undertaken. While conventional construction methods include machinery enhanced by using human labour, DF offers a variety of tools from industrial robots and drones to computer numerical control (CNC) milling, as well as laser cutting, water-jet cutting, and three-dimensional (3D) printing. DF machinery has limitations, including working area and payloads. They are also constrained by the materials used in the process. The SG process is driven by intelligent materials that may respond to changes in external stimuli, activated by humidity, heat, light, water, or kinetic movement. The output represents the final configuration of the system.

2.3 Specifying the geometric features, the type of DF and constraints

The geometric features of the form—such as being a double-curved, complex, having a gyroid surface etc.—need to be described in order to make clear the relationship between the material, form and generation method. Shell structures at construction scale require additional criteria on geometry, including weight, span and thickness, which are significant parameters in assessing the lightweight properties of the system.

DF techniques are evaluated in three main categories—namely, additive, subtractive and formative methods. While additive techniques are driven by layering materials on top of each other, such as the use of 3D printing, material pieces are removed from the whole to build the intended shape in subtractive milling and cutting, such as with CNC milling, and laser or water-jet cutting. Formative methods allow force to be applied to give the material a specific shape, such as folding by robots (Bonwetsch et al. 2006). Robotic fabrication for specialized tasks allows experimentation with different materials and conditions, including additive, subtractive and formative methods.

In addition, the type of DF and any machinery constraints should be described. If the output is generated by the activation of materials through environmental stimuli, the required external conditions should also be specified.

2.4 Applying efficiency and sustainability criteria

Lightweight structures are considered to be material-efficient because material strength is optimally used, and no resources are wasted (Schlaich, 2000, p 178). Being lightweight is determined by the ratio of span to weight (span: weight) that is applicable to the shell structures at construction scale**.**

Incorporating DF to the design processes allows *design automation* that increases efficiency by reducing errors and achieving greater accuracy in the output, as well as a greater speed by achieving *time efficiency*.

Having *demountable* components enables ease in transportation and demolishing processes by considering the entire life-cycle of a building. Including them reduces overall energy consumption.

Producing no waste in construction makes a significant contribution to sustainability. Additive and formative techniques using DF produce no waste. Subtractive methods have advantages over additive methods, such as 3D printing, by generating single components that can be demounted. However, additive methods can also be demounted based on the relationship between the chosen material and type of the DF, such as brick layering by robots or winding carbon and glass fibre.

Intelligent materials can respond to external stimuli, such as changes in heat, humidity, light, pressure etc. Material is seen as a machine in these processes (Menges and Reichert, 2015). A responsive system comprising intelligent materials that can adapt to environmental changes *using no energy* can be applied in various parts of the building, and its sub-systems and will certainly lower energy consumption overall.

The projects need to be evaluated according to the predefined efficiency (E) and sustainability (S) criteria, including being *lightweight* at construction scale, *design automation*, *time efficiency*, *being demountable*, *producing no waste* and *using no energy*.

3. Material-based Computational Design (MCD)

The projects selected for analysis in the present research all represent the state of the art in MCD, albeit but a limited sample of the latter. They enable identification of a framework for the MCD that can be allied to all projects. The critical projects about in the last decade are selected according to how they use materials in the design process as grouped in three, including: (1) Material Performance (2) Informed Materials (3) Programming Materials. The projects in the first group are based on exploring the capabilities and limitations of the materials applied to lightweight structural shell systems at construction scale. Outputs are generated by both DF techniques and human labour brought together to build large-scale units. In the second group of projects, the use of DF is prioritized in the process. Thus, the constraints of the fabrication method dictate the materials that are provided. The third group includes materials that are responsive to external stimuli and can be programmed a priori to activate through the use of CD processes. The SG method, as identified for the third group, includes DF techniques along with chemical reactions.

3.1 Material Performance

The strength and other characteristics of the materials can be determined by generating mechanical and physical tests. Performance analysis and optimization can also be used to integrate material properties into the overall form in the CD model at the early stage of the design process by exposing the limitations of the construction method. Thus, the most appropriate solution is created by evaluating all the constraints and re-interpreting materials at construction scale.

3.1.1 Describing the general workflow of the MCD system

Material Performance (MP)-based projects explore the capabilities and limitations of the materials. Thus, material type and properties are identified initially in the process and associated with form, construction, analysis, and optimization. The workflow of an MCD system based on MP is detailed by way of a flowchart (Fig. 1).

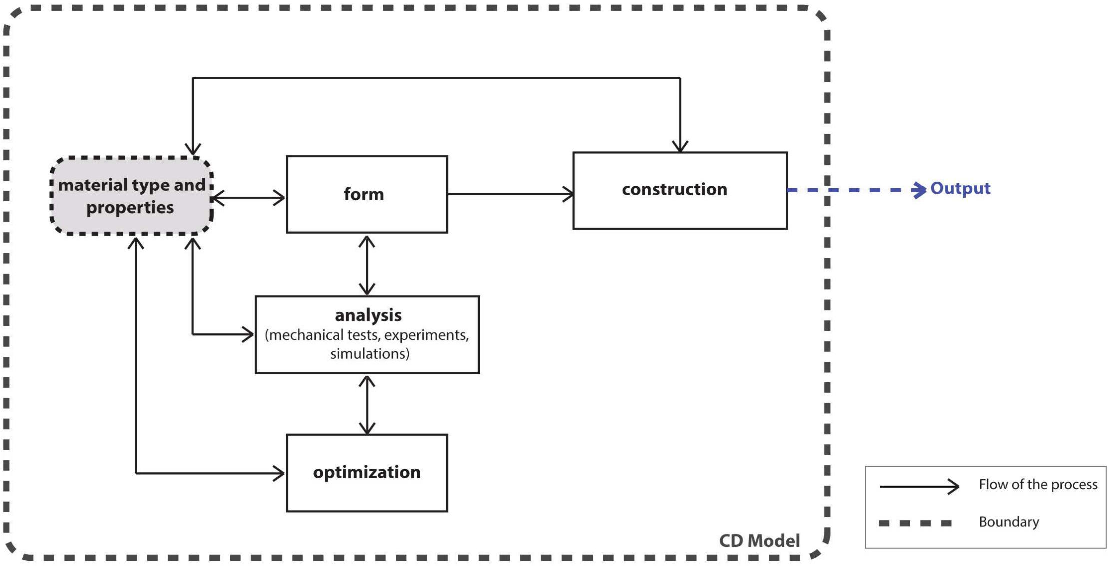

Figure 1. Workflow of MP-based projects showing the integration of materials into the MCD process.

3.1.2 Identifying the material, generation method and output

Since material properties dictate the overall architectural form in MP-based projects, the principles of the material system need to be identified in the process. Then, the architectural geometry is generated based on the constraints related to the material system and generation method that may vary from DF by the use of industrial robots and drones, to conventional construction methods enhanced by the use of human labour and machinery. The selected design projects are generated by well-known materials, such as wood, carbon fibre, glass fibre, concrete and stone, by determining their limitations and improving their current uses.

Wood obtains specific characteristics—such as elasticity and anisotropy—that depend on the direction of the grain. In one of the earliest examples (MP.1), the anisotropy of the timber material and its formal characteristics pertaining to bending were researched and experimented. A CD model was generated according to the limitations of the materials used and investigation of the biological systems, in which architects, engineers and scientists with different expertise collaborated in design and performance analysis. The geometric model was associated with the Finite Element Method structural analysis model (Fleischmann et al., 2011; Menges, 2011). The fabrication techniques used in the process may vary according to the tasks undertaken. As a continuation of the research into the anisotropy of the wood, another fabrication technique is adopted from industrial sewing integrated with robotic fabrication, in which the patterning and connection techniques of the components were specified according to the thin plywood panels used for the double-curved shell structure (MP.2) (Schwinn et al. 2016). In addition to the plywood panels, lightweight carbon and glass fibre composites with high tensile strength were tested in shell structures integrated with robotic fabrication, including industrial robots and drones. Since carbon fibre is stiffer material than glass fibre, the former can be used for load transfer, while the latter is suitable for spatial partitioning. Lightweight fibre composites perform well, in terms of material self-weight, for larger span structures (MP.3; MP.4) (Yunis et al., 2014; Dorstelmann et al. 2014; Reichert et al. 2014; Felbrich et al. 2017).

Pioneers such as Torroja, Isler and Candela designed shells with a variety of forms through analytical solutions. Today, the limitations of concrete as a structural shell material are also being tested. A cable-net and fabric formwork system was designed to reduce material waste by improving traditional formwork structures and using reusable components. Carbon fibre-reinforced concrete was sprayed as a thin layer to form a shell prototype by calculating the distribution of non-uniform forces with a specialized analysis method (MP.5) (Veenendaal et al. 2017). In addition to innovation in the use of concrete, masonry systems are enhanced as well. The double-curved shell made of thin limestone, fabricated by water-jet machines, achieved a relatively large span without using any reinforcement and mortar through the application of the structural principles of historic stone cathedrals (MP.6) (Block et al. 2017). Figure 2 depicts the material systems and the generation methods for the selected structural shells.

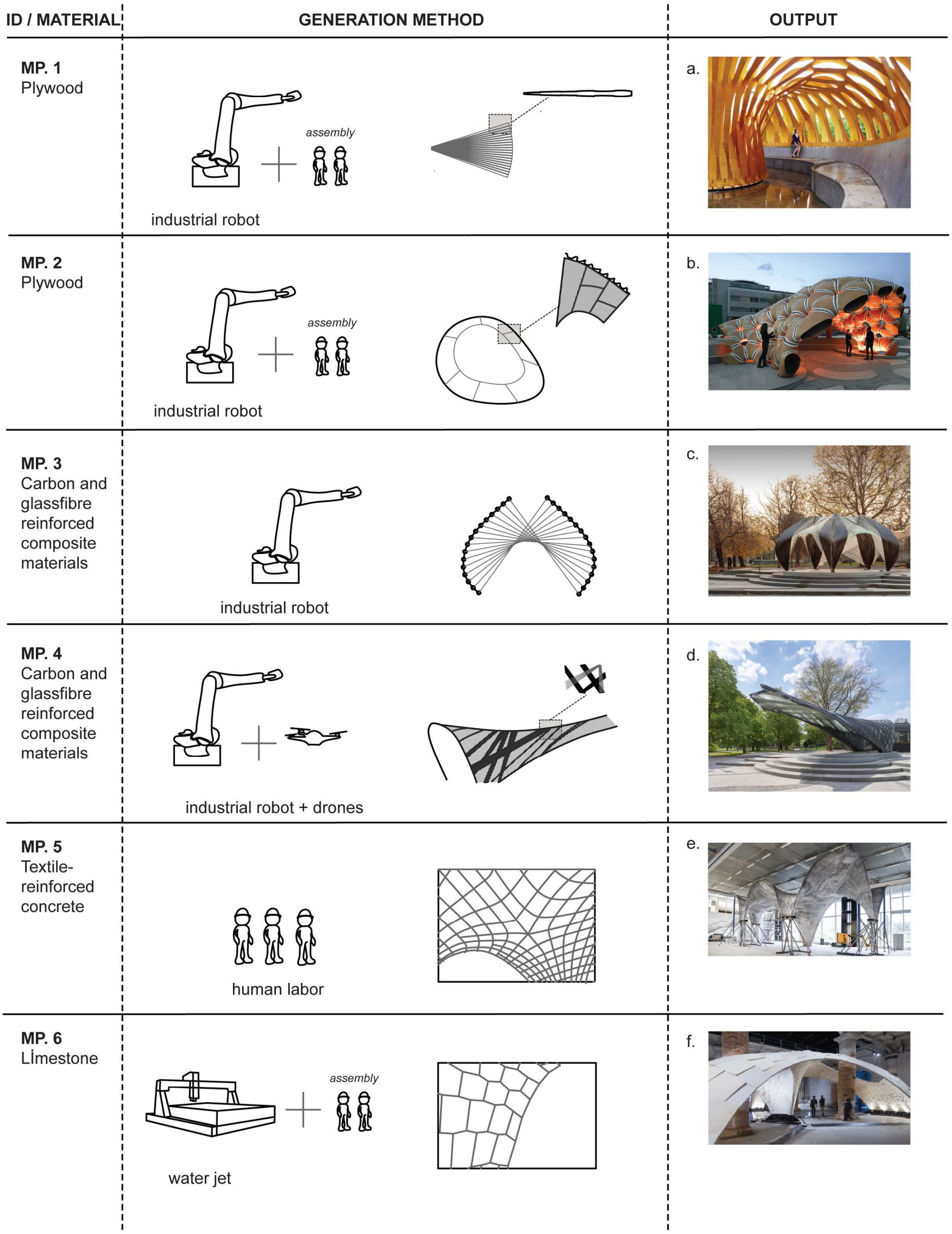

Figure 2. Materials, generation methods and outputs in MP-based projects (a.URL1; b.URL 2; c. URL 3; d.URL 4; e.URL 5; f.URL 6)

3.1.3 Specifying the geometric features, the types of DF and constraints

The projects in this category are at construction scale and the geometrical features—including weight, span and thickness values—are available. The ratio of span to weight (span: weight) is calculated to determine the efficiency of the system, in terms of being lightweight. A combination of conventional construction techniques, including human labour along with DF, is used in the process.

Table 1. Geometric features, types of DF and constraints in MP-based projects.

ID	Geometric feature	Thickness	Weight	Span	Ratio (span: weight)	Type of DF	Constraints DF machinery
MP.1	Bending-active structural shell	6.5 mm	400 kg	10 m	10 m : 400 kg= *0.025 m/kg*	Industrial robot: Subtractive	Predefined working area/ material
MP.2	Double-curved shell structure	3 to 6 mm (4 mm average)	780 kg	9.3 m	9.3 m : 780 kg= *0.012 m/kg*	Industrial robot: Subtractive	Predefined working area/ material
MP.3	Shell structure	4 mm	320 kg	8 m	8 m: 320 kg= *0.025 m/kg*	Industrial robot: Additive	Predefined working area/ material
MP.4	Cantilever structure	2 mm	1,000 kg	12 m	12 m: 1,000 kg = *0.012 m/kg*	Industrial robot + drones: Additive	Predefined working area/ payloads/ material
MP.5	Double-curved shell structure	3–12 cm (7.5 cm average)	20,800 kg	20 m	20 m: 800 kg= *0.00097 m/kg*	None: Additive	Not applicable
MP.6	Double-curved shell structure	5–12 cm (8.5 cm average)	23,700 kg	16 m	16 m: 23,700 kg = *0.00068 m/kg*	Water jet: Subtractive	Predefined working area/ material

3.1.4 Applying efficiency and sustainability criteria

Lightweight structures with high strength are considered to achieve the best performance with high efficiency. The criterion of being lightweight applies to all thin shells at construction scale. Design automation and time efficiency are achieved using DF in construction processes. All the projects are demountable, if necessary because they are made from pieces—the only exemption being MP.5, which is a continuous surface made out of concrete. For MP.3, MP.4 and MP.5, the construction process produces no waste since additive techniques are used.

3.2 Informed Material

The common feature of projects in the Informed Material (IM) category, which prioritizes DF in the process, is the limitations of the DF machinery. These include the predefined working area, payloads and materials used in CNC milling, laser cutting, water-jet cutting, and 3D printing or robotic fabrication, coded for specialized tasks.

3.2.1. Describing the general workflow of the MCD system

It has been identified that the method of DF dictates the overall architectural form. Form, analysis, and optimization steps are associated with the fabrication process in which the material is informed. The output work may vary from material to product and construction scales. The workflow of the MCD system based on IM is detailed by way of a flowchart (Fig.3).

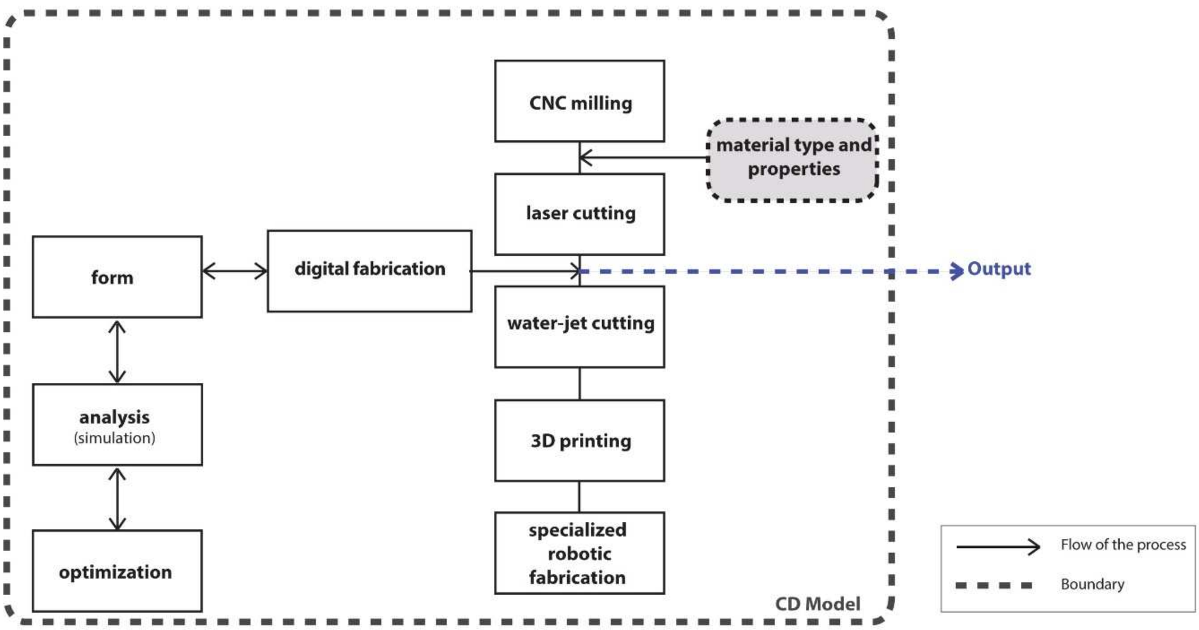

Figure 3. Workflow of IM-based projects showing the integration of material into the MCD process**.**

3.2.2 Identifying the material, generation method and output

Using DF, it is possible to re-interpret brick as one of the most common architectural materials for masonry systems. Industrial robots were used in one of the earlier projects, in which bricks were brought to the specific positions in space to form a double-curved wall structure (IM.1). The overall geometry was produced according to the order of the material with a constructive logic. While design was considered as the production of data, fabrication was seen as the processing of the material. Additive principles were implemented by stacking the bricks. Industrial robots have the ability to place individual brick pieces precisely according to the coordinate points defined in the numerical model (Bonwetsch et al. 2006). While ground robots—such as industrial robots and CNC machines—are constrained by their predefined working areas (limiting thus the scale of the working pieces), aerial robots are not limited by set boundaries. Brick-like polyurethane foam modules were used in another project, in which the digital design data was converted to the behaviour of the aerial robots—more specifically, drones. An algorithm for building a vertical structure was used by informing the macrostructure of the foam modules. The Computer Aided Design (CAD) design data was translated into control data for the robot (IM.2) (Willmann et al., 2012; Augugliaro et al., 2014). Although using aerial robotic construction eliminates the boundaries of the working area, the constraint of the payloads emerges as a limit. Examples related to the use of robotic fabrication and automation process at large scale can be extended towards various other materials, such as polymer-based composites, wood, metal, etc. (Braumann and Brell-Cokcan, 2012; Hack et al., 2013, Willmann et al., 2016).

Existing materials and products can be hierarchically grouped into quantum, atom, mid-scale, whole, parts, set and systems. The common design process is usually terminated at the component level and not at the material level. Generally, materials are selected from databases without designing them (Ashby, 1999; McDowell et al., 2010). Material design is examined in three scales that are varied in their functions. While nano-scale design is supported by atomic-scale simulations and carried out by molecular modelling, micro-scale design includes a collection of nano-structural building blocks. Meso-scale design deals with continuum modelling of larger scales, such as grain and phase (McDowell et al., 2010). By using computational models and simulations, it is possible to discover different possibilities for nano-scale structures of the materials and translate them into the product and construction scale. For instance, the minimum strength of graphene is ten times higher than steel, albeit being just 5% of the weight of steel. In one recent research study, a new material—with one of the highest strength values yet recorded—was created by translating the two-dimensional (2D) graphene into a three-dimensional (3D) surface, a 3D-printed gyroid structure, made out of photopolymer (IM.3). According to the findings, the most important feature affecting the strength of a material is the geometric configuration (Qin et al. 2017). This finding can be applied to large-scale building materials as well. High strength and lightweight materials can be obtained by providing the same geometrical conditions. Paper is a well-known example, wherein resistance against loads can be increased by adapting the material into cylindrical or folded form.

There is an ongoing interest in integrating 3D printing technologies with material properties. In one case, a photopolymer structural shell was formed by heterogeneity in the material due to the differentiation of its density, driven by structural performance (IM.4) (Oxman, 2010). 3D printing technology is extending further today, towards the use of multiple materials with a high level of resolution and through increasing complexity in geometry. By using a 3D grid-matrix—referred to as a 'voxel matrix'—it has been possible to design highly sensitive and high-resolution multi-colour, resin-based products, through the use of data instead of a geometric model (IM.5) (Bader et al., 2018).

3D printing technologies can also be implemented at the building scale by using various materials, including brittle materials, such as concrete by Contour Crafting (IM.6) and sandstone by D-Shape technology (IM.7). New technologies developed have significant advantages over traditional building methods in terms of on-site production, elimination of waste material and enabling time efficiency (Lim et al., 2012; URL 13). There are additional studies developed for extra-terrestrial environments, including the Moon and Mars, in which 3D printing technologies are being investigated—namely, the use of in-situ materials. Current examples of 3D printing at construction scale can be extended into various other materials, such as metals, bio-composite materials etc.

Figure 4 depicts the materials, generation methods and outputs of the selected projects.

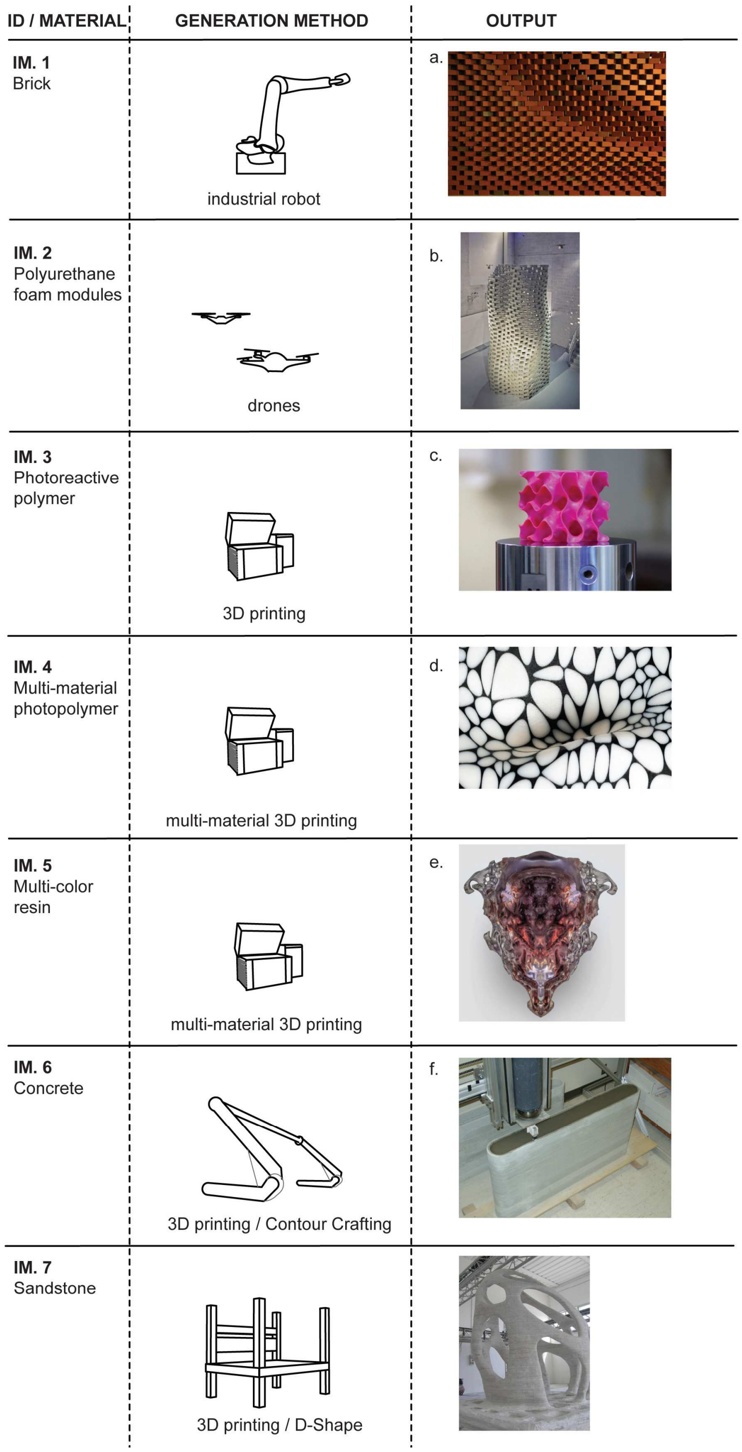

Figure 4. Materials, generation methods and outputs in IM-based projects (a. URL 7; b.URL 8; c. URL 9; d.URL 10; e.URL 11; f.URL 12; g. URL14)

3.2.3 Specifying the geometric features, the type of DF and constraints

The geometric features of the projects and constraints of the machinery are identified based on the DF methods used (Table. 2). In IM-based projects, additive techniques are included since they are able to build the global form with a predefined construction logic by informing materials. For the subtractive and formative processes, individual pieces can be produced. However, they need to be assembled toward the global form as a separate task. These processes overlap with the studies under Material Performance in Section 3.1, similar to MP.1, MP.2, and MP.6, in which subtractive techniques carried out by industrial robots or water jet were implemented to cut the plywood or limestone pieces.

Table 2: Geometric features, type of DF and constraints in IM-based projects.

ID	Geometric feature	Type of DF	Constraints DF machinery
IM.1	Double-curved surface	Industrial robot: Additive	Predefined working area / material
IM.2	Double-curved surface	Drones: Additive	Payloads / material
IM.3	Gyroid structure	3D printing: Additive	Predefined working area / material
IM.4	Geometry in any level of complexity	3D printing: Additive	Predefined working area / material
IM.5	Geometry in any level of complexity / high precision	Voxel printing: Additive	Predefined working area / material
IM.6	Geometry in any level of complexity	3D printing: Additive	Predefined working area / material
IM.7	Geometry in any level of complexity	3D printing: Additive	Predefined working area / material

3.2.4 Applying efficiency and sustainability criteria

Design automation and time efficiency are enabled by using DF methods, which are valid for all of the projects. IM.1 and IM.2 are demountable, since the type of material used consists of pieces. Additionally, the projects do not produce waste since they are fabricated by additive methods.

3.3 Programming Materials

The shape of a material may change due to temperature, mechanical and chemical effects. Smart materials—including phase-shifting magnetorheological, piezoelectric, thermos-chromic, shape-memory, and photochromic materials, etc. that respond to external environmental conditions such as loading conditions, temperature and humidity—play an important role in materials research. In projects based on Programming Materials (PM), the material's response to external stimuli is activated by environmental factors, the forces applied, chemical reactions or other changes in the physical environment.

3.3.1 Describing the general workflow of the MCD system

A CD model is generated according to the properties of the materials and connects to form, analysis and the optimization processes. Spontaneous formation conditions can be provided to generate the output in the process by activation of the materials. DF techniques, such as 3D printing or laser cutting, and SG approaches, such as chemical reactions, can be incorporated into the system. The workflow of the MCD system based on PM is detailed by way of a workflow (Fig.5).

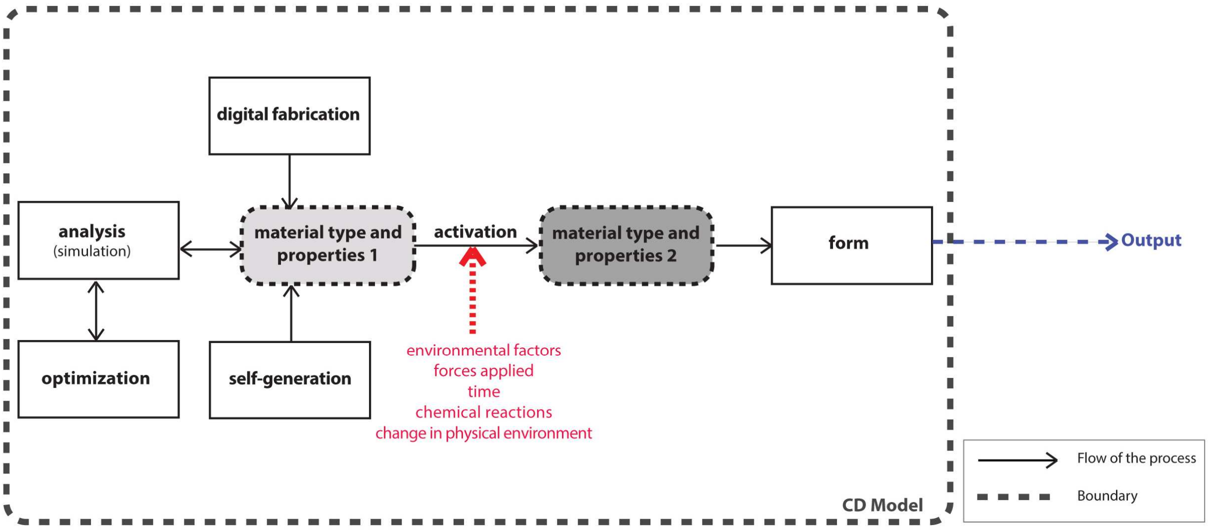

Figure. 5 The workflow of PM-based projects showing the integration of material into the MCD process.

3.3.2 Identifying material, generation method and output

In one pioneering project, thin wood panels, generated by robotic fabrication, were developed. These could be opened and closed according to variable humidity conditions provided without the use of any technical equipment or energy (PM.1) (Correa et al. 2013; Reichert et al. 2015). Similarly, a structural shell was composed of bi-metal modules fabricated by laser-cutting techniques that were able to respond to environmental conditions—more specifically, heat (PM.2) (URL 16). Since it is critical to design new materials with different properties (Ashby, 1999; McDowell et al., 2010), material can be designed by assembling the components consisting of atoms and molecules in a bottom-up approach called ‘molecular nano-technology’ or ‘molecular fabrication’ (Sanchez and Sobolev, 2010). In parallel to this, synthetic biology deals with design problems at different scales, from material to product design and from architecture to urban design, addressing materials at nano-scale.

The concepts of metabolic materials and living buildings were evaluated by Kenzo Tange in the 1950s through a re-interpretation of the Japanese architectural trend, which links buildings and organic biological growth, by bringing a different perspective to form, sustainability and the built environment. Today in the discipline of architecture, synthetic biology is moving from the conceptual to the practical phase (Armstrong 2011; 2014). In this process, natural elements interact directly with building materials in the design and production processes, such as the proposal to repair and reconstruct the damaged wood-pile foundations of Venice, which have been under water for centuries and experience degradation due to salt and organic life. It is foreseen that organic chemicals reacting with carbon dioxide and minerals under water will produce a new structure from artificial limestone rocks to support existing building foundations (PM.3) (URL 17). Similarly, an experimental photo-bioreactor application, activated by light, was carried out, in which micro-algae-containing, flat-panel-façade systems produced biomass as a renewable energy source. The façade system also provided dynamic shading, sound and heat insulation (PM. 4) (URL 18). The material behaviour of such systems can be tested through simulations in CD models prior to being applied in the real world.

Robotic technologies are necessary for many industries, from architecture to product design and the automotive industry etc. However, such mechanisms often involve complex electromechanical devices that may bring difficult installation conditions and cause technical failures and significant energy consumption. Self-assembly is a process in which a regular structure is formed through local interaction of non-regular parts. This type of programmable material is dynamically variable in terms of form and function. The objective is defined as ‘real material robotics’ or ‘robots without robots’. Four-dimensional (4D) production is described as a process to generate smart materials that can serve different functions. In 4D production, the material acquires the ability to transform from one state to another. Beyond 3D production—where multiple materials can be used—time is considered the fourth dimension. By using such a method, it is possible to convert a product or mechanism from 2D to 3D geometry or from 3D to another 3D geometry. For example, a linear element produced by 3D printing can be placed into water and converted into another shape after a certain time. The system would only need a simple energy input (PM.5) (Tibbits 2012, 2014).

Developments in advanced scientific applications and technologies—such as nano-technology and production and identification of nano-materials—are critical in materials science. The general framework of the materials is specified by artificial meta-materials, which can transform features not found in nature. Being independent of scale, the strategy can be applied widely, from nano- to large scale systems. In a recent study, a meta-material (PM.6) was fabricated with laser-cut cardboard or 3D printed thin polymer sheets consisting of cubes that could be converted into different forms through kinetic movement—more specifically, by swinging. Reconfigurable meta-materials that consist of simple geometries would provide an important usage for the building industry as well (Overvelde et al., 2017).

Figure 6 shows the materials and generation methods along with the activation and outputs for the selected projects.

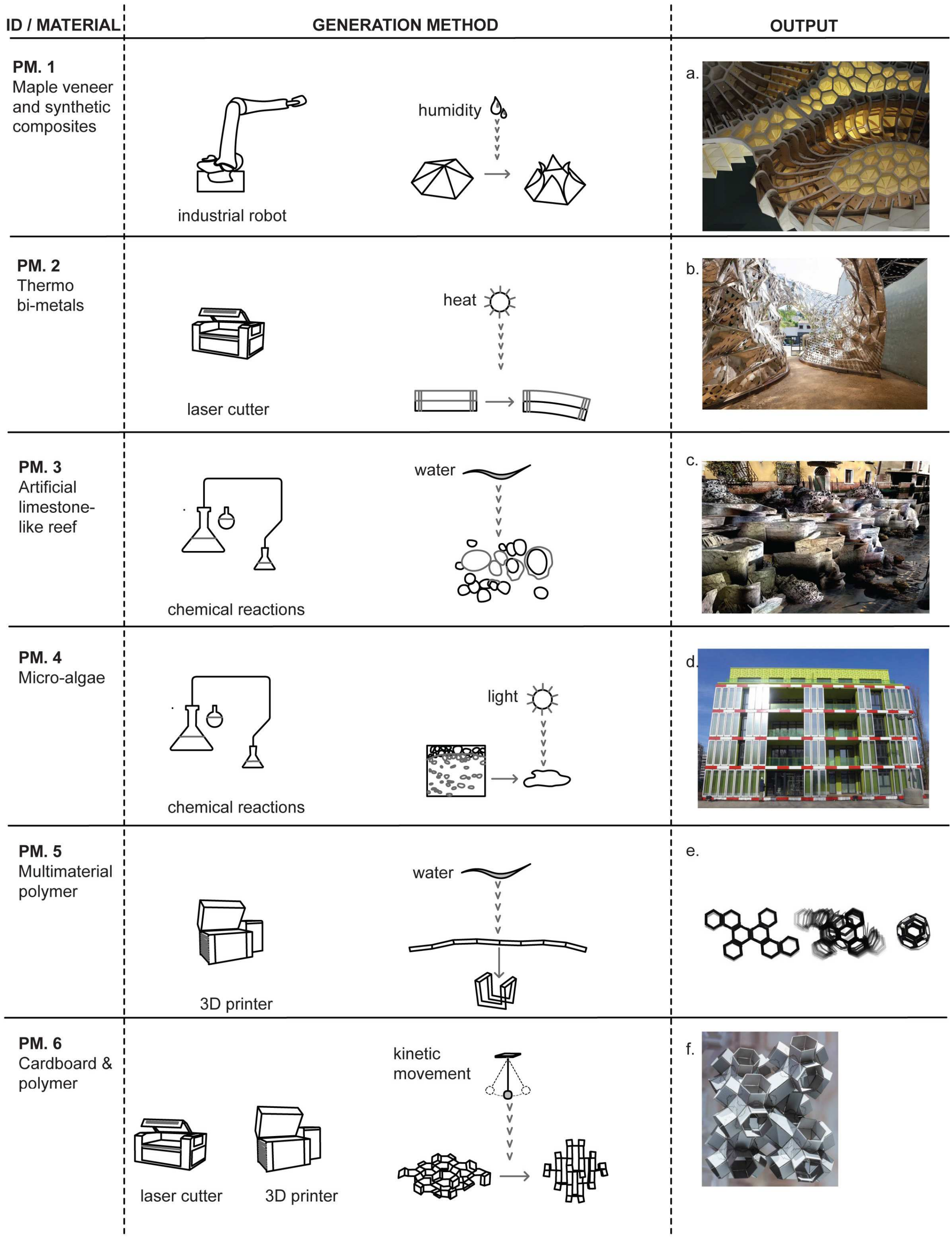

Figure 6. Materials, generation methods and outputs in PM-based projects (a.URL 15; b.URL 16; c. URL 17; d.URL 18; e.URL 19; f.URL 20).

3.3.3 Specifying the geometric features, the type of DF and constraints

The geometric features, types of DF, and the constraints related to the DF machinery and required environmental conditions for activation are detailed in Table.3.

Table 3: Geometric features, type of DF and constraints in PM-based projects.

ID	Geometric feature	Type of DF	Constraints	
			DF machinery	**Required environmental condition for activation**
PM.1	Complex geometry	Industrial robot / Subtractive	Predefined working area / material	Humidity
PM.2	Double-curved surface	Laser cutter / Subtractive	Predefined working area / material	Heat
PM.3	Complex geometry	None	Not applicable	Chemicals in water
PM.4	None	None	Not applicable	Light
PM.5	Transformation from 2D to 3D or from 3D into another 3D geometry	3D printer / Additive	Predefined working area / material	Water
PM.6	Transformation from 3D geometry into another one	Laser cutter or 3D printer / Subtractive or additive	Predefined working area / material	Kinetic movement

3.3.4 Applying efficiency and sustainability criteria

All projects driven by the PM are self-generated without energy use to achieve their final states. Design automation and time efficiency are enabled using DF methods applicable in PM.1, PM.2, PM.5 and PM.6. Additionally, since the material type consists of pieces, PM.1 and PM.2 are also demountable. PM.3, PM.4 and PM.5 do not produce waste since they are fabricated by additive methods or chemical reactions.

4. Results and Discussion

The selected projects are evaluated in terms of materials, methods used and project scales. Moreover, the predefined criteria used to calculate their E+S ratings are presented, the aim being to guide the decision-making processes of architects.

4.1 Materials, methods and scales of the projects

Although the projects are grouped according to the roles of the materials in the processes, there are certainly intersections among different clusters. For instance, some of the studies (MP.1, MP.2, MP.3., MP.4, MP.6) for which Material Performance is evaluated in Section 3.1 are directly related to the studies carried out by the Informed Material studies evaluated in Section 3.2, which use of DF in their processes. Some other studies in the Programmable Materials category (PM.1, PM. 2, PM. 5, PM. 6) in Section 3.3 also overlap with Section 3.2. Additionally, the project IM.4, driven by structural performance, overlaps with the studies undertaken in the MP category. However, it is excluded from the first group since it was not a built project at construction scale.

Table. 4 underlines that MCD is evaluated from two different perspectives. In the first, material properties are integrated with critical parameters related to form, performance and fabrication using CD methods. In the second perspective, computation—namely, Computational Material Design (CMD)—is used to improve material properties. Both perspectives can be evaluated in terms of their applicability to construction and buildings, although the majority of the studies in the subject area were developed for a single type of material or a particular scale.

Table 4. Materials, methods, and scales of the selected projects in MCD**.**

ID	Material	Method	Scale
MP.1	Plywood	CD	Construction
MP.2	Plywood	CD	Construction
MP.3	Carbon and glass fibre-reinforced composite materials	CD	Construction
MP.4	Carbon and glass fibre-reinforced composite materials	CD	Construction
MP.5	Textile-reinforced concrete	CD	Construction
MP.6	Limestone	CD	Construction
IM.1	Brick	CD	Construction
IM.2	Polyurethane foam modules	CD	Construction
IM.3	Photoreactive polymer	CD/CMD	Product/ Material
IM.4	Multi-material photopolymer	CD/CMD	Product/ Material
IM.5	Multi-colour resin	CD/CMD	Product/ Material
IM.6	Concrete	CD	Construction
IM.7	Sandstone	CD	Construction
PM.1	Maple veneer and synthetic composites	CD/CMD	Construction/ Material
PM.2	Thermo bi-metals	CD/CMD	Construction/ Material
PM.3	Artificial limestone-like reef	CMD	Construction/ Material
PM.4	Microalgae	CMD	Construction/ Material
PM.5	Multi-material polymer	CD/CMD	Product/ Material
PM.6	Cardboard, polymer etc.	CD/CMD	Product/ Material

4.2 Calculation of the E+S Rating

The selected projects are also evaluated based on efficiency (E) and sustainability (S). For all projects driven by MCD, being lightweight, enabling design automation, and time efficiency are key criteria for the evaluation of the E value; being demountable, producing no waste and using no energy are considered critical in assessing the S value. The E & S criteria are explained in detail in Section 2.4. Additionally, Sections 3.1.4, 3.2.4, 3.3.4 have described how the E+S criteria are associated with the selected projects under three categories—MP, IM and PM—as detailed in Table 5. Based on the analysis of the selected projects, the rating for E+S is calculated by assigning a value of "1" for each applicable item. Here, the total sum is calculated to produce the aggregate E+S rating. The use and type of DF in the processes affected the projects greatly. It is verified that the MCD systems offer both efficient and sustainable design systems, in which their E+S ratings range from 2 to 5. MP.3 and MP.4, which explored the limits of the materials in shell structures by integrating additive DF methods, received the highest rating (5), among all the nineteen selected projects. Using material as the driving force in CD processes would increase both the efficiency and sustainability of the system.

Table 5. Evaluating efficiency and sustainability criteria in the MCD.

ID	Type of DF	E: Lightweight (construction scale)	E: Design automation	E: Time efficiency	S: Demountable	S: No waste	S: No energy use	Rating for E+S
MP1	Subtractive	1	1	1	1			4
MP2	Subtractive	1	1	1	1			4
MP3	Additive	1	1	1	1	1		5
MP4	Additive	1	1	1	1	1		5
MP5	None	1				1		2
MP6	Subtractive	1	1	1	1			4
IM1	Additive		1	1	1	1		4
IM2	Additive		1	1	1	1		4
IM3	Additive		1	1		1		3
IM4	Additive		1	1		1		3
IM5	Additive		1	1		1		3
IM6	Additive		1	1		1		3
IM7	Additive		1	1		1		3
PM1	Subtractive		1	1	1		1	4
PM2	Subtractive		1	1	1		1	4
PM3	None					1	1	2
PM4	None					1	1	2
PM5	Additive		1	1		1	1	4
PM6	Subtractive/Additive		1	1			1	3

Following the evaluation of the E+S ratings, a network diagram has been generated by ConnectTheDots, open-source software for analysis of networks showing the relationships between the selected projects and stated E &S criteria (Fig. 7). The analysis indicates that—while *design automation* and *time efficiency* criteria obtain 16 connections (i.e., the maximum)—*lightweight* and *no energy use* criteria obtain only 6 connections (i.e., the minimum). As a result, although the majority of the projects in MCD provide design automation and time efficiency by using DF, lightweight systems at construction scale and systems using no energy are not widely applicable and only can be found in specific groups as MP- or PM-based projects.

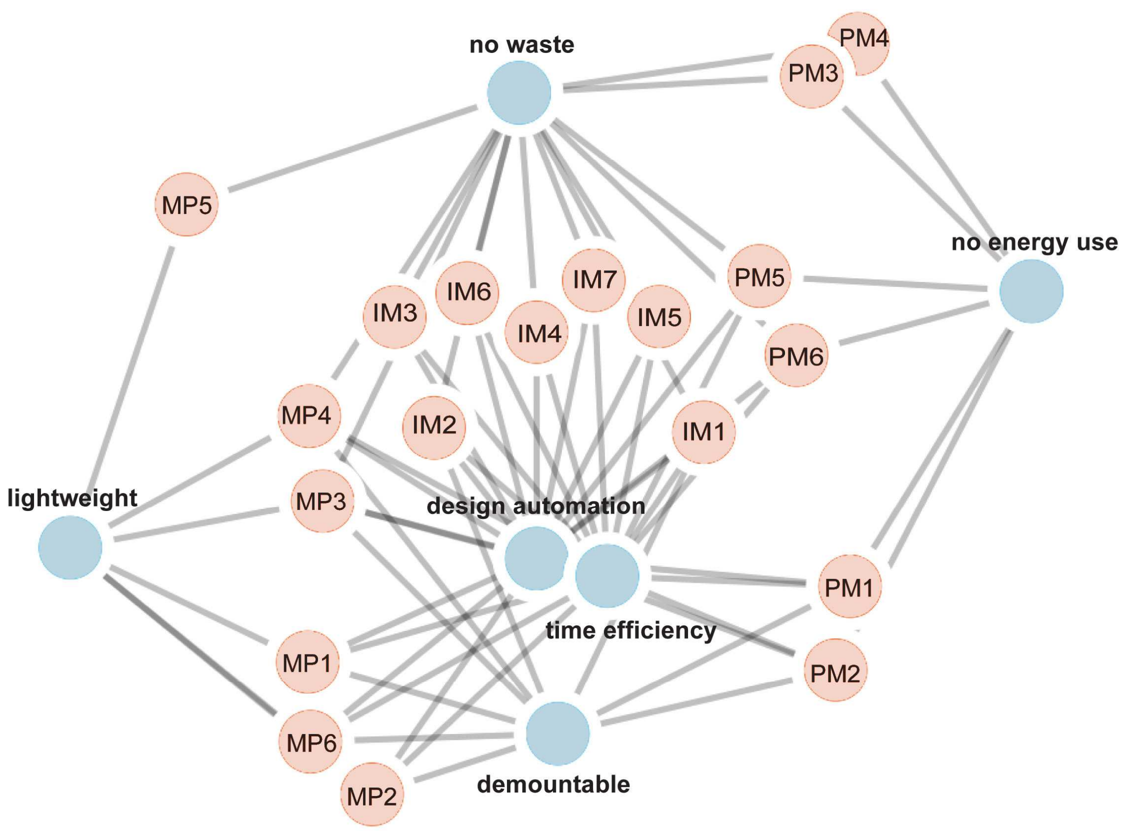

Figure 7. Network diagram showing the relationships between the selected projects and E and S criteria.

5. Conclusion

The present research has detailed the crucial role of materials in architectural design processes. Since CD advances mean material has become the leading force in the architectural design process today, it is critical to understand the behaviour and properties of materials. MP-based projects are driven by lightweight shell structures at construction scale, in which selected materials are exposed to their limits. IM-based projects prioritize the constraints of the machinery, in which material is informed. The third group, PM-based projects, explores the dynamic properties of materials in response to their external conditions.

By evaluating the research and experiments with MCD, two significant findings can be stated:

1. Materials are incorporated into the design process mainly by two approaches. The first deals with integrating existing materials (such as brick, limestone, polymer, wood, GFRC, concrete) and their properties with other parameters such as form, performance or fabrication by CD. The second concerns enhancing material properties to create new materials (such as artificial limestone, micro-algae) by CMD. The scales of the projects may vary from material to product and construction.
2. MCD systems offer both efficient and sustainable design systems, verified by calculation of their E+S ratings based on predefined criteria. The majority of the MCD projects are developed using DF, and the role of the materials differs in MP-, IM- and PM-based projects. MP-based projects in construction scale have the advantage of being lightweight, evaluated in terms of efficiency. The use and type of DF are critical for assessing efficiency and sustainability in all projects. Using DF, design automation and time efficiency are achieved, as repetitive tasks are undertaken quickly and precisely. While additive DF methods have the advantage of producing no waste, design projects assembled by pieces have the advantage of being demountable. Systems activated without energy use in PM-based projects can make a significant contribution to sustainability. MP.3 and MP.4, which explored the limits of the materials in shell structures by integrating

additive DF methods, received the highest E+S rating (5) among all the nineteen selected projects. Additionally, a network diagram, which depicts the relationships between the selected projects and E and S criteria, has been generated.

CD and DF have brought the influence of technology in the fields of architecture and design to the forefront. It is now possible to produce new materials based on expected conditions and requirements by computational methods, instead of using existing materials driven by mass production. Additionally, DF techniques support customized construction.

Some of the analysed projects have been developed as prototypes at material or product scale—further research should be undertaken to implement these at construction scale. For example, translating a meta-material made from cardboard into a durable, recyclable, biodegradable, energy- and raw-material-efficient new building material would make an enhanced structural, environmental, and ecological performance possible. Projects using no energy should be developed further along with the lightweight projects at construction scale. They need to be better integrated into the MCD systems in general, which can be investigated along with the reuse of materials. Research in the field of biomimicry also becomes critical, in order to learn from biological systems and implement its intelligence in the innovation of new materials that can be integrated into nature seamlessly, by considering their entire life-cycles.

It is possible to foresee that architecture and design applications will continue to develop on the axis of 'materials' in the future. In this direction, an architect is expected to acquire and develop knowledge about materials, advanced mathematics, geometry, and coding, as well as skills to construct CD models. Interdisciplinary collaboration with material scientists is thus especially important. The result of such work will mark the impact of the role of the materials in design, innovation in building materials and thus further enhance architectural design, construction and buildings.

References

1. Agustí-Juan, I. and Habert, G. (2017). Environmental design guidelines for digital fabrication, *Journal of Cleaner Production*, 142, 2780-2791.
2. Ahlquist, S., Kampowski, T., Torghabehi, O.,O, Menges, A. and Speck, T. (2015). Development of a digital framework for the computation of complex material and morphological behavior of biological and technological systems. *Computer-Aided Design*. 60, 84–104.
3. Armstrong, R. (2011). How Protocells Can Make 'Stuff' Much More Interesting. *Architectural Design*, March/April, 81: 2, 68-77.
4. Armstrong, R. (2014). Designing with Protocells: Applications of a Novel Technical Platform. *Life* (2075-1729). 4:3, 457-490.
5. Ashby, M. F. (1999). *Materials Selection in Mechanical Design*, Butterworth-Heinemann, Oxford-UK; (in) McDowell, D.L., Pancal, J.H., Choi, H., Seepersad, C.C., Allen, J.K., Mistree, F. (2010). Integrated Design of Multiscale Multifunctional Materials and Products, *Elsevier*, Burlington-MA.
6. Augugliaro, F., Lupashin, S., Hamer, M., Male, C., Hehn, M., Mueller, M. W, Willmann, J., Gramazio, F., Kohler, M. and D'Andrea, R. (2014). The Flight Assembled Architecture Installation. *IEEE Control Systems Magazine*, 04, 34 Cooperative Control (2014), 46–64.
7. Bader, C., Kolb, D., Weaver, J. C., Sharma, S., Hosny, A., Costa, J. and Oxman, N. (2018). Making data matter: Voxel printing for the digital fabrication of data across scales and domains. *Science Advances.* 4:5, eaas8652.
8. Block P., Rippmann M., Van Mele T. and Escobedo D. (2017) The Armadillo Vault: Balancing computation and traditional craft, *FABRICATE 2017,* A. Menges, B. Sheil, R. Glynn and M. Skavara (editors), UCL PressLondon, 286-293.
9. Bonwetsch, T., Kobel, D., Gramazio F. and Kohler, M. (2006). The Informed Wall applying additive digital fabrication techniques on architecture, Proceedings of the 25th Annual

Conference of the *Association for Computer-Aided Design in Architecture (ACADIA),* sf: 489-495.

10. Braumann J.and Brell-Cokcan, S. (2012). Digital and Physical Tools for Industrial Robots in Architecture: Robotic Interaction and Interfaces. *International Journal of Architectayural Computing*. 4:10, 541-554.
11. Casakin, H. (2010). Visual analogy, visual displays, and the nature of design problems: the effect of expertise, *Environment and Planning B: Planning and Design*, 37, 170-188.
12. Coyne R. (2005). Wicked problems revisited. *Design Studies*. 26, 5-17.
13. Correa, D., David Krieg, O.; Menges, A.; Reichert, S. and Rinderspacher, K. (2013) HygroSkin: A prototype project for the development of a constructional and climate responsive architectural system based on the elastic and hygroscopic properties of wood; Proceedings of the 33rd Annual *Conference of the Association for Computer Aided Design in Architecture (ACADIA),* Cambridge, 24-26 October, 2013, 33-42.
14. Cross N. (1984). *Developments in Design Methodology*, JohnWiley, Chichester, Sussex.
15. Cross N. (2000). *Engineering Design Methods: Strategies for Product Design*, JohnWiley, New York.
16. Dorstelmann, M.; Prado, M.; Parascho, S.; Knippers, J. and Menges, A. (2014) Integrative computational design methodologies for modular architectural fiber composite morphologies, Proceedings of the 34th Annual Conference of the *Association for Computer Aided Design in Architecture (ACADIA),* Los Angeles 23-25 October, 2014, 219-228.
17. Felbrich, B.; Früh, N.; Prado, M.; Saffarian, S.; Solly, J.; Vasey, L.; Knippers, J. and Menges, A. (2017) Multi-Machine Fabrication: An Integrative Design Process Utilising an Autonomous UAV and Industrial Robots for the Fabrication of Long-Span Composite Structures; Proceedings of the 37th Annual *Conference of the Association for Computer Aided Design in Architecture (ACADIA),* Cambridge, MA 2-4 November, 2017, 248-259.

18. Fleischmann, M.; Lienhard, J. and Menges, A. (2011) Computational Design Synthesis: Embedding Material Behaviour in Generative Computational Processes*; 29th eCAADe Conference* Proceedings, University of Ljubljana, Faculty of Architecture (Slovenia) 21-24 September 2011, 759-767.

19. Goel, V. (1992). Ill-structured representations for ill-structured problems in Proceedings of the *Fourteenth Annual Conference of the Cognitive Science Society*, Lawrence Erlbaum Associates, Publishers, Hillsdale, New Jersey, 844-849.

20. Gramazio, F. And Kohler, M. (2008). *Digital materiality in architecture*. Baden, Switzerland: Lars Müller Publishers.

21. Habert, G., Arribe, D., Dehove, T., Espinasse, L., Le Roy, R.. (2012). Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges. *Journal of Cleaner Production*, 35, 250- 262.

22. Hack, N., Lauer, W., Langenberg, S., Gramazio, F. and Kohler, M. (2013). Overcoming Repetition: Robotic fabrication processes at a large scale. *International journal of architectural computing.* 3, 11, 285-99.

23. Kolarevich, B., and Klinger. K. (2008). *Manufacturing Material Effects Rethinking Design and Making Architecture,* Routledge, New York: 196 -198.

24. Lim, S., Buswell, R.A, Le, T. T, Austin, S.A, Gibb, A. G. F and Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21, 262–268.

25. McDowell, D. L., Pancal, J.H., Choi, H., Seepersad, C. C., Allen, J.K. and Mistree, F. (2010). *Integrated Design of Multiscale Multifunctional Materials and Products*, Elsevier, Burlington-MA.

26. Menges, A. (2011) Integrative Design Computation: Integrating material behaviour and robotic manufacturing processes in computational design for performative wood constructions; Proceedings of the *31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Banff (Alberta) 13-16 October, 72-81.
27. Menges, A. (2016) Computational Material Culture. *Architectural Design,* 76-83.
28. Menges, A. and Reichert, S. (2015). Performative Wood: Physically Programming the Responsive Architecture of the HygroScope and HygroSkin Projects, *Architectural Design*, John Wiley & Sons Ltd., pp. 66-73.
29. Philipp, B., Breitenberger, M., D'Auria, I, Wuechner, R. and Bletzinger, K., U. (2016) Integrated design and analysis of structural membranes using the Isogeometric B-Rep Analysis. *Computer Methods in Applied Mechanics and Engineering*: 312–340.
30. Qin, Z; Jung, G.S.; Kang, M.J and Buehler M. J. (2017).The mechanics and design of a lightweight three-dimensional graphene assembly, *Science Advances, vol.3, no.1.*
31. Rajabzadeh, S. and Sassone, M. (2017). Brick Patterning on Free-Form Surfaces. *Nexus Network Journal.* 19, 5–25.
32. Reichert, S., Menges, A. and Correa, D. (2015) Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. *Computer-Aided Design.* 60, 50–69.
33. Reichert, S., Schwinn, T., La Magna, R., Waimer, F., Knippers, J. and Menges, A. (2014). Fibrous structures: An integrative approach to design computation, simulation and fabrication for lightweight, glass and carbon fibre composite structures in architecture based on biomimetic design principles. *Computer-Aided Design.* 52, 27–39.
34. Reitman, W. (1964). *Heuristic decision procedures, open constraints, and the structure of ill-defined problems,* in Human Judgement and Optimality EdsMShelly, GBryan, John Wiley, New York, 282-315.

35. Oxman, R. (2012). Informed tectonics in material-based design, *Design Studies*, 427-455.
36. Oxman, N. (2010). *Material-based design computation.* PhD Thesis, Massachusetts Institute of Technology.
37. Overvelde, J.T. B, Weaver, J.C, Hoberman C. and Bertoldi K.(2017). Rational design of reconfigurable prismatic architected materials. *Nature*, 541, 347–352.
38. Sanchez F., K. and Sobolev, K., (2010), Nanotechnology in concrete – A review, *Construction and Building Materials*, 24 2060–2071.
39. Schlaich, J. (2000). Lightweight Structures, *Widespan Roof Structure*, eds. Barnes, M. and Dickson, M., Thomas Telford Publishing, UK, p: 178.
40. Schwinn, T., Krieg, O., and Menges, A. (2016). *Robotic Sewing: A Textile Approach Towards the Computational Design and Fabrication of Lightweight Timber Shells,* in Proceedings of *the 36th Conference of the Association for Computer Aided Design in Architecture (ACADIA),* Ann Arbor, 224-233.
41. Suwa, M., Gero J. and Purcell T. (1999). Unexpected discoveries and S-inventions of design requirements: a key to creative designs, in *Computational Models of Creative Design* IV, Eds J S
42. Tibbits, S. (2012). Design to Self-Assembly. *Architectural Design*. 82:2, 68-73.
43. Tibbits, S. (2014). 4D Printing: Multi-material Shape Change. *Architectural Design*, 84:1, 116-121.
44. Veenendaal D., Bakker J. and Block P. (2017) Structural design of the flexibly formed, mesh-reinforced concrete sandwich shell roof of NEST Hilo, *Journal of the International Association of Shell and Spatial Structures*,58(1), 23-38.
45. Willmann, J., Augugliaro, F., Cadalbert, T., D'Andrea, R., Gramazio, F. ve Kohler, M. (2012). Aerial Robotic Construction Towards a New Field of Architectural Research. *International Journal of Architectural Computing*, 3, 10 (2012), 439 - 459.

46. Willmann, J., Knauss, M., Bonwetsch, T., Apolinarska, A., A., Gramazio, F. and Kohler, M. (2016). Robotic timber construction: Expanding additive fabrication to new dimensions. *Automation in Construction.* 61, 16–23.

47. Yazici, S. and Tanacan, L. (2018). A study towards interdisciplinary research: a Material-based Integrated Computational Design Model (MICD-m) in architecture. *Architectural Science Review*, Vol. 61, Nos. 1–2, 68–82.

48. Yunis, L., Kyjánek, Dörstelmann, M., Prado, M., Schwinn, T. and Menges, A. (2014) Bio-inspired and fabrication-informed design strategies for modular fibrous structures in architecture; Proceedings of the *32nd eCAADe Conference*, Newcastle upon Tyne, England, UK, 10-12 September 2014, vol.1, 423-432.

49. URL 1: http://icd.uni-stuttgart.de/?p=4458; last accessed on: 24.11.2019.

50. URL 2: http://icd.uni-stuttgart.de/?p=16220; last accessed on: 24.11.2019.

51. URL 3: http://icd.uni-stuttgart.de/?p=8807; last accessed on: 24.11.2019.

52. URL 4: http://icd.uni-stuttgart.de/?p=18905; last accessed on: 24.11.2019.

53. URL 5: http://www.block.arch.ethz.ch/brg/project/full-scale-construction-prototype-nest-hilo-shell-roof; last accessed on: 24.11.2019.

54. URL 6: http://www.block.arch.ethz.ch/brg/project/armadillo-vault-venice-italy; last accessed on: 24.11.2019.

55. URL 7: http://dfab.arch.ethz.ch/web/e/lehre/81.html; last accessed on: 24.11.2019.

56. URL 8: http://dfab.arch.ethz.ch/web/e/projekte/209.html; last accessed on: 24.11.2019.

57. URL 9: http://news.mit.edu/2017/3-d-graphene-strongest-lightest-materials-0106#.WHD7e8tcFuI.twitter; last accessed on: 24.11.2019.

58. URL 10: http://www.materialecology.com/projects/details/monocoque-1; last accessed on: 24.11.2019.

59. URL 11: http://www.creativeapplications.net/c/data-driven-material-modeling-at-the-mit-media-labs-mediated-matter-group/; last accessed on: 24.11.2019..

60. URL 12: http://contourcrafting.com/building-construction/; last accessed on: 24.11.2019.

61. URL 13: https://d-shape.com; last accessed on: 24.11.2019.

62. URL 14: https://www.dezeen.com/2009/06/22/radiolaria-pavilion-by-shiro-studio/; last accessed on: 24.11.2019.

63. URL 15: http://icd.uni-stuttgart.de/?p=7291; last accessed on: 24.11.2019.

64. URL 16: http://www.evolo.us/architecture/bloom-by-dosu-is-environmentally-responsive-installation/; last accessed on: 24.11.2019.

65. URL 17: https://www.dezeen.com/2014/05/30/movie-rachel-armstrong-future-venice-growing-giant-artificial-reef/; last accessed on: 24.11.2019.

66. URL 18: https://www.dezeen.com/2013/04/15/arup-unveils-worldsfirst-algae-powered-building/; last accessed on: 24.11.2019.

67. URL 19: https://selfassemblylab.mit.edu/4d-printing/7jg5shnczd26kw1ukgj8iek73y3e1e; last accessed on: 24.11.2019.

68. URL 20: https://wyss.harvard.edu/a-toolkit-for-transformable-materials/; last accessed on: 24.11.2019.

Material-based Computational Design (MCD) in Sustainable Architecture

Highlights

- Material is the driving force in architectural design process run by computational design.
- Critical projects are identified based on how material is incorporated into the process.
- Selected projects are analysed towards calculating their E+S ratings.
- Material-based Computational Design generates efficient and sustainable design solutions.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: