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Ingrid Paoletti
Massimiliano Nastri *Editors*

Material Balance

A Design Equation

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Preface

The study is carried out by detecting and explaining the main areas of research and development of the experimental laboratory *Material Balance Research* within the Architecture, Built Environment and Construction Engineering—ABC Department at the Politecnico di Milano, which hosts the analysis activities, both theoretical and applied, by researchers related to academic, production and construction realities in the international field. The laboratory's activities are determined through multidisciplinary studies (cognitive and conceptual, methodological and instrumental) of multiple areas related to technological evolution and the needs of environmental balance within the contemporary scenario. In this regard, the study on the scientific and disciplinary formulation of *Material Balance* is outlined according to the fundamentals of the "polytechnic culture", promoting the principles and procedures oriented to the needs of limiting non-renewable resources, reducing polluting emissions and "transformation" (of processes, technologies and materials) in order to limit the impacts on the environment: these ethical and cultural references contribute to establishing strategies, criteria and areas of analysis and application, through the development of themes and objectives aimed at supporting innovation within the technological culture of design and architectural technology.

The study and research activity by the experimental laboratory *Material Balance Research*, considered within this first "manifesto", are determined through:

- the analysis and application of the potentialities expressed by the evolution of technical, computer and productive supports, able to encourage the activities of information management and transformation (according to *computational design* practices), modelling and simulation aimed at architectural design, building systems and components (according to *parametric architecture* and *driven design* practices), up to testing and physical checking (through the use of *soft robotic systems*, *3D printing* and *CNC machines*);
- the analysis and application methods of new processes of transformation and operation of traditional materials, evolved or resulting from recycling processes, with the aim of identifying the perspectives for reuse within many different expressive and functional, productive and executive areas;

- the investigation of sociocultural and physical interactions with the anthropocene in the current context, through the examination of the different forms of incidence and action towards the environment, supporting the methodologies and modes of action aimed at establishing the conditions of balance between human activities and both living and natural cycles;
- the analysis and methods of integration and interaction of biological organisms within the functioning and configuration of architecture, building systems and components for energy saving and production, air pollution reduction, improvement of environmental quality and biodiversity, biodegradable material production, alternatives to polluting construction materials and even food supply;
- the analysis and procedures for the investigation and optimization of the internal and external spaces of the architecture, with the aim of determining forms and interventions of environmental and sensory calibration (thermal, lighting and acoustic), with the help of both modelling and digital simulation devices and specific physical, systemic and material applications.

On this basis, the definition of the first "manifesto" assumes the objective to set the cultural and scientific fundamentals, to detect the main areas of research and the criteria of analysis and development. Therefore, with respect to the specificities of the topics examined, the theoretical and operational framework provided within this contribution is proposed as a conceptual, strategic and methodological reference to continue the studies around the *Material Balance*, in order to identify, articulate and develop further areas of theoretical and applicative study in line with the challenges and the environmental, expressive, functional and constructive needs of the contemporary and future design scenario.

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Contents

Chapter 1
The Material Balance Manifesto. Scientific Approach and Methodologies

Ingrid Paoletti and Massimiliano Nastri

Abstract This introductory chapter examines the contents and processes of the Material Balance principle, according to the relations of equilibrium that account for streams by which energy is produced, exchanged, transformed and consumed (i.e. with the application of the "law of conservation of mass"): the analysis focuses on the relations established by the "closed systems", the "unsteady state system" and the "mass balance system" until the mechanical and physiological observation. The examination investigates the elaboration as a practice of sensitive design based on the organic composition of the artificial apparatus (as systems, components and materials described as "programmable pro-active structures") and how the production, consumption and distribution activities have a direct relation with nature (mainly considering the effects of pollution controls). The study of the Material Balance Model provides a framework for analyzing alternative methods of resource and residuals management, with the aim of providing measures of performance (as guides for the technological research and for the environmental design) and of developing the new approaches to calibrate productivity and eco-efficiency. On this basis, the scientific research is intended to "model" and to visualize the conditions posed by the environmental reality of reference, through devices able to assume the modalities of experimentation and simulation: the work on Material Balance implies the objectives to incorporate environmental issues both in production efficiency models and in pro-active eco-efficiency research methods, involving the incorporation into technical design and building processes. This approach considers the development of technical elaboration of the environmental reality and the anticipation of the environmental outcomes (limiting the conditions of consumption and accumulation caused to the productive and constructive operations). Moreover, it focuses on the functional, productive and material optimization with the support of new forms of calibration and material densities, morpho-typological sizes and structural performances (with

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less material and wasted energy), with the use of "digital/virtual design" procedures, "productive/constructive customization" technics and "executive design" methods.

Keywords Material balance principle, processes and physical relations · Declination of material balance to mechanical and physiological characteristics · Technological research, environmental design and calibration of eco-efficiency in transformation processes · Procedures of knowledge, unveiling and manipulation of reality · Technical elaboration and anticipation of environmental outcomes · Functional and material optimization and "productive/constructive customization" technics

1.1 A Design Equation Coming from Engineering

The *Material Balance*, as for the *Mass Balance* principle, is a consideration of the *input*, *output* and distribution (of materials, energy and/or substances) between streams in a process or stage. The *Material Balance*, on its semantic model, deals with material and/or energy quantities as they pass through processing operations. According to this principle, the *balances* are statements on the conservation of mass (and they are fundamental to the control of processing, particularly in the control of yields of the products) showing:

- the relations of equilibrium that account for streams by which energy is produced, exchanged, transformed and consumed;
- the quantitative account of the redistribution of material and/or energy that occurs when anything happens;
- the balancing "volume reconciliation" to ensure the exact account of volumes of *in-* and *out-of-scope* source which maintains along the supply chain, provided that the volume or the ratio of sustainable material integrated is reflected in the product. In particular, considering the *output*, no (physical, chemical) difference exists between *in-scope* and *out-of-scope*;
- the challenging complexity of after-use material and/or energy streams.

The *Material Balance*, as a principle, deals with the application of the law of conservation of mass which can be compared to an "accounting" for material, according to the basic theories of Ayres and Kneese (1969). Their study (on comprehensive analysis and management of residuals and pollution) determines a fundamental reference on the consideration of the "residuals-generating materials flows" (to the mass balance principle) and of the concept of pervasive (pollution) externality. On this basis, the principle of the *Material Balance* considers that *if waste assimilative capacity of the environment is scarce, the decentralized voluntary exchange process cannot be free of uncompensated technological external diseconomies unless all inputs are fully converted into outputs, with no unwanted material residuals along the way and all final outputs are utterly destroyed in the process of consumption.*

The *Material Balance* contemplates the ratio between the quantities of materials that enter and leave any system or process which is based on the principle of the "law of conservation of mass" (this law states that matter is neither created nor destroyed in the process and the total mass remains unchanged): so the process can be defined as one or a series of operations in which materials are carried out and a desired product is result in the end, where the system can be defined as any arbitrary portion of a process to consider for analysis and the system boundary must be fixed in each problem. Specifically, the *Material Balance* is articulated through some main typologies as:

(a) the "closed systems", where process considers that materials are placed into the system at the beginning of the process, held for a period of time (known as "residence time" or "retention period") during which the required physical and/or chemical changes are occurred. Then, products are removed all at once after this time and no masses crossed the system boundary during this time, proposing the equation:

$$\text{Input (Initial quantity)} = \text{Output (Final quantity)}$$

(b) the "unsteady state system", where process considers that not all of the operating conditions remain constant with time, and/or the flows in and out of the system can vary with time, hence the accumulation of materials within is explained by the equation:

$$\text{Input} - \text{Output} = \text{Accumulation}$$

(c) the "mass balance system", where process considers, according to the "law of conservation", that matter can be transformed into other matter or energy but can never vanish: all *inputs* used in the production processes are resulting in an equivalent residual or waste. This process is widely used in engineering, chemistry, environmental impact assessment and complementary in energy, population and other major complex systems, often linked to entropy: here the *input* passed in the system (*through design*, with the materials used in building components, elements and whole constructions, as a *generation* activity) and the resulting *outputs* includes consumption (of raw materials and energy) and accumulation (of waste) as explained by the equation:

$$\text{Input} + \text{Generation} = \text{Output} + \text{Consumption} + \text{Accumulation}$$

Moreover, the *Energy Balances*, inside the *Material Balance* conception, are used in the examination of the various stages of a process, over the whole process and even extending over the total production system from the raw material to the finished product. On this basis, material and/or energy quantities can be described by material and/or energy balances, which are statements on their conservation (in respect of the "law of conservation of mass") as expressed through:

$$\text{Mass In} = \text{Mass Out} + \text{Mass Stored}$$

Just as mass is conserved, so energy is conserved in processing operations. The energy coming into a unit operation can be balanced with the energy coming out and the energy stored:

$$\text{Energy In} = \text{Energy Out} + \text{Energy Stored}$$

which can be articulated through the relation:

$$\text{Raw Materials} = \text{Products} + \text{Wastes} + \text{Stored Materials}$$

also deepened through the relation (where Losses are the unidentified materials):

$$\text{Raw Materials} = \text{Products} + \text{Waste Products} + \text{Stored Products} + \text{Losses}$$

The materials have to be considered whether they are to be treated as a whole, a gross mass balance, or whether various constituents should be treated separately and if so what constituents. The energy takes many forms (such as heat, kinetic energy, chemical or potential energy, but because of interconversions it is not always easy to isolate separate constituents of energy balances) which can be calculated on the basis of external energy used (according to the product or to raw material processed). The energy consumed in production includes *direct energy* (used on the farms, in transport, in factories and in storage, selling) and *indirect energy* (which is used to actually build the machines, to make the packaging, to produce the electricity and the oil and so on).

The material and energy balances make it possible to identify and quantify previously unknown losses and emissions, expressing how:

- the balances are useful for monitoring the improvements made in an ongoing project, while evaluating cost and benefits;
- the raw materials and the energy in any manufacturing activity are not only major cost components but also major sources of environmental pollution, and inefficient use of raw materials and energy in production processes are reflected as wastes.

The declination of the *Material Balance* may be articulated, then, from the mechanical point of view, which implies the balanced and optimized formulation between:

- the acquisition and application of the requirements and related parameters, according to the functions and performance expected from the systems, components and materials;
- the composition, physical, chemical and material calibration, with respect to the expected stresses and performances (as a result of *mass customization* modes), reducing the use of materials for product development.

At the same time, the declination of the *Material Balance* from a physiological point of view is expressed with respect to:

- the application of stimuli, stresses and loads (physical and mechanical, environmental and sensorial), to which corresponds the “automatic” reaction (in “active” or “passive” form) by systems, components and materials according to the specific morphological, functional and performance modification capabilities;
- the combination of “sensory” equipment, devices and actuation criteria by systems, components and materials, having “intelligent” and “technical” properties (whether in part or integrated form) which enable them to react to induced impulses.

The elaboration is clarified as a practice of *sensitive design* focused on the organic composition of the artificial apparatus, its articulations and surface extensions (in the form of *bioreactive artificial bodies*) which involve as sensory receptors with respect to the information received in order to proceed with movements and geometric and physical, dimensional and connective variations, as expressed by the *balance information* through the relation:

$$\text{Input Information} = \text{Learned Information} + \text{(Re)Actions}$$

The complexity of the physical balance system results from the difference between the energy put into the “dense network sensing” of “bodies” related to systems, components and materials and the energy used, as through the relation:

$$\text{Total Body Energy} = \text{Energy Stored} + \text{Energy Intake} - \text{Energy Output}$$

The declination of *Material Balance* with respect to physiological characteristics leads to the elaboration of systems, components and materials described as “programmable pro-active structures” reacting based on input values also generating, as products, bio-reactions, bio-energy and/or bio-mass (which can also be used to produce energy, i.e. electricity). These products are developed according to:

- the responsive and reflexive approaches which provide a series of mediated environmental reactions;
- the responsive interaction with sophisticated reflexive capabilities to interpret and to react to environmental loads.

This *Material Balance* concept observes how the production, consumption and distribution activities have a direct relation with nature, which provides raw materials to the economy for its production and consumption activities:

- the residuals from both the production and consumption processes usually remain and they usually render "disservices" (such as waste and pollution). Although, some of these residuals from production and consumption activities are ultimately returned to nature and are recycled (and not all emission of residuals causes pollution damage because of assimilative capacity of the environment);
- the energy taken out of the environment reappears somewhere else in the economic system, even though it might have a different form and appear as waste products (Lauwers et al. 2009).

The early approaches dealt with pollution respect of productivity and efficiency values and measures focused upon the effects of pollution controls upon (macro and micro) economic and social scales (i.e. consequences of integrating the "conservation laws" of materials and energy into the microeconomic models of production, consumption, and general equilibrium; Krysiak and Krysiak 2003). The *Material Balance* model provides a useful framework for analyzing alternative methods of resource and residuals management, i.e. in industrial and agricultural performance measurement systems, where the pollutant factors are on the rise and therefore many conventional methods of performance measurement have proven incompatible with the "material flow conditions" (Ausubel and Sladovich 1989).

Coming now at the design perspectives, the most important one for our purpose, the study gives an interpretation of the *Material Balance* equation in order to support a statement and a model to develop innovation, as research group, that could foster an agenda and consequent actions for the coming years.

Specifically, on this basis, the orientation is aimed at:

- developing a new approach to calibrate creativity and eco-efficiency (Arabi et al. 2017);
- providing measures of performance that can serve as guides for the technological research and, particularly, for the environmental design;
- adjusting traditional methods of production in order to integrate environmental concerns and social values into the technical and economic efficiency measures.

The activity, research and application, according to the principles of the *Material Balance* is a cognitive practice aiming at re-balancing our activity on the planet.

As a cognitive practice, the activity aims at replacing the phenomenal "real event", modeling the conditions posed by the environment, through experimentation and simulation.

The perspective at the design and research level focuses on the outcomes of the *Material Balance* equation, for the transformation of contemporary architecture (at an expressive, morpho-typical, functional and constructive level) with respect to different factors.

First of all the interdisciplinary acquisition of knowledge, processes and technologies from other sectors (especially those of advanced experimental and industrial nature) which can be adapted to the development of new systems, components and materials.

In this regard, the activity of the research group is proposed in the form of *agency* (or "exchange structure"; Davidson 2002) aimed at a *technology push* essentially supported by the performance requirements achieved by the functional needs of architecture, which can be identified as the main "engines" of innovation promoted by production potential (Flichy 1995, tr. it. 1996; Sobrero 1999).

Secondly the aim is containing the physical, material and energy resources for systems and components construction: through the development of advanced processes and devices, capable of including the globality of parameters, variables and constraints for the optimization of results.

Third, the calibration of shape and density with respect to the actual performance required.

Therefore, on this basis, working with a Material Balance Design equation means recognizing a new approach to resources, materials, energy and production can be able to invert the environmental decline of the anthropocene.

Moreover, the Material Balance Design practice implies that the resources extracted from the environment should eventually become wastes and pollutants, considering that recycled materials are energy consuming and imperfect, therefore this process cannot fully compensate and that waste is equal in mass to the difference between total raw material *inputs* to the process and useful material *outputs*.

However, in this scenario the products are more complex and this leads to an increase of *input* mass and wastes. The process wastes far exceed the mass of materials that are finally embodied in useful products (Villalba Méndez and Talens Peiró 2013). The emissions could be reconstructed as a subsystem of a comprehensive *production-cum-abatement technology* when treated as *inputs* in production functions (Pethig 2006). Moreover, according to *Material Balance*, the "emission function" is treated as a production *input*, as a production function with material and non-material *inputs* and bounded marginal product of the material *input*, then as a well-behaved production function with emissions as an *input* (Ebert and Welsch 2007).

The study on *Material Balance* for Design implies the attempts to incorporate environmental issues both in production efficiency models and in pro-active eco-efficiency research methods, and so involving the incorporation into technical design and building processes (Coelli and Lauwers 2007). In particular, the methodological orientation in the study, research and application activities focuses on the possibilities of supporting sustainable development in the construction sector, assuming the need to contain energy consumption and to reduce polluting emissions compared to the use of solutions capable of establishing high "environmental performance".

In this regard, the methodological orientation is articulated through the elaboration of conceptual and operational apparatus referring to the fundamentals and needs of environmental sustainability.

The "eco-efficiency" of the transformation processes, for which the design, production and construction elaboration (understood as an *environmentally conscious design* activity) is determined, in a global way, both in the interaction with the equilibrium of the ecosystem and in the acquisition of the appropriate levels of environmental and settlement quality (Slessor 1997).

The paradigms of sustainable development are defined with respect to the consequences of environmental impacts (caused largely by the management activities, especially energy management, of buildings) and aimed both at protecting the environment and bio-ecological balances, and the conservation of non-renewable resources (materials and energy).

The interactive articulation of contents, procedures and objectives with respect to the determination of the conditions of balance with the environmental system (in general, with respect to resources, constraints and contingency of phenomena), is identified as a system defined by "constructed" conditions (according to the "method of complexity"; Morin 1977, tr. it. 2001).

In the following chapter a detailed analysis will be developed on the fold a *Material Balance* for architecture and design. In particular these aspects will be taken into consideration:

- the technological culture and the procedures of knowledge, unveiling and manipulation of reality, through the development of the activities of technical elaboration of the environmental reality and the activities of anticipation of reality and environmental outcomes with the aim of limiting the conditions of *consumption* and *accumulation* caused to the productive and constructive operations (Par. 1.2);
- the procedures of functional, productive and material optimization, according to the analysis and support of new forms of calibration and material densities, morpho-typological sizes and structural performances with less material and wasted energy and the criteria related to "digital/virtual design" procedures, "productive/constructive customization" techniques and "executive design" methods (Par. 1.3).

1.2 Technological Culture and Procedures for Knowing, Revealing and Manipulating Reality

The activity of study, research and design according to the *Material Balance* principles is carried out as a process that makes use of the faculties of "manipulation" of reality and processes that interact with the environment proper to the "technological action" (Fadini 2000, p. 47) through the "manipulation" (including virtual) of the physical and procedural, productive and constructive aspects (Nacci 2000, p. 296). Specifically, the "manipulation" of reality (physical and immaterial), in the characteristics of the generation and in respect of both management and limitation of the conditions resulting from *consumption* and *accumulation*, is determined:

- as an operation both "poietic" (in the Aristotelian sense), as a practice based on the assumption and interpretation of data and notions learned from reality and the environment and, on these foundations, addressed to action through forecasting and planning methods (Gehlen 1978, tr. it. 1983), and "autopoietic", as a practice based on experiential acquisition for the purposes of action (Maturana and Varela 1984, tr. it. 1992);
- as an expression of the ability to "give form" (according to the "constructivist" position; Borutti 1997) and to "manifest" reality through the adoption of "calculating" and predictive tools and practices (Cacciari 2000, p. 15) (Fig. 1.1).

The "manipulation" of physical reality, according to the optimization and management of the contents related first to *generation* and then to *consumption* and *accumulation*, is proposed as an instrumental and "finalized" activity, typical of the *homo faber*, aimed at the development of procedures and operating methods for the realization according to the conceptual and design, productive and constructive, environmental and energy balances (Arendt 1958, tr. it. 1964, pp. 220–221). Therefore, the activities of study, research and application according to the *Material Balance* principles, in accordance with the specific "finalized instrumentation" of the *homo faber*, involve either the formulation of the cognitive and operative modalities for the

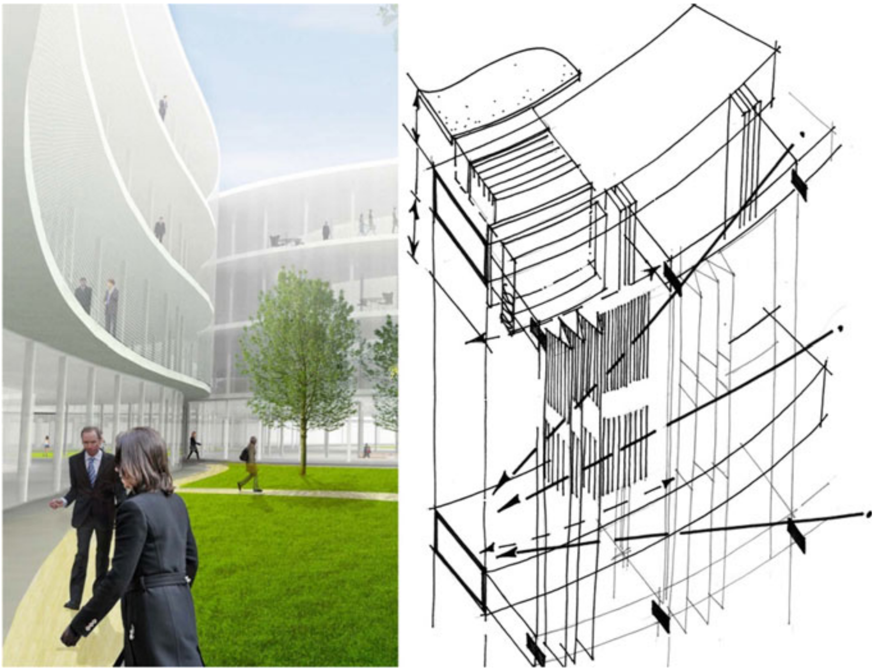


Fig. 1.1 Preliminary analysis and design of the morpho-typological, functional and environmental constitution of the façade and shading devices (Massimiliano Nastri, Università Commerciale "Luigi Bocconi" of Milan; concept design of the "Campus Bocconi". Study of the envelope systems)

intervention towards reality and in respect of resources, balances and eco-systems (Jonas 1974, tr. it. 1991), the extension of the criteria of "possession of the sense of reality" (Leroi-Gourhan 1955, tr. it. 1961, pp. 75–76), either the formulation of the "executive dexterity", as an "operational" application of the experience (i.e., as an acquisition of the technical-manual practicality proper to the *jongleur* described by Gillo Dorfles 1965, p. 86) aimed at making visible and "manipulating" phenomenal reality (Leroi-Gourhan 1964, tr. it. 1977, pp. 379–384) (Fig. 1.2).

The principles of the Material Balance Design are outlined with respect to the procedures of investigation, exploration and "systematization" of the environmental, productive and constructive reality of reference (Popitz 1995, tr. it. 1996). The reality of reference, in which the conceptual orientations, the methods of knowledge and operational intervention are configured, is understood as a "technically organized" context (or "technically conditioned"; Galimberti 1999) and structured overall by technique.

These techniques determine the rational way of "access" and "understanding" of the physical, phenomenal and environmental reality: in these terms, the activity of analysis, elaboration and execution with respect to reality is available as a method of knowledge, as a "disposition of fabrication" and as a work of "unveiling" the physical and material, performance and potential contents of the reality under study. In other

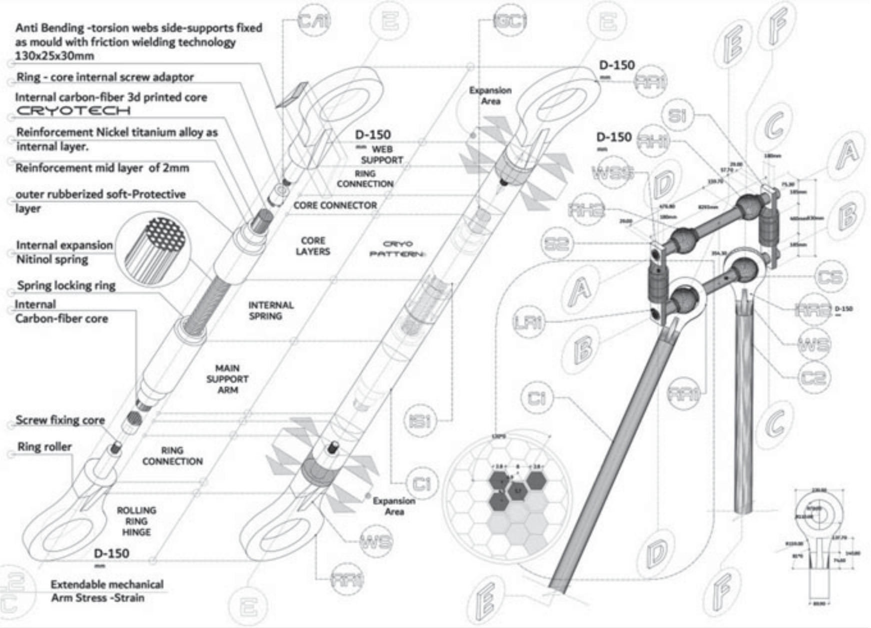


Fig. 1.2 Extendable 3D hinged Mechanical Arm. Self Deployable Structure: executive design of the inflatable skin which activates the structure to self-deploy using the "origami" manner for two main passes for each support (© Courtesy of Mohamed Ahmed Mahfouz, Home Is Mars. Mechanical extendable Arm)

words, in the reference and application of Martin Heidegger's theory on technique, the activity of study, research and application is affirmed as an ability to "dispose" what is offered and made possible by the reality and as an ability in the *conduction* of knowledge, procedures and means towards *production* (1953, tr. it. 1976) (Fig. 1.3).

The disciplinary, operative and experimental approach of the *Material Balance* is thus structured in the concreteness of the reality, where the activity of analysis, elaboration and execution takes place on the basis of the link between "science" (that is, knowledge) and "power" (Galimberti 1999, p. 61), by supporting:

- the formulation of the characteristics of anticipation and forecasting with respect to the conditions of *consumption* and *accumulation* resulting from the *generation*, as a "Promethean" expression of the contribution due to *téchne*;
- the "revelatory" and "productive" expression, as a "way of unveiling" the environmental reality (in the Heideggerian perspective) which consists both in 'knowing the "truth of things", in order to bring it to light' (Spengler 1931, tr. it. 1992; p. 79), and in "making happen in presence" and "leading out" the knowledge from reality itself (Bufalo 2011, p. 28);
- the implementation of the Heideggerian "unveiling" as a capacity to "arrange in new relationships" what is offered and made possible by the environmental reality, as a capacity or "dispositive force" in the *conduction* (i.e., in the articulation and fine-tuning) of knowledge, procedures and means according to the design and construction objectives aimed at limiting the conditions of *consumption* and *accumulation*;
- the elaboration of results, products and "artifacts" as the "unveiling provocation as téchne" (Mazzarella 1993), understood as a practice that aims to examine the "internal functioning of things" (Deutsch 1997, tr. it. 1997, p. 12) (Fig. 1.4).

Therefore, *Material Balance* is carried out in accordance with the principles of the work of "unveiling" (outlined by Martin Heidegger), aimed both at "making in presence" and "leading out" knowledge from reality, and action, as "production" towards the environmental reality ("used" by the *téchne*), understood in "manipulable" and "calculable" form (Cacciari 2000). The formulation of the operative activity, aimed at the intervention towards the environmental reality, involves the anticipation and the simulation aimed at exercising, at the moment of the concrete action, the management and the direction of the productive and constructive operativeness (Fig. 1.5).

The adoption of the *Material Balance* design strategy is determined according to the procedures aimed at anticipating the outcomes and consequences within the environmental context, in order to reduce the conditions of *consumption* and *accumulation* due to production and construction, management and use up to disposal. In this regard, the scientific framework calls into question the support of the technological culture of design aimed at stimulating the approach based on the set of knowledge related to the analysis and anticipation of reality, bearing in itself the "component of planning and therefore of calculating forecast" (Cera 2007, pp. 68–69). On this basis, the design activity is constituted through:

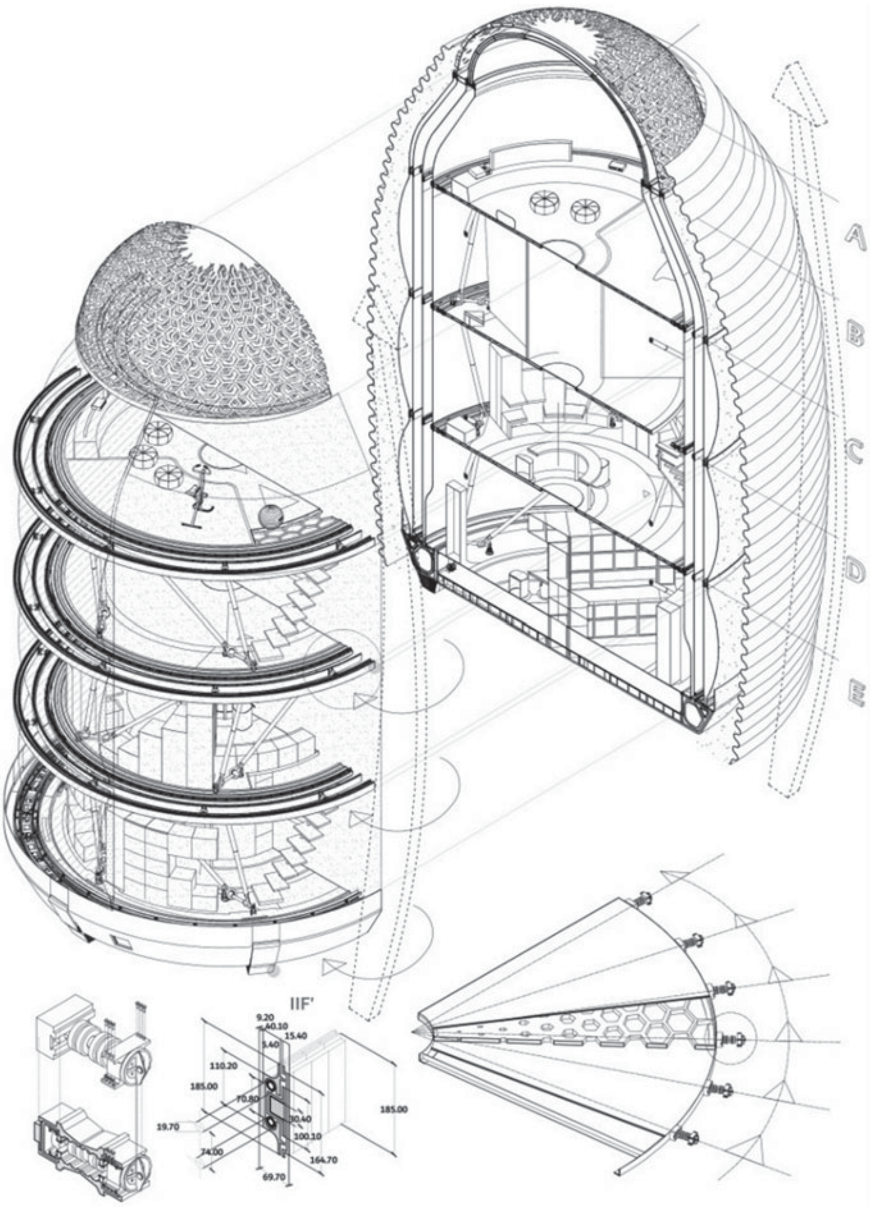


Fig. 1.3 Development of the tower of the Martian colony showing the multi-layered building envelope consisted of 3D-printable regolith and the internal based inflatable skin that helps in triggering the deployment of the mechanical compressible structure (© Courtesy of Mohamed Ahmed Mahfouz, Home Is Mars. Interior of the Martian colony)

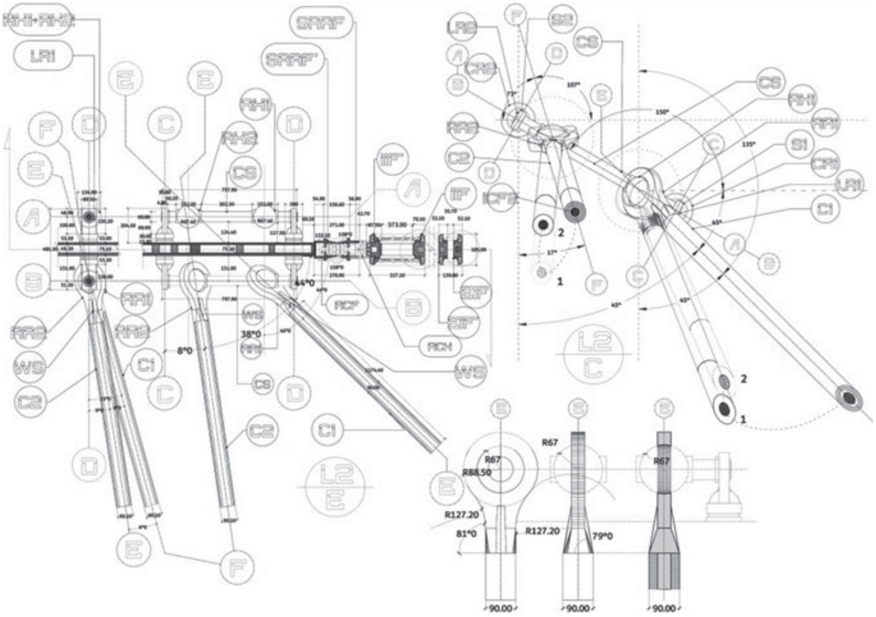


Fig. 1.4 Study of the yet complex 3D-hinge function which can perform a limited 3D-XYZ axis rotation with three axial movements rotation around its axis and rotation while following the deployment path. The ring hinge is reinforced by dual side web to reduce the side stresses such as bending and horizontal sheer forces (© Courtesy of Mohamed Ahmed Mahfouz, Home Is Mars. 3D hinge system)

- the integration of the contents and methods oriented towards forecasting and "optimization of the results according to the adoption of analytical procedures" (Asimow 1962, tr. it. 1968 3rd ed., p. 10);
- the practices of "projection" and simulation (in an experimental way, to perform tests and checks), for which the activity is defined as a technical procedure of "rational forecasting" (with a "temporal" and, therefore, "Promethean" function) to arrange, organize and anticipate the outcomes and consequences within the environmental context, arriving at the definition of a model of reality not yet existing, whose informative, decisional and forecasting aspects appear (Nastri 2018);
- the practices of "artificial reproduction" (in a simulated form) of the contents, data and procedures to be examined and with respect to which to arrange the criteria for productive and constructive intervention, also foreseeing possible critical and unforeseen situations;
- the practices of "modelling" (provided with heuristic function), for which the knowledge of the properties of reality (according to the characteristics of the "modelled" domain) allows to formulate forecasts (on "modelled" phenomena). The cognitive and operational processes take place as a practice of "modelling"

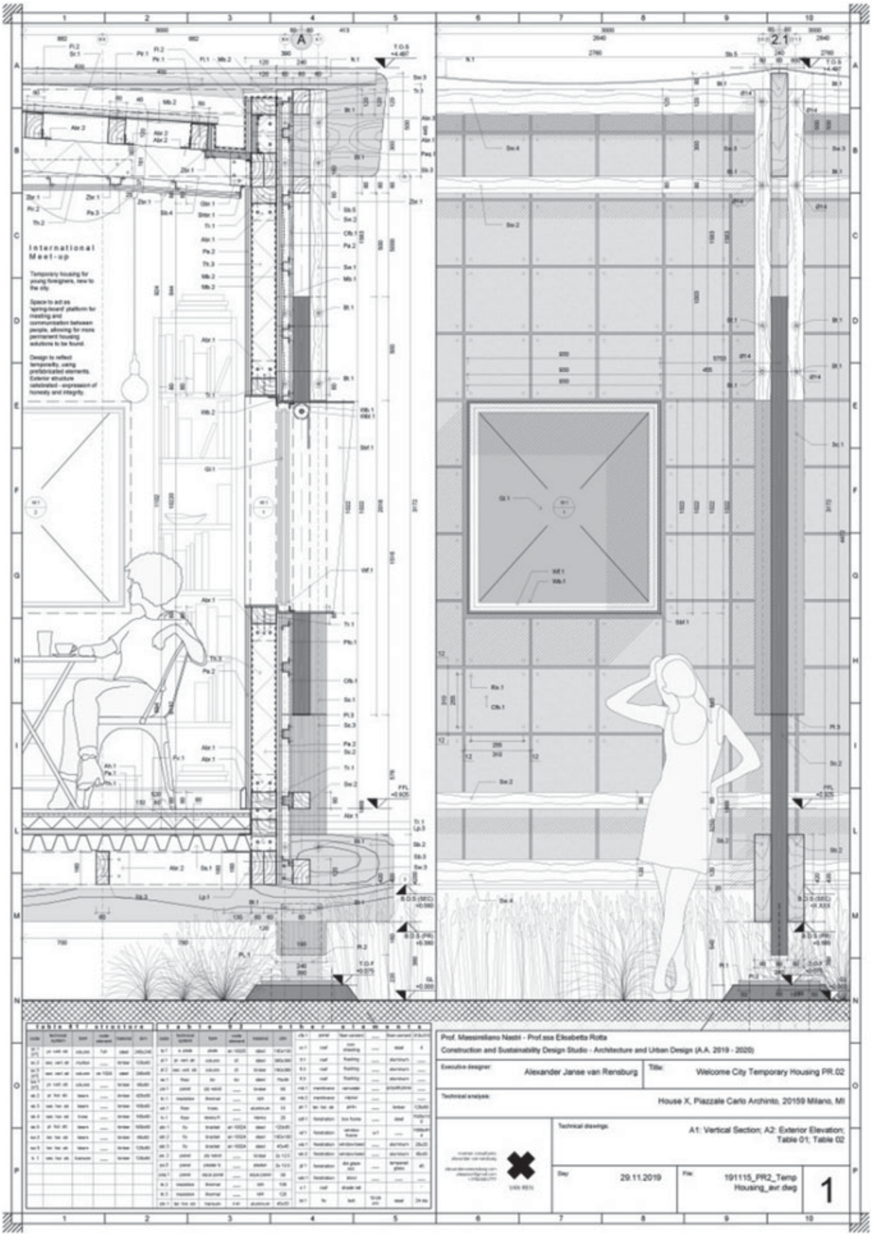


Fig. 1.5 Executive elaboration and construction simulation of the technical interfaces (through the development of construction drawings), according to the typological and connective arrangement of the elements and joining devices (© Courtesy of Alexander Philip Janse van Rensburg, Welcome City Project, Milan)

through the formulation of “interpretative models”, through the activity of organization and intelligible reproduction of reality and of the environmental context: these are defined as the totality of the “possible determinations”, that is, as a result of a “construction”, a representation and a “planned configuration” with respect to which to proceed at an experimental and simulative level (Borutti 1991, 1997);
- the practices of “manipulation” and “exploratory forecasting” aimed at structuring and simulating reality, so that the elaboration processes propose the “construction of a real-world analogue that can be subsequently manipulated in order to discover its functioning under new circumstances” (Waddington 1977, tr. it. 1977, p. 202) (Fig. 1.6).

1.3 Functional, Production and Material Optimization Procedures

The adoption of the *Material Balance* principles is determined within the *digital fabrication* procedures in the experimental design, production and construction scenario, aimed at the development and execution of complex building systems and architectures defined by overcoming the limits related to feasibility conditions (physical, dimensional and morpho-typological).

The activity, through the use of operational methodologies acquired and transferred from industrial sectors characterized by the use of advanced technologies, considers the development of cognitive, technical-scientific and applicative guidelines for the realization of optimized systemic and compositional solutions, coordinated in the design, production and construction phases in a way related to the increase of economic, management and environmental effectiveness.

The adoption of the *Material Balance* principles, according to the use of digital production systems, considers:

- the elaboration and realization of products of reduced mass, able to favour the containment of energy resources (during the production and management phases), and the composition of models and prototypes able to re-elaborate traditional solutions;
- the design, production and executive elaboration of systems, components and elements with high morphological and connective complexity, according to customized solutions, without the constraints due to traditional methods of realization.

The study, research and application activity observes the potential and prospects established by the *digital fabrication* procedures, according to the opportunity to develop technical solutions with calibrated geometric composition, with the help of multiple materials and determined according to the “physical transformation” of requirements and performance (Fig. 1.7).

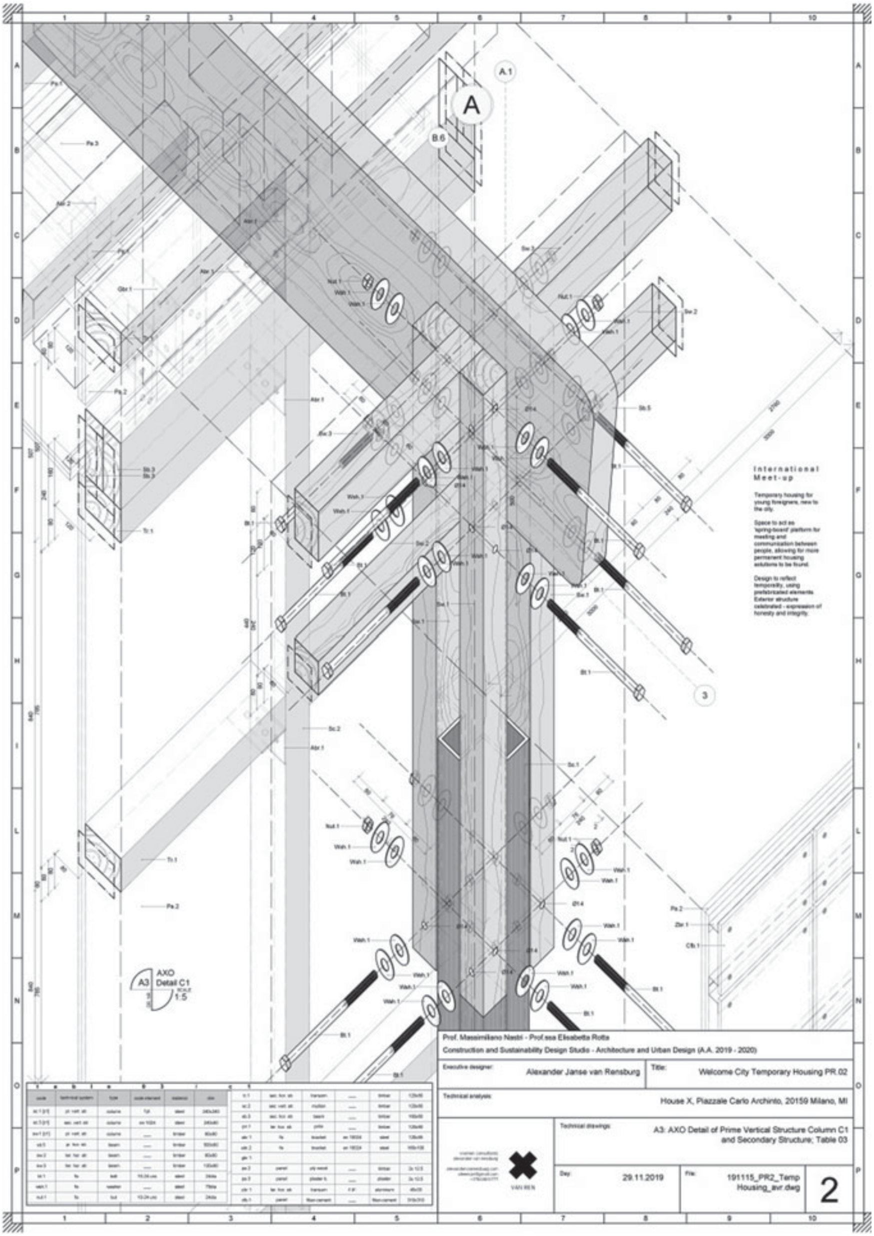


Fig. 1.6 Design and construction simulation of the technical interfaces (through the development of assembly drawings), according to the arrangement of the sequences and joining devices (© Courtesy of Alexander Philip Janse van Rensburg, Welcome City Project, Milan)

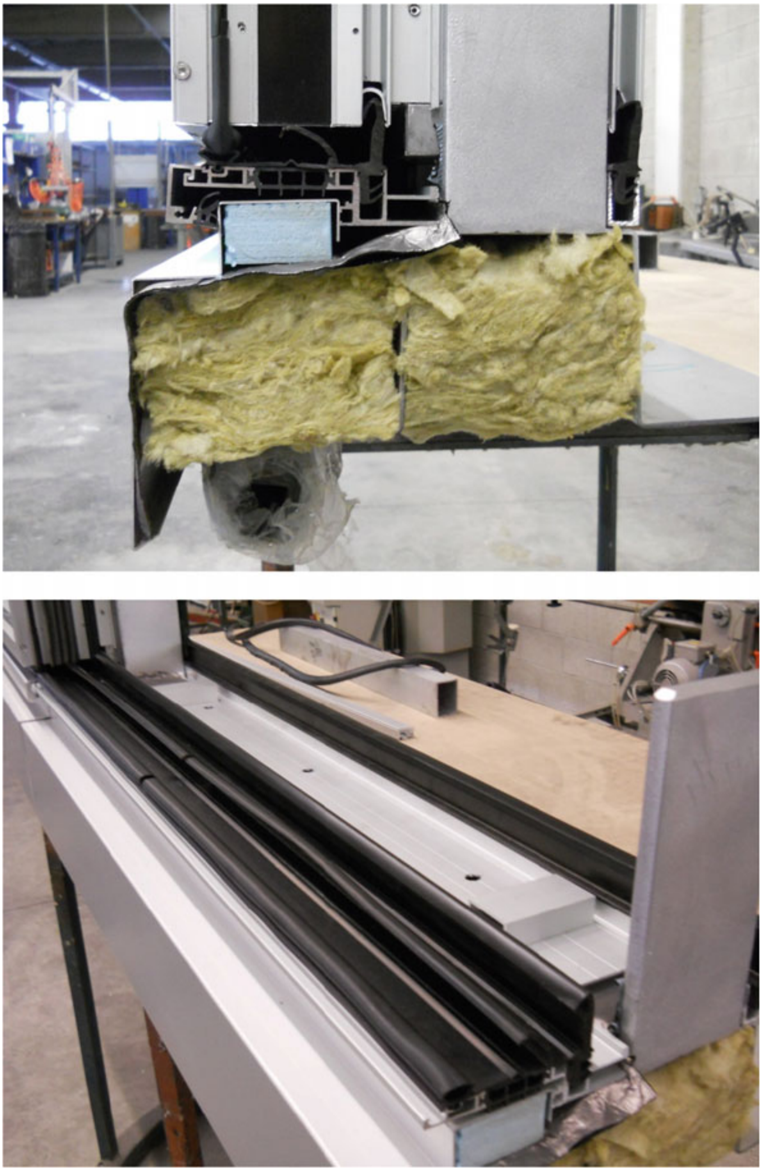


Fig. 1.7 Physical modelling, connective experimentation and construction simulation of components and technical interfaces of prefabricated façade system in the laboratory (Massimiliano Nastri, Tecnet Tower, Milan; executive design of the building envelope)

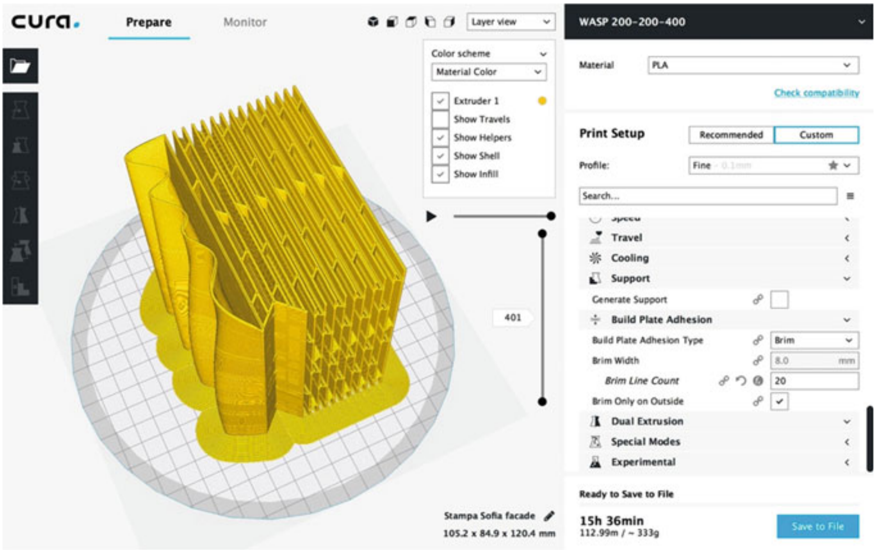
In this respect, the operational procedures under consideration include:

- the development of the three-dimensional digital configuration of building systems, components and technical elements, subsequent optimization according to requirements and printing in 3D modes;
- the development of three-dimensional and complex geometry solutions of integrated typology, examining the possibilities of avoiding critical conditions due to the combination of elements and joining devices according to traditional solutions;
- the optimization of the production lines, in order to reduce the quantities of material (calibrated with respect to the actual functional needs), to avoid the production waste and to limit the use of energy resources and polluting emissions.

These activities consider the *topology optimization* procedures concerning geometric and physical calibration (i.e., according to the finite elements calculation method), oriented to the development of specific performance conditions according to the integration and application of *additive manufacturing* procedures. Specifically, the technical-scientific contribution includes the methodological guidelines established by the three-dimensional digital configuration and subsequent optimization according to the requirements and content resulting from the environmental and energy analysis. In this regard, the operating procedures under examination include:

- the functional and structural development of the building systems, components and technical elements through the simulation and the virtual modeling;
- the development of the numerical parameters relative to the models, foreseeing the calibration of the models with the results of the tests focused on the material characterization;
- the interaction between the production parameters and 3D printing processes, in order to calibrate the physical composition through the identification and optimization of the parameters, aimed at providing and meeting the conditions of balance between costs, quality and reduction of both energy and materials consumption;
- the development of the building systems, components and technical elements optimized with respect to the actual climatic and environmental stresses (i.e., thermo-hygrometric, lighting and acoustic needs and comfort requirements in interior spaces), through the conception of new perspectives both of compositional and functional articulation (in *free-form* mode), and of physical and material stratification (Fig. 1.8).

Material Balance principles are oriented to the examination of materials with respect to their processes of change from "stable entities" to "designable entities" (according to the characteristics of "changed physicality", which the experimental research tends to transform into "dense" and "interface of intelligent systems") according to a specific "performance program" (Altomonte 2004, p. 42). The elaboration towards the materials as "designable entities" is addressed with respect to the outcomes of solutions in which functions tend to become "complex" (in a "controlled" and "managed" way) and combined (in *solid state* form), realizing multiple performances through the correlation of different agents.



WASP 200-200-400

Material: PLA

Print Setup: Custom

Profile: Fine - 0.1mm

Color scheme: Material Color

☑ Extruder 1
☐ Show Travels
☑ Show Helpers
☑ Show Shell
☑ Show Infill

Generate Support ☐

Build Plate Adhesion Type: Brim

Brim Width: 8.0 mm

Brim Line Count: 20

Brim Only on Outside ☑

Stampa Sofia facade
105.2 x 84.9 x 120.4 mm

Ready to Save to File

15h 36min
112.99m / ~ 333g

Fig. 1.8 Study of 3D-printed façade system which actively participates in housing thermal comfort conditions, thanks to its customable and optimized shape made to host installations and to regulate solar radiation: the façade is assembled with light manageable components printed in recyclable PET-G, reducing waste and costs in every stage of LCA (© Courtesy of Sofia Peviani, Additive manufacturing design potential for sustainable architecture)

This by means of: the integrative possibilities of the functions, where relations and (physical, performance) interfaces between individual parts and materials in a system or component are arranged; the elaboration of the building systems, components and materials conceivable in custom made form, with the action towards the contents and data in order to perform certain functions and without having to adapt to the limits imposed by the original and predetermined properties; the elaboration of the building systems, components and materials with respect to their ability to react to environmental stimuli, according to "passive" or "active" regulation processes induced by multiple loads (electrical and chemical, thermal and lighting) that modify, through alterations in the physical or chemical structure, the physical and functional arrangement; the development of the building systems, components and materials integrated with "natural" systems, up to the form of *naturoid* organisms, i.e., as "machinations" which aim to reproduce, manage and metabolise natural processes, according to the criteria of "active understanding" (Negrotti 1999, 2000) (Fig. 1.9).

The activity is outlined according to the procedures aimed at the "transformation" of what has been acquired and disposed by the environmental reality, according to the references around the cognitive and operative elaboration understood as "transformative act" and "metamorphosis" (Warner 2004).

The activity, as a "transformation" of the contents and data acquired by reality, takes place as the generative" practices (with regard to generation and consumption contents), defined as technological processes through which to act on the material

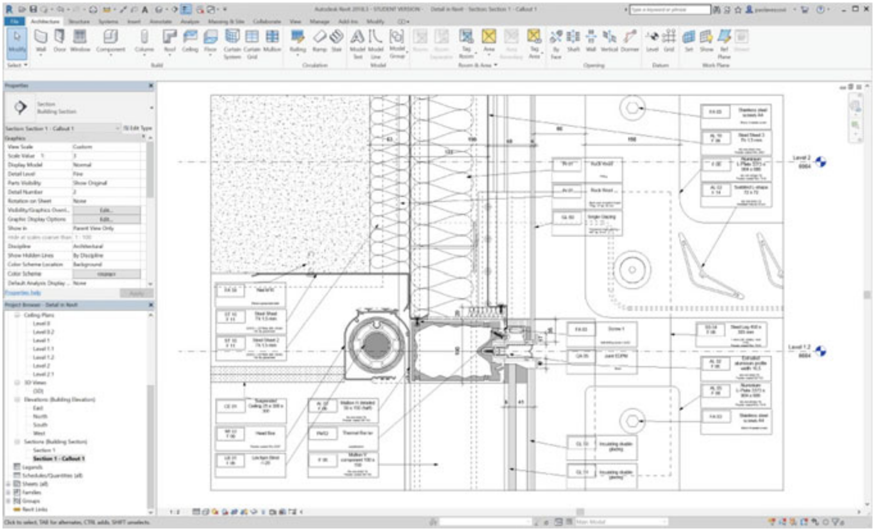


Fig. 1.9 Executive design of the shop drawing reworked through the application of Revit, providing a high detail comparable to that originally executed in AutoCAD. Parametrization of the system: automatic reference to the detail section through the provision of call-out, elaboration of customized components saved in the software libraries for subsequent applications, automatic change of the geometric model by varying the associated parameters, dynamic insertion of materials, dimensions and codes (© Courtesy of Paola Vescovi, Future Façades and Executive Design. Parametric and Dynamic Methodologies for Technical Processing of Advanced Building Envelopes)

aspects, i.e., which show the potential for mutation in compliance with specific physical characteristics. This is done through strategies aimed at incorporating, within the design, production and construction processes, the capacity to preserve (or intensify) performance and rebalancing relationships (Southwick and Charney 2012) and the "regenerative" practices (as action towards content acquired by accumulation), defined as technological processes by which an attempt is made to reproduce or renew the initial state and properties of a substance or a material.

The activity of cognitive and operational processing is aimed at the reproduction of the properties following the loss of functionality, total or partial, supporting the techniques of "re/generative" resilience, "dynamic adaptation" and "metamorphosis" (with particular attention to the *eco-mimesis* processes) (Fig. 1.10).

1.4 A Backcasting Approach

In conclusion we should think that the possibility to go deep in the process thanks to computational tools, digital fabrication, scientific knowledge, technical culture and applied methods can help us to set where we would like to be in the future and have a "backcasting" approach, setting the roadmap to arrive at that desired result.

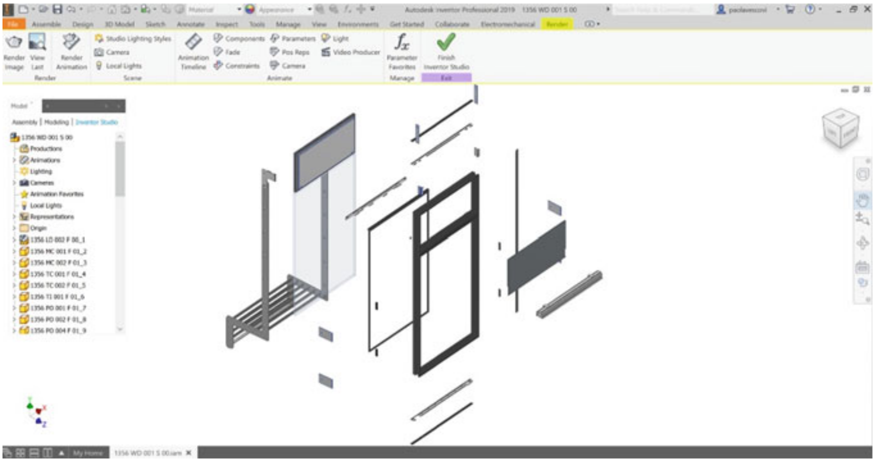


Fig. 1.10 Configuration of the façade panel processed in Inventor starting from the Revit model. Inventor environments applied for the executive design of fabrication drawings and assembly drawings: detailed modelling of three-dimensional components in Inventor Part, mounting of the single elements of the panel in Inventor Assembly, layout of the graphic-descriptive panels provided with automatic dimensions and codes in Inventor Drawing (© Courtesy of Paola Vescovi, Future Façades and Executive Design. Parametric and Dynamic Methodologies for Technical Processing of Advanced Building Envelopes)

In the field of future studies the traditional *forecasting* approach is still dominant, where the idea is to make previsions on mainstream trends. However, in complex systems, it will hardly generate solutions that could be long lasting. In architecture a more interesting approach, is *backcasting*, intended as a method to analyze future with the focus on a preferable scenario. The fundamentals of this approach were outlined by John B. Robinson on the nineties but they remain still today meaningful as they concern less with a possible, plausible or probable future and more with the construction of a progressive knowledge, a physical feasible scenario, a set of skills, which starts from a future end-point to the present (thus “back casting”).

This result should be identified in the three main ambits of university mission that is the first sector—education, the second sector—research—and the third one—the impact on society of our activities.

To leverage the level of knowledge is today a need that cannot be postponed to have a more informed society, to contrast populism and have a democracy of technology and materials, accessible, transparent and caring to our environment.

The idea of this is to put the architectural project at the center of debate as a complex phenomenon, able to build a synthesis of scientific, social, political and cultural points of view, in a period where the anthropocentric perspective has radically changed our approach to the environment, to construction, to technology and materials, given their impact and effects on scarcity of resources.

Here is where architecture and design can give a real contribution to the debate, in a variable, multicultural, trans-disciplinary and fast changing society.

The question is not to anticipate the future but to build it.

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Chapter 2
Designing Responsible Material Cultures

Ingrid Paoletti

My experiments are not always interesting,
But not always uninteresting like nature,
That is beautiful, not because it changes beautifully,
but simply because it changes.
(Paik)

Abstract Material is the first and ultimate substance of any design process. Never than ever today's material evolution has to deal with the strong changes in cultural, epistemological and social conditions requiring a new balance. Similarly to Glaucus's metamorphosis, we will have to accept to lose some parts of our contemporary way of designing to gain a new capacity to address climate change and bio diversity loss from the very beginning of our projects. The idea of this chapter is that the action is urgent and can be done through a new responsible material culture capable to design innovative material systems which are precise, thanks to computational tools, but also care at environmental and human impact. This emergent scenario needs a new figure of designer between *bricoleur* and engineer.

Keywords Metamorphosis · Innovative material systems · Responsible material culture · Digital culture · Designer · Bricoleur

2.1 Glaucus's Metamorphosis as the Expression of Our Times

Our contemporary times are characterized by a profound transformation, blurring, merging of disciplines, gender, nature and man. Boundaries are no more fixed and penetrate each other, and the sensation of acceleration is frightening.

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Hartmut Rosa sustain that technology has produced new ways to be efficient as the prize of alienation, strong competitiveness and fleeting of the context (Rosa 2015). We have new means that allow us to be more productive in a specific time unit but we also have to cope with the acceleration of options which requires a continuous effort of social adaptation to avoid the risk of losing possible precious connections (*Anschlussmöglichkeiten*).

Is transformation a punishment or a rescue?

I will introduce Ovid's Metamorphoses as an analogy with our times.

The fate of Glaucus the fisherman, Ovid tells us, was to see his human form transformed into a superior, semi-god condition. A necessary condition for this metamorphosis to take place is the loss of memory of its previous state. In return, Glaucus will obtain foresight.

The law of conservation of mass: the form changes, but the matter remains unchanged. A new balance!

Glaucus the fisherman is the initial state; the divine Glaucus is the transformation, translation into new forms and shapes of the matter according to a vision of scientific research attentive to the equilibrium of the planet. It represents the real idea of transformation, seeking alternative solutions to the use of contemporary materials which present interruptions in the natural chain of transformation or long degradation times.

Chaos is the beginning, which announces the cosmogenic nature of the poem's metamorphoses and establishes the physical basis for this transformation. The starting point is the instability of the four elements creating the world: earth, air, fire and water.

In the flux of this vortex human bodies are subject to transformation either due to external forces (the divine or nature—divine as well) or to internal very strong emotional forces.

> Is pushed by my inspiration. O gods, if these metamorphoses are yours, inspire my design, so that singing the beginning of the world unravels uninterrupted until my days.[1]

The blurring of divine and natural in a new human can be taken as today's condition. Contemporary social pushing for increased life span, drives us continuously toward the search of meaning and legacy. Are we human or are we half immortal, divine, long lasting? Technology is dissolving the boundaries of our condition and of the matter with work with.

Gods were the ones setting our limits in the past. Who or what is setting these limits today? Ourselves?

Many of Ovid's tales start from human weaknesses. Today our weakness is to have climate change and pollution as the result of exceeding consumerism. We have exploited the soil and nature at a magnitude unseen by any generation, receiving as a "contrappasso" the violence of our own waste.

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[1] Translation by the author Ovidio, Metamorfosi. Testo latino a fronte. Vol. 1: Libri I-II.: A. Barchiesi Mondadori, 2015.

The challenge contemporary scientific research faces is the need to accompany the process of transformation of the atoms that compose each material into a conscious cyclicality that does not know interruptions, while transforming, aggregating and inventing new materials for design. We need to put our ecological intentions in material and component design.

In the process of metamorphosis, you lose identity, which is ours today? Which one are we gaining and striving for?

In our times personal history somehow becomes a collective history. Our path weaved with nature, the more we try to alienate ourselves from it, the more it attracts us back as a magnet. We are the environment!

One of the frightening aspects of metamorphosis is that past may be gone but consciousness stays, leading to fear of future.

The planet is forcing us to adapt, with commitment as well as with pain, it's the only way to see the future, as Glaucus.

In the XV Book Pythagoras sees in Rome the essential necessity for change due to decadence. I think we are in similar times, where a radical change is needed due to the damage we have caused to our planet (Fig. 2.1).

Fig. 2.1 Glaucus, the fisherman transformed in a semi-god and Scylla

2.2 Material Balance Equation as a Design Theory

In a purely scientific sense, material balance refers to the renowned equation of the “mass balance”, which is an application of the conservation law theory. The main statement is the conservation of mass in the analysis of physical systems. By accounting for material entering and leaving a system, mass stays and cannot disappear or be created spontaneously.

The material/mass balance equation is widely used in engineering, chemistry, environmental impact assessment and complementary in energy, population and other major complex systems as we have seen in Chap. 1.

Mainly it is linked to entropy and the conservation of energy, that is a fundamental rule of the material world.

In this chapter I will ask the reader to make an effort of imagination, thinking to transpose the traditional equation in a design theory. This effort, hopefully pleasant, will lead to a radical change in the way we think at input, output, consumption and accumulation in design.

Material Balance in the field of Architecture interprets the equation looking at our input to the world through design, what we generate with the materials we use in architecture, which are the systems we build and how can we deal with consumption and accumulation.

Accumulation is one of the major issues of contemporary practice as it can become waste, thus negatively impacting the planet. A waste that is environmental but also social and economic.

How can we “balance” the effects of our design activities, in order not only to cope with a fast changing context, but also to be proactive for a radical change?

The association of the term *Balance* with *Material* as a design theory has an innovative significance, as it allows to take into consideration the future impact we carry on earth and which scenarios we can foresee (Cross et al. 1974; Ziauddin and Sweeney 2015).

Above all it’s important to recognize where the word “balance” comes from and how we intend in this context: etymologically the word was used first in Old French “balance” (in the XII century) which means “scales, apparatus for weighing by comparison of mass” (Oxford online dictionary).

This definition clearly shows that in its roots, the word has the concept of mass comparison, where the boundaries of the system must be clearly defined.

Today, however, these boundaries are blurring: subject and object, technique and tools, natural and artificial. The balance we want to work with is an attempt, an action that puts into the equation different variables without having a perfect energy correspondence.

In particular, Material Balance for design is a purpose as much as it’s a method and a process.

A purpose, in the context of architecture, that emerges as a path, a guideline and a sense of direction in the approach to designing innovative products, systems and buildings, to balance the impact of material consumption on earth. A method that allows to find traces, to set a path and not only to verify the results.

Finally a process, as the resources which are used to develop a new idea are balanced at the start, aiding in a correct equilibrium of input resources, output and consumption.

The primarily objective is to be able to control, prevent and manage a negative accumulation transforming it into a positive impact on the built environment and on society in general.

In our vision, ideas, concepts, tools and processes to transform the built environment need to be addressed thanks to our way to design in order to spur the best performances of any intervention with an ingenious creativity. Balance not only as a technological issue, but as a socio-economical drive, a human and semantic rudder, an eco-cultural niche (Ingold 2013).

Material is the first and ultimate substance of any design process and balance is one of the most important laws of nature, this is our common ground, here is where we can be effective.

2.3 XXI Century Tools: Algorithmic Design and Digital Fabrication

Among all the possible tools available for the designer in the XXI Century I will expand here on two of them, that will lead to my personal idea of the designer in the last chapter.

The first one is the contemporary capacity of computational (algorithmic) design, which has completely revolutionized the way we use to think, as it allows—and forces us—to describe and investigate reality in a mathematical way, understanding and playing with rules.

The second one is digital fabrication, i.e. the possibility to design with machines, using their own language. A radical change in the perspective of designers that usually work with defined products and assemble them.

Both tools are engaging the human/designer activity.

Going deeper in the first tool we can say that computational design refers to a procedure which interprets mathematical data with the idea that a process can be informed in order to give directional results.

The computational method can engineer a specific form with specific performances while drawing it from a very early stage, thus really influencing the design.

Depending on the specific use of the material, each designer can decide to activate certain properties over others and these embedded properties of the material become active drivers of the design.

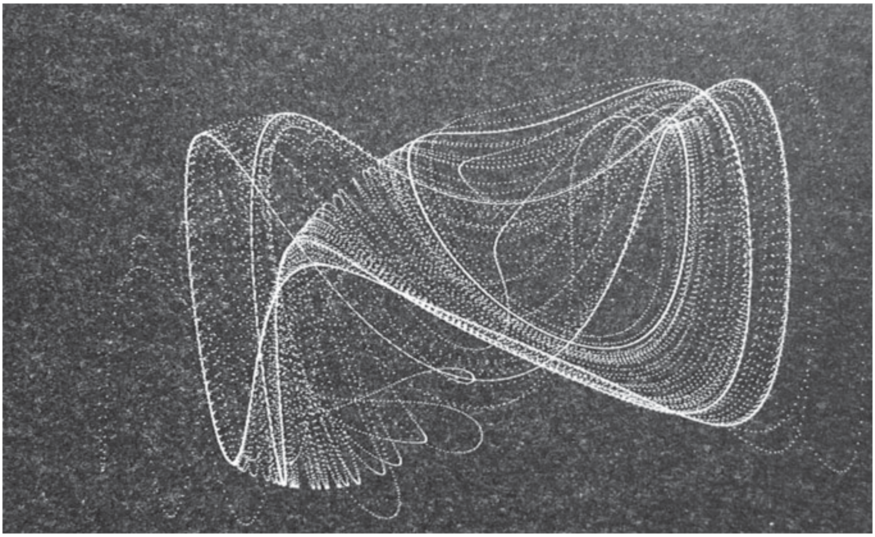

Fig. 2.2 Lorenz attractor shaping curvilinear shapes

> The critical dimension of architecture challenges the code not through transgression but through effectively operating between definitions within the code itself (Reiser and Umemoto 2006, p. 187).

The advancement in the possibility to "compute" and therefore to add information while developing a specific product, widens the opportunities to create new objects that can be optimized in shape, material and production methods.

In Architecture and Construction, this translates to a real enhancement of the possibility to conceive and create innovative ways of building a system or a component. Its main concern lies with the process of dealing with information, increasing the level of accuracy of the project. A sort of new medium, like the pencil, "as accessible, as pervasive as air" (Petroski 1990; preface) (Fig. 2.2).

The second tool, that is Digital Fabrication, require not only digital dexterity but a robust material sensibility that precedes digital mediation. In fact, specific techniques normally vary from one place to another but share a common knowledge based on the inherent properties of the materials used.

While the fabrication of complex forms requires highly expert labor and manual work to achieve considerable results, the digital fabrication process is digitally-controlled, which employs a hardly comparable vocabulary of formal possibilities without the need of any labor following the design phase.

Manufacturing techniques and innovative production methods in construction often seem quite resilient to change in architecture. This is due to traditional construction methods and consolidated processes of production where innovation is often a very slow process which is driven by economic factors more than the need of effective new products or systems.

However, today's advanced construction processes are driven by novel design procedures, among them computational design which enables new ways of manufacturing (Naboni and Paoletti 2015).

This means that a new way of conceiving mass customization can be determined by instruments and tools enhanced by workflow information.

Providing individually customized products by using adaptable computer-aid processes and organization structure with reasonable low costs and lead-time will also accelerate the integration of personalized products into a traditional process and their physical assembly.

Compared with mass production, a wide range of combinations of product features may result in innumerable variants for a single product, which makes the number of product variants increase drastically. Product family design, recognized as an effective means to support product variety with minimal data redundancy, has become one of the prevailing approaches in implementing building technology (Nardi 1994).

New ways of designing products, systems, and goods are driving a small revolution in manufacturing that refers to the possibility to customize from the very beginning, not only the design, but also materials and machines.

The process of advanced manufacturing is driven by digital fabrication, which is a manufacturing process developed in an industrial context where precision and direct production is required—for instance, automotive, industrial design and mechanical products—and that, nowadays, is becoming more commonplace and adaptable to other sectors. It is deeply connected to the change in digital technologies and their higher accessibility that enables a more direct production out of design drawings thanks to parametric software and user-friendly interfaces with versatile machinery.

Along with advancements in software, the use of computer numerically controlled machines (CNC) and robotic arms have opened new frontiers of investigation in Architecture. Thanks to the bi-directional communication between digital information and material properties, design and fabrication tend to increasingly coincide, sharing common programming platforms and virtual environments.

Some of the existing instruments for digital manufacturing include CNC for milling and cutting, CNC for folding, CNC for molding and Additive Manufacturing (Fig. 2.3).

These aspects of the design process are crucial to a correct Material Balance in our contemporary society and for our future. It is evident that in the time of digital information, dissemination and democratization of knowledge, technical-scientific disciplines undergo gradual but revolutionary changes that will lead to a better balance with the environment.

2.4 Designing Responsible Material Cultures

The relationship between matter, form and fabrication has always been evolving, and it is highly connected to the meaning we give them in technological scenario of a certain period. However material culture has developed in the last century faster

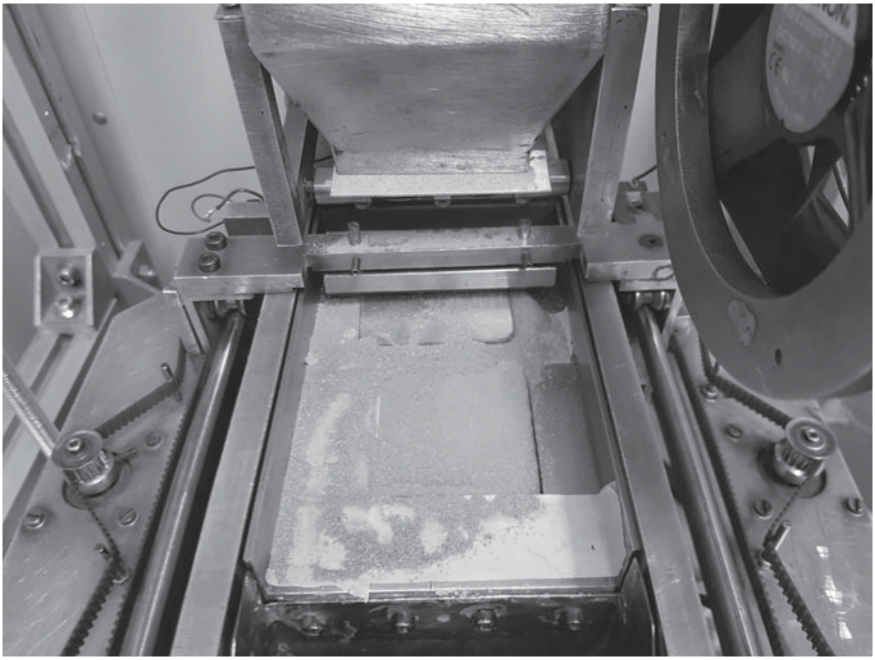

Fig. 2.3 Sand sintering for innovative material systems components (Politecnico di Milano)

than ever, due to the development of digital information environment, stretching its definition of representation of society (Boivin 2010).

Material is a medium of expression that works with the powerful tool of imagination, it's a symbolic medium. Our imagination is modified by the digital technologies in which we are literally immerged, and the production of artefacts is changed by the fabrication machines. The material inspiration acts as a reciprocal creative intelligence to today's dominant formal imagery.

The advantage of using innovative tools to renew our material culture, as architects, gives the possibility to integrate the absolute precision of the digital process of design and fabrication to the challenging implicit imperfection of handcrafts and natural techniques reshaping and enhancing our creativity.

While digital models and virtual tools provide an affordable and ubiquitous alternative, prototyping remains a powerful means of exploring design options, vetting technologies, rehearsing processes, addressing performance uncertainties, assessing user experience, and gaining confidence on innovative technologies.

We continuously build 'material systems' that are demonstrators of the possibility to engage with environmental issues through a distributed creativity (Bijeker et al. 2013; Wilson 2017).

That material culture shapes our ideas is an ancient matter, but today's availability of innovative materials from the Nano to the Meso scale, and the Macro scale open the design to a multitude of alternatives. Materials can be customized down to their molecular properties and this capacity has an enormous impact on related fields of science. Among them, architecture is not immune to these challenges, due to its dual nature of humanistic and technical subjectivity (Bertoldini 2003; Picon 2010; Reymond 1860).

So how can we embed material systems that has their own symbolic meaning into design, and furthermore, how can we transform them—like Glaucys—to send impactful messages in the world we are living in?

My personal idea is that we have to foster the design of responsible material cultures, not only as the expression of a community—that is nowadays impossible to define-, but as a plurality of issue, heteronomous, but linked by the same urgency: the need to protect our environment and species.

The fragility of the environment we inhabit today requires a new politics of material systems that should embed sustainable action from cradle to cradle, in an economy of means were we have to become aware of what usually escapes us, our on waste.

We have always thought at material culture in design as a sort of neutral catalogue that comes, in a linear process, at a certain point of the design workflow, mainly at the end, expressing the will of the actors. This is not possible anymore, material properties are the seed and the cradle of any design process, interpreted by our "semantic capital" as Floridi states (Floridi 2018), continuously blending analog and digital tools.

Our intention should take in consideration also any possible waste, considering materials not as new plastic and malleable matter but as a substance with history and value.

An architect in today's world, works on the edge of formal possibilities and material constraints, extending the limits of what is possible, and thus, often, embracing an innovation that should take into account responsibility.

This design approach has to start from microscopically study of new and wasted materials, to embedding matter properties in computational workflow, down to producing architectural demonstrator, becoming a strategy to tackle the emergency of the vulnerability of planet.

This exploration of form and material questions our attitudes towards material culture and propose a novel tectonic that could represent our contemporary society. New meta-materials and meta-components that have blurred the usual boundaries between natural and artificial and between their own inner categories. A continuous Metamorphosis (Fig. 2.4).

2.5 Contemporary Designer Between Engineering and Bricolage

From the scenario above, it is clear that a new figure of designer is coming along. The availability of computational tools on one side, the stimulating scenario of digital

Fig. 2.4 STRUNA, Milan “La Triennale” exhibition “999. A collection of questions about contemporary living”. SAPERLab by Politecnico of Milano (2018)

fabrication and the wide urgent question of climate change and scarcity of resources put into the hand of designers a completely new responsibility.

A new syntax that is created from natural, recyclable and advanced materials, often available from waste and exiting materials.

This contemporary designer stands between the engineer approach and the *bricoleur* (Lévi-Strauss 1964).

From engineering disciplines we can take the incredible knowledge developed by the instrument of the scientific method and the possibility to study materials at a really small scale.

From the *bricoleur* practice, the designer uses the technique to assemble materials that have a history, that could be residual, or traces of previous artefacts or waste.

It is essential for a society like ours, challenged by scarcity of resources, to imagine new material cultures. A perspective oriented towards the future but at the same time retrospective and inclusive, because it is open to the new brought by the “old” (Thomsen and Tamke 2014).

All in all, computational tools inform traditional crafting techniques towards the formation of novel architectural systems, mediating the high precision of digital fabrication machines and processes, and the imperfections inherent to natural material systems. A fruitful translation that allow imagining new construction methods, advanced workflows and, last but not least, a richer creative potential for future designers (Oxman 2016).

In this context, the disciplinary fields are necessarily blurring, due to the contamination with material sciences, biology and anthropology.

With the scale of the planet as the spherical horizon of such activities, it is not surprising that these problems are all linked together and relate to our first assumption: continuously re-imagining a Material Balance Design.

By discovering affinities and alliances with both the sciences and the theoretical humanities, architecture can begin to reassess its privileges, priorities and capacities to leave its mark on our fast changing society.

As Ovid states in the last lines of his poem, transformation is the only way to leave a legacy, to be reconnected to nature, which lives besides and beyond us, continuously.

> And also the disk of this god, when it rises red in the morning and blushes when it sets on the horizon; but at its peak it is candid, because there the air is pure and far away it can escape the exhalations of the earth. Nor can the moon be the same at night: it is smaller today than tomorrow if it is in a growing phase, bigger if it is in a waning phase. And then don't you see that the year unfolds in four different seasons, as if trying to imitate our life?

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Chapter 3
Digital Culture and Non-designing Approach

Marta D'Alessandro

Abstract In the last decades, academics and intellectuals have been facing the implications of technological transformation and human-machine interaction. This paper represents a contribution on some theoretical aspects, recurring in the activities of professionals dealing with architectural design in computational environment. The use of parametric and computational design processes and techniques enhances our ability to understand and mold our environment, but most importantly it shapes the way we think, communicate, and see ourselves and our world. This research explores the possibility that, within the computational environment, humans are exploring non-typically-human ways to design and create artifacts.

Keywords Digital culture · Human-technology ecosystem · Non-designing approach · Digital creativity

3.1 Introduction

This paper contributes to the speculation, underway within Material Balance Research group, on some theoretical aspects, recurring for professionals dealing with architectural design in computational environment. Material culture and how technological innovation has led to a radical transformation of architectural language have been the subject of debate, at Politecnico di Milano, for years now. Recognizing the importance and autonomy of each theoretical reflection, contextually to the design process, the topic come back on track, enriched by a wide-ranging experimentation in the field of innovation in architecture.

The practical implications of what Carpo (2013) has called "digital turn" have been widely analysed. Therefore it is necessary, today, that Architecture contributes to the foundations and theoretical constructs of the new design practices. Doing that, Architecture theory has to open to new methodologies belonging to disciplines

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apparently distant from the more technical aspects of the project, as Futurology or Anthropology. In fact, this allows Architecture "to move with freedom and productive autonomy between sectors of time, place and values that otherwise might seem to us to be impossible" (Bertoldini 1996), combining the empirical experience and theoretical speculation.

3.2 Human Transformation: A Punishment or a Rescue?

> It was a premonition that human thought, in changing its outward form, was also about to change its outward mode of expression; that the dominant idea of each generation would, in future, be embodied in a new material, a new fashion; that the book of stone, so solid and so enduring, was to give way to the book of paper, more solid and more enduring still. (Hugo 1831)

Today, technology pervades all human activities. Sometimes, technology's action patterns evolve autonomously, making us fear prefiguring dystopian scenarios in which the human being is destined to final solution. However, we can state today that the digital mean will allow human perpetuating itself as it is volatile, intangible but, at the same time it is more indelible and indestructible than stone.

Since the beginning of this century, academics and intellectuals, belonging to various knowledge areas, have been facing the implications of technological transformation and human-machine interaction. There are evidences that the progressive development of computer-based design techniques deeply transforms the process of creativity (Bredella and Höfler 2017; Quantrill 2002). The use of parametric and computational design processes and techniques enhances our ability to understand and mold our environment, but most importantly it shapes the way we think, communicate, and see ourselves and our world (Culbertson 2018; Coates 2010; Lee 2018) (Fig. 3.1).

The digital design thinking has led to the development of new software platforms, innovative fabrication techniques and interactive environment (Kilian 2013). Several field studies have been realized in order to understand the role played by the digital design environment in the cognitive design process and design thinking (Lee et al. 2018; Lostritto 2016; Hoffmann et al. 2016; Gibson 2007; Kurtoglu et al. 2009). In a perspective of digital environment, creativity has started to take a new shape: digital creativity, defined as "the creativity manifested in all forms that are driven by digital technology" (Lee and Chen 2015). As Lee and Chen state (ibid.):

> Being digital represents an easy distribution of information into a number of bits through computers, easy dispersion of information through the Internet to any person who needs it, multiplying value through social net-works, etc. Furthermore, through using a wide variety of digital technologies, individuals can extend their own creativity, which until now may have remained untouched and unstimulated within themselves.

An important aspect of digital creativity are the possibilities offered by the integration of computer and human abilities. Computer-human integration will enable forms

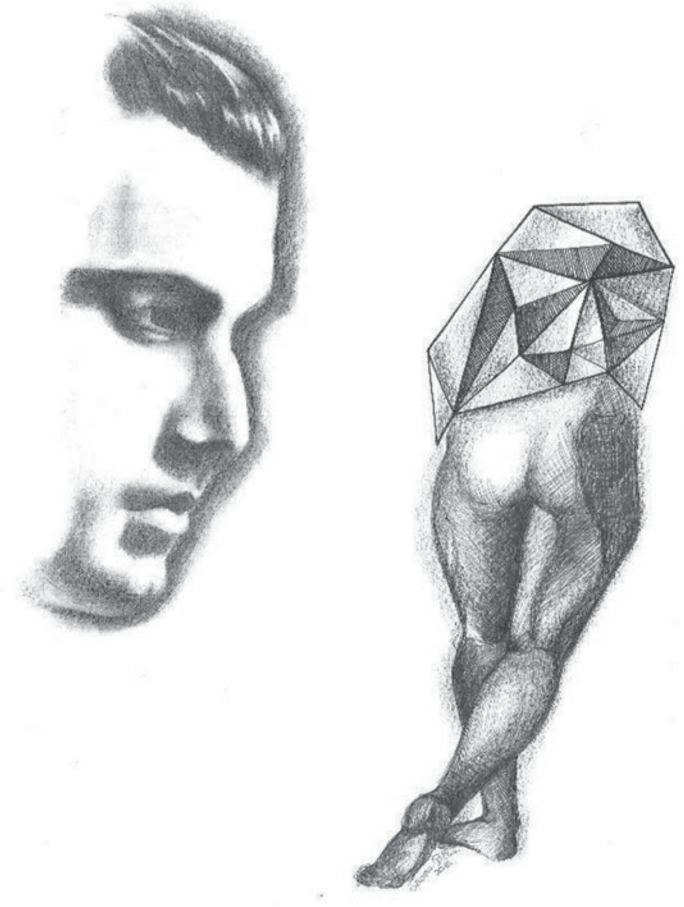

Fig. 3.1 Exile, Susanna D'Elia, 2016. Courtesy of the artist

of expression unique to emerge (ibid.). According to Egan and Cagan (2016) human designers may draw upon their expertise, intuition, and creativity, while computational approaches are used to algorithmically configure and evaluate design alternatives quickly. Thus, new technologies are not to be isolated from traditional media, as innovation may arise by the combination of analogue and digital techniques and design methodology (Symeonidou 2018).

3.3 Digital Means: Prosthesis or Organ?

> The Ammophila Hirsuta gives nine successive strokes of its sting upon nine nerve-centres of its caterpillar, and then seizes the head and squeezes it in its mandibles, enough to cause

> paralysis without death. […] The Ammophila, we imagine, must learn, one by one, like the entomologist, the positions of the nerve-centres of the caterpillar. […] But there is no need for such a view if we suppose a sympathy (in the etymological sense of the word) between the Ammophila and its victim, which teaches it from within, so to say, concerning the vulnerability of the caterpillar. This feeling of vulnerability might owe nothing to outwars perception, but result from the mere presence together of the Ammophila and the caterpillar, considered no longer as wo organism, but as two activities.
>
> (Bergson 1907)

As de Azúa (2008) states, the first drawings invent the vision as a properly technical instrument to expand human body. Images appeared when humans felt the need to convert themselves in the point of view. Cutting cleanly human acting from his animal substratum, probably, images even invented human beings. And from that moment humanity has inevitable proceeded along a technological path, defining from time to time extensions of its animal-instinctive life: the prosthesis. Digital tools revolution in the designer profession has received growing attention during the last decades, since it supposedly orients human thinking and inexorably drives drawing, designing and thinking activity. Actually, digital tools are not used as prosthesis.

Researchers have been used different definitions to refer to the current technological circumstance and resulting human, as “second digital turn” (Carpo 2017), “fourth revolution” (Floridi 2014), the “new Golem” (O. Longo 1998). These definitions open up the possibility of a synthesis between human and artefacts, where instruments are not just exteriorization of the human body but human internalizes more and more instruments, to the point that it is difficult to distinguish in a current human being the biological characteristics by technological ones. O. Longo (2001) defines this hybrid biologic, mechanic and electronic being as Symbiont, “a stable and strictly integrated association between two organisms of which one, the host, constitutes the other’s habitat”.

Summarizing, if the position of Sapiens in the world was made possible due to specific anthropological unhooking—external prosthesis, extension of humans corporal life—sapiens’ final technological turn is made possible thanks to technological hooking. Before the “Symbiont”, human action has been always completely projected outside his physical body. This extroflection phenomenon, makes human able to recognise itself as the acting subject.

Sini (2009) use the word *prosthesis* with a wide semantic meaning: προσ τίθημι (to put behind, to attach) or προ τίθημι (to expose, to put forward), and describe it as follow:

> […] a flint leaf is obtained from a block of stone. For its preparation it requires a *mediation*, also called *double corporal action*. This action must first of all move or extend itself to an “object”, for example a stone used as a pin, as an extension of the hand; and then, precisely by using this “object”, the action must produce another “object”: the flint leaf, which is separated from the block of stone. This double action first requires a *diverted purpose*: something that is no longer part of the body, and that is not identified with the action, which assumes a *potential exosomatic sense* (act A to get B). In order to generate a situation in which human beings can equip themselves with instruments, something should happen, that is specifically human: something starts from the body, project itself outside of this and become an *exosomatic phenomenon*, a kind of mirror. Thanks to this mirror the subject, who

> before acted unconsciously, see himself acting and enter in the area of knowledge where not only "he knows how to do" but "he knows what he is doing". The action described above requires a "project" that translates into a "methodological procedure", or, in the terms mentioned above, in a prosthesis.[1]

Everything changes when we act with the help of technology. Describing design contemporary scenario, Leoni (2018) states that possibly humans are unconsciously exploring new kinds of intelligence. As he internalize tools, human in exploring the insect's action, which establishes a close continuity with the surrounding world. "Let's take an ant. The ant is alone and hyper-connected: the whole world is inside the ant, the anthill is inside the ant" (Leoni 2018).

Summarizing, we can define an *instinctive way* to make, which is typical of Insect Kingdom, that constitute a continuity with their environment—as example Ammophila Hirsuta-caterpillar, ant-anthill, spider-spider web—and an *intelligent way*, that is characteristic of Sapiens (flint leaf-block of stone). Currently, the border between these ways are blurred, as some mediated action in the Animal Kingdom can be observed (latest study on crows, for example, show that they are really capable technologist within birds' species). However, the typical action of human together with machine is something that is not more just intelligent but actually it is not even instinctive (Fig. 3.2).

3.4 Non-designing Approach

Digital tools currently threaten to subvert substantial aspects of human praxis, shortening the distance between stimulus and response, and removing the concept of physical space from human activities. Going to the root of the human-technology relationship allows as advancing hypothesis on the rule of design in a computational environment, even more so considering that human mind is affected by an extend and intense transformation every time it interacts with a computational machine, at a motoric and cognitive level. In fact, the technological component is now becoming more and more accelerated, intimate and widespread within humans, altering their cognitive, emotional, perceptive, physiological, phenotypic and genotypic capacities. Continues O. Longo (2005) "the cognitive unit" man-with-computer "is essentially

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[1] Traslated by the author. Original text: "[…] una lamina di selce ricavata da un blocco di pietra esige, per la sua preparazione, una mediazione o una doppia azione corporea. Questa azione deve anzitutto trasferirsi o prolungarsi in una 'cosa', per es. un sasso usato come percussore, cioè come un prolungamento della mano o del pugno; ma poi, utilizzando appunto questa 'cosa', l'azione deve produrne un'altra, la lamina di selce staccata dal blocco di pietra. Questa doppia azione richiede dapprima uno scopo deviato, qualcosa che non fa più corpo e non si identifica con l'azione e che assume perciò un potenziale senso esosomatico (agire A per ottenere B). Quindi, procurarsi un percussore atto a battere o a colpire con precisione e con forza, per produrre uno strumento ulteriore, in grado di tagliare, lacerare, raschiare ecc. L'intera azione esige un 'progetto' da tradursi in un 'procedimento metodico', ovvero, nei termini sopra richiamati, in una protesi.

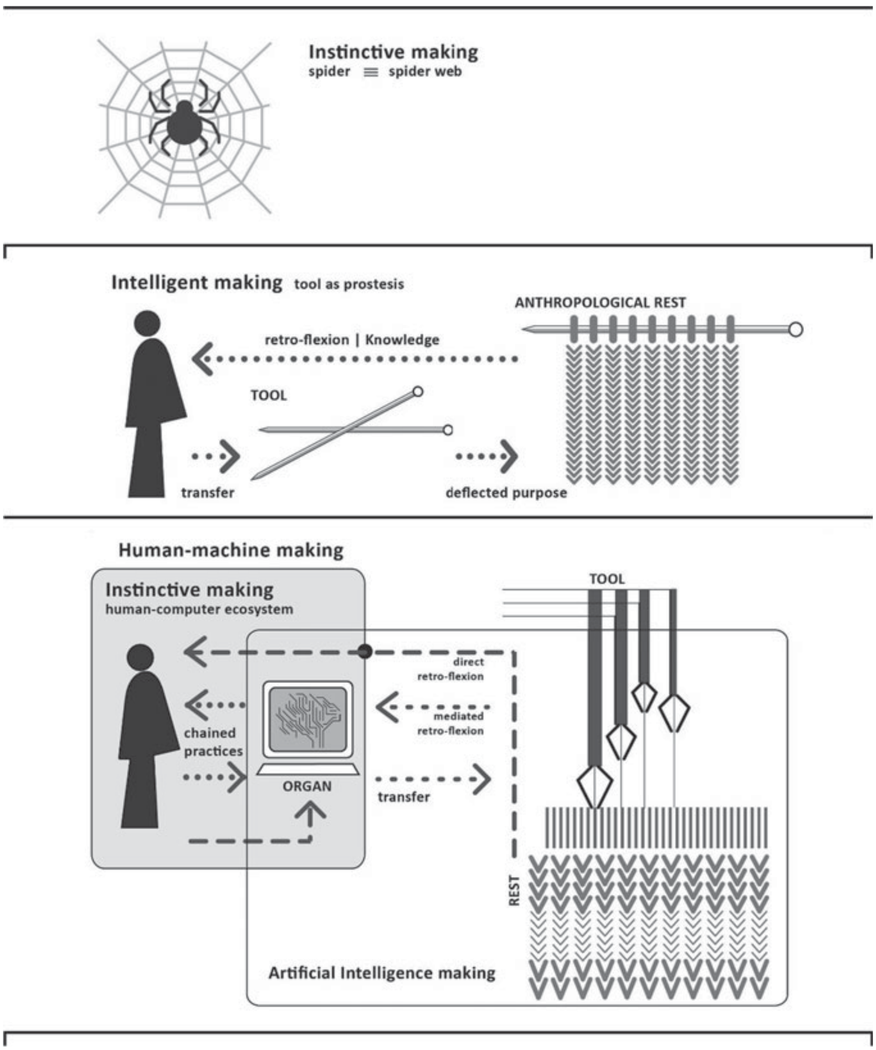

Fig. 3.2 Instinctive, intelligent and human-machine making, taking as example the knitting process

different from the cognitive unit” man-without-computer “, and notes that “the evolution of technology contributes powerfully to our evolution, even coinciding with it” (ibid.) and constituting a new evolutionary unit that is constantly changing.

When the notion of space, together with the very existence of a pre-anthropocene human being, fall, a new approach to the project becomes indispensable, a “non-design” thinking, focused on the excretion of human technological metabolism (Leoni 2018). The consequences are crucial for the designer’s profession, who has the social task of thinking about waste. Leoni continues by saying that if designing, in any context, means to focus on something, with respect to which everything else is waste, then thinking about discard is impossible, if not in an extremely oblique, indirect and never thematic way. Indeed as the discard becomes the main design issue, it also becomes something essential, and therefore what was just promised to do has been infringed.

Therefore, the big question of a new architecture for the Anthropocene: is it possible to think in a *non-designing* way? Are humans able to think, to make, to inhabit the world, the places, the situations, in a non-designing way.

According to Leoni (ibid.) it is difficult to teach human to be not focused on a design object. This requires the ability to focus on discard without centering on it, and then to be not designer, that look forward something with its own shape—μορφή, with respect to which everything else is waste. Designer should transform himself into *picker of insurgencies*. Transforming human thinking and creativity, digital technology is probably what will allows humans to build something, without centering on it, picking the insurgencies, as the first symptoms of Anthropocene manifestations. When the human-machine ecosystem will be able to intercept insurgencies, beyond human, beyond project, beyond thinking, then the discard of 300,000 years of Sapiens' activity will get a new revolutionary treatment.

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Chapter 4
Simulation Driven Design

Samir Al-Azri

Abstract Simulation has long been a significant design driver in the building industry. To simulate is to foresee and understand the outcome of your design decisions. The scale of buildings makes the simulation process very important, specifically, that many projects are only executed once. Overtime, simulation tools have been developed to further enhance the design process. This chapter will discuss the simulation tools being explored in the building design lately, comparing the frequently used optimization process to a new form of intelligence aided design. It will explore the use of applied artificial intelligence, more specifically Machine Learning, in a simulation driven process and its potential applications in a material balanced building design.

Keywords Simulation-driven design · Artificial intelligence · Machine learning · Post-optimization · Neural networks

4.1 Introduction

Sustainable design is becoming a term that dissociates us from problems of our own doing. The premise is that we have created an untenable environment climatically, socially and economically, with justifiability, and have an altruistic choice moving forward. This creates a nonchalant attitude where the actual implications are not experienced instantly. The mindset can be changed if its named "Responsible Design" embedding the idea that we are not privileged to decide the future of the world's state but rather obligated to not only maintain it and progress it as well. Any product of historical human ingenuity would not be applauded if it was at the cost of an unlivable world today. Sustainability is at times also associated with doing or producing less, consuming less, building less, and operating less. This conflicts with our nature of design thinking and inventive solution-finding. The resources we consume today

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were not exhausted in the past, and hence we have an opportunity and a duty to maintain and discover future resources.

Sustainability is difficult to reduce to a simple equation. What we do know is that material is one part of that equation, and that material has many equations in our design ecosystem. As materials evolve, new mechanisms are required for their incorporation in the design and fabrication process. These advanced materials will have unconventional methods for sourcing, production, transportation, and assembly. They will exhibit improved mechanical, thermal and acoustic properties which enhance the built environment. Moving towards an age of mass customization, the materials we envisage will be site, project, and performance specific. Our understanding of the relationship between the matter and energy of materials has been distorted, often addressing them distinctly. To assimilate and efficiently composite these materials into a standing structure, a profound understanding and modeling of the patterns of its behavior is required. This can be achieved through tools that will simulate the performance of the material and associating it with the different layers of building compositions. A process that leverages on the advancement of the digital development to model the lifecycle of the material, from source to operation and finally to reutilization. Simulation Driven Design is the process that attains this capability and will be addressed in this chapter within the scope of its relation to building design.

4.2 Simulation-Driven Design

Simulation Driven Design is a process that allows the designer to simulate the performance or behavior of a design problem and using it to generate and explore the design solutions (Karlberg 2013). The key terms in this process are “Generation” and “Exploration.” The form, behavior, and design generated are a product of the simulation that has been constrained by the designer’s input and his modeling of the problem. An abundant number of solutions are provided in an efficient timeframe to be evaluated and explored. This provides a better comprehension of the problem in hand through the solution exploration exercise. The design process shifts from one relying on the designer to envision a possible solution to a process where the designer understands what elements can drive the project to a given result. An interpretation of simulation-driven design is the use of Topology Optimization (TO), primarily in the product design of many industries. The optimization process would converge to an optimal design bounded by constraints and set load conditions. This technology was limited to parts where the essential behavior of the product is mechanical, with the objective of minimizing material.

The process is more complicated when addressing buildings. Building design considers many other factors, tangible and intangible. From an engineering perspective alone, a façade intended to be designed by an optimization process will have to perform adequately in terms of structural stability, energy performance, lighting, and acoustics to name a few. This is considering the factors that could be potentially modeled mathematically and excluding any subjective design intent. A project, in this case, will have to address all these factors while proposing an aesthetically acceptable façade.

Furthermore, building design is a discipline that requires a lengthy period to identify the impacts of any design decisions. A building will take years from the design phase to the execution where the wrong assumptions or shortcomings are noticed. Unlike product design, our iterations are limited to computer models. Only specific sizes of building elements can be prototyped to a meaningful scale. While we are limited to prototyping the part, the building will perform and be experienced as a whole. The scalability and knowledge timeframe make it challenging to anticipate the implications of the design inputs before the building is completed, making the cumulative experience of the designer a valuable commodity. Henceforth, optimization problems were only successful in solving micro-challenges, e.g., a joint (Fig. 4.1), and failed at addressing the macro problems of a building as an accumulated complex system. One of the drawbacks of the optimization process is the bulk of data that is generated through the thousands of iterations, of which none are made available for further analysis. This presents a missed opportunity for designers to examine solutions that are not considered "optimized." A better process would provide all the generated data as solution sets, which are explored in real-time to allow us to make informed decisions concerning the design. It would be a method of making use of data that is generated daily in each project, instead of discarding it, or even worse, storing it unutilized.

Fig. 4.1 Section of Topology Optimized steel joint prototyped using PLA 3D printing. Image courtesy of Politecnico di Milano graduate research

4.3 Post Optimization and Machine Learning

To rethink the design approach given the limitations of optimization, data identified as information/experience is considered as a driving component of the design process. Unlike the optimization process that depends on user-defined algorithms to iterate through solutions and produce a single optimum result, data is now employed as the central element in the simulation process. An optimization process can be used to gather, process and produce this data; however, it should not be regarded as the core of the simulation. A technology that could provide this workflow is Machine Learning (ML).

> Machine learning is the study of computer algorithms that allow computer programs to automatically improve through experience. (Mitchell 1997)

Machine learning can be described as a model that has the capability of learning on its own from data (experience) without any further programming from the user. It uses algorithms and statistical models to perform tasks depending on the model type. The data produced can be fed back into the model in an iterative process to improve its performance. Since the model has data as its main constituent, its accuracy is dependent on the type and amount of data provided. In general, design data in terms of parameters and outputs are not usually stored in a useful form. Building energy performance or structural modelling data is not shared beyond the engineers realms, and post-occupancy evaluation is seldom collectd. This makes data aggregation for future simulation problematic. It can yet be overcome by using simulation to generate the data required to feed the ML model. This will allow for a controlled data set which is reliable and needs no further processing. An example of this is the open-source CARLA project, which is a simulator for autonomous vehicles. Collecting data for every driving scenario is a challenging task which is solved by using a simulator to provide the data for training the machine driving the autonomous vehicles (CARLA 2019).

Machine learning processes can be generally categorized in one of four; supervised, unsupervised, semi-supervised and reinforced learning (Salian 2018). Supervised learning uses labeled data set from the user and has many different models (i.e., linear regression or decision trees). It is generally used for corresponding inputs to outputs to form predictions, inference, and classification. An example would be predicting the construction cost of a project based on historical data of projects completed. Unsupervised learning tends to identify the patterns and recognize the structure of input data, which is not labeled (i.e. output not provided). This can be used in a generative process to produce designs where the underlying association between the design input and produced outcome is not easily comprehensible. An example is trying to use the association between the geometry of the building with its pictures in social media to design a building that encourages public engagement.

Semi-supervised learning involves a data set that has both labeled and unlabeled data. This model is similar to the supervised data, however not all data is labeled but can still be used to inform the model. Reinforced learning is based on a merit system where the model is rewarded for every task that is considered favorable. It is an iterative process where the performance of the model is improved, the more task or actions are completed, and the model improves in predicting the best move for the highest reward. A robot trying to learn the fastest way to transport material in a construction site is a possible use.

4.4 Generation to Knowledge

What I cannot create, I do not understand—Feynman

The quote above was left on the blackboard of the physicist and Nobel Prize winner Richard Feynman. It emphasizes the concept that every existing entity can be understood. To create something is to understand it, but can we create and then understand? The power of ML is in its ability to provide an alternative perspective into any given problem. The interaction between matter and its effect on our entire ecosystem cannot be visualized by one discipline at one given level. Allowing machines to identify the patterns that generate the material world around us provides us with the opportunity of simulating this world, even if we do not see the associations quite yet. To visualize is to understand. The complexity of our challenges today lies in the relation of our local built environment to the global ecosystem. Such a dense cluster of correlations can only be grasped by processing powers beyond human capabilities.

In 2017, the research team at DeepMind launched AlphaGo Zero, a new release of their previous program AlphaGo that competes at Go, an ancient Chinese board game (Fig. 4.2). The previous release did eventually beat the number one ranked player. The revolution in this version, however, is that AlphaGo did not need any historical input data, and rather used self-play to learn the game in less than 4 h (Silver et al. 2017). Furthermore, it beat the previous versions and proved to be faster and more efficient in its power consumption, with the carbon footprint of many machine learning programs being criticized of late. The game of Go uses stones on a 19 × 19 grid and is a more complex strategic game than chess with a 10 to the power of 170 possible board configurations (DeepMind 2017). This complexity was handled only with the help of Deep Neural Networks. Neural Networks are a type of unsupervised learning that mimics the process of our brain neurons in processing information. It recognizes patterns between multiple layers of the data to structure relationships between them. The ability of an ML to self-play (or self-learn) is a significant feature that allows us to have a model that will learn from simulating an exponential number of scenarios and assist in analyzing the action with the best reward, even without understanding the inference of that action. It is a superior analysis process to what we have been accustomed to, and offers an opportunity of reassessing the way we design buildings.

General Adversarial Networks (GAN), is another type of unsupervised learning where a set of two models that compete against each other in an adversarial process while being trained simultaneously (Goodfellow et al. 2014). The unique capability of this model, relevant to building design, is to generate images based on real data

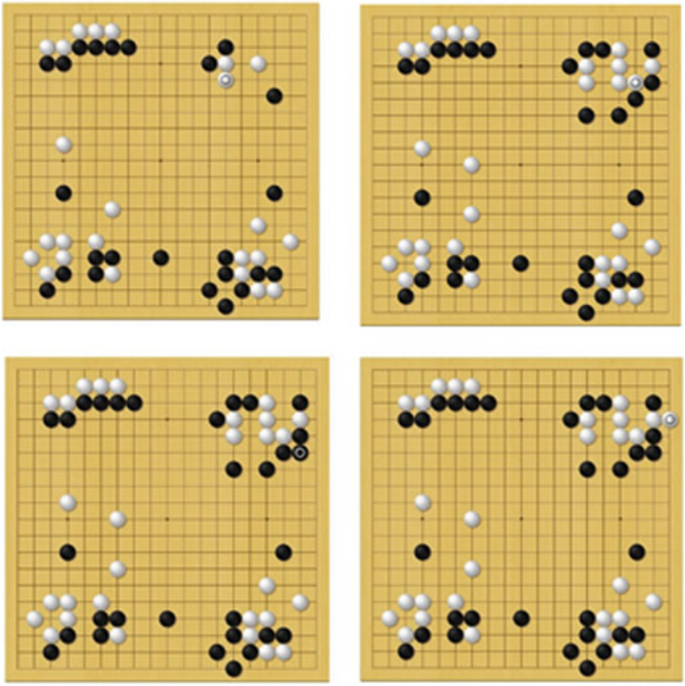

Fig. 4.2 Go board configurations of a game between AlphaGo Zero and AlphaGo Lee. Image Courtesy of AlphaGo-Games

set. A generator would learn to create the input set while a discriminator learns to differentiate the new images from the original data set. Images are the most basic form of design representation and a model handling data in the same format is a game-changer, tapping into a communication medium that is valued by the field. It encourages the creative aspects of the discipline to be engaged with the more scientific aspects of building design. GANs have been used to produce many creative works including paintings (Christies 2018). The proposition here is not a general artificial intelligence that takes over the design process, but an applied one that extends the creative streams of the designer through an exploration exercise of generated solutions. A recent study by Chaillou explored the capabilities of GANs in generating building footprints, layout organization and even style transfer with intriguing results (Fig. 4.3). The intervention of the designer was included in altering the input data between iterations before it is looped back into the ML (Chaillou 2019).

Fig. 4.3 Style Transfer modern to baroque. Image courtesy of Stanislas Chaillou

4.5 Future Studies

The proposed application for ML in this case and relevant to material, is a model that will use data generated from simulating the life process of materials from the cradle to the grave in various design scenarios. The input data can be in the form of building loads and geometry. The output data generated from simulations can be in the form of carbon footprint, financial cost and mechanical performances. This data can then be used by the model to predict the efficiency of the design in terms of material use. This simulation would significantly increase the design iteration cycle, as the ML model once trained is faster at providing feedback than a conventional optimization process. A rapid way of exploring design options would encourage designers to consider more sustainable solutions in a time-constrained project timeline.

In this digital era, it is inconceivable to make any decision without leveraging on the data we are constantly producing. Given the considerable implications of the AEC industry on our environment, data should be given more weight in the workflow to advance the simulation process, not only in the form of big data, but also machine and simulation data. From the models above, the potential of ML in exploiting data as a design driver is evident. Simulation-driven design will be further enhanced with the integration of ML alongside optimization, and can provide intelligent assistance to the human centered approach to design. Such a process is more geared towards solution generation and investigation rather than validation and optimization of an intuition. It could be a critical point in changing the way we perceive and approach building design. An approach that takes us a step closer to balancing how we consume material, utilize it, and accumulate it sensibly.

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Chapter 5
Material Agency and 4D Printing

Giulia Grassi, Bjorn Eric Sparrman, and Skylar Tibbits

Abstract Material agency presents a radical shift in design thinking: matter is deemed as the active generator of design. This chapter investigates the potentialities of the synergy between adaptive materials and emergent additive manufacturing techniques. In this context, 4D printing is explored as the tool that enables the material-centered design and fabrication approach. By means of this technique, it is possible to generate stimuli-responsive material systems that can enact self-adaptation of architectural constructs, responding to environmental change with a shape-shifting behaviour. Moreover, a fast, innovative, 3D printing method, Rapid Liquid Printing, allows for this process to potentially scale up to an architectural scale, as it offers the opportunity of quickly printing at large-scales with a wide array of materials, from industrial grade rubbers to responsive silicones.

Keywords 4D printing · Material agency · Responsive materials · Shape shifting · Rapid Liquid Printing

5.1 Introduction

The flexible nature of advance manufacturing is more than just an enabler of formal complexity; it is rather seized as a chance to rethink the whole design-to-production chain (Mcgee and de Leon 2019). Digital technologies elicited an invigorated interest in materiality, bridging the gap between the digital and the physical world.

Through material engineering we have the ability to understand and know the genotypic genetic heritage of materials and through computational design we can embed data in material systems as phenotypes. Programmable matter implies the

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design of physical engineered matter that change form and/or function in a predicted way (Campbell et al. 2014). This approach has sparked a renewed attraction to smart materials, however it is still struggling to get to mass market for a variety of reasons including the immaturity of the technology and the unreadiness of infrastructures to accommodate the fabrication shift.

Among digital fabrication techniques, additive manufacturing has the potential to disrupt the construction industry, generating new economics dynamics more oriented to a customized production, and blurring traditional roles, due to its innate multidisciplinary (Grassi et al. 2019). The additive model of formation of 3D printed objects enables heterogeneity through multi-material printing and topological optimization of resources.

Even though the digital revolution is having a deep impact on architecture and construction, we are still attached to conventional methods like 3D printing of clay bricks or concrete houses which are created with the same mindset of traditional architecture. Automation is employed solely for its precision and complexity-enabling skills; however, we are not yet fully leveraging its morphogenetical principles.

Through 3D printing each feature can be designed and fabricated differently with no extra costs, this has aroused the crave for excessive resolution (and excess of data) resulting in additive opulence (Carpo 2017). On the other hand, the granular level of detail can be also exploited to engineer sophisticated building components or objects.

A new approach is based on material as active generator of design. Indeed, programmable materials can offer a new paradigm for construction by self-sensing, self-adapting, self-assembling, (Tibbits and Cheung 2012) and hybrid additive processes are the future of this field (Tibbits 2016). As a result, 4D printing, or additive manufacturing of responsive material systems, is the ideal fabrication process to exploit programmable matter as a material whose properties can be programmed to achieve specific shape transformation or property change (Hawkes et al. 2010).

5.2 Adaptation

As designers we share the responsibility of foreseeing where technology is leading our practice and in which ways it is influencing our lives.

How are we planning to fight climate change related issues with technology, if technological progress is the cause itself?

> Technology wasn’t invented by us humans. Rather the other way around. As anthropologists and biologists admit, even the simplest life forms, infusoria (tiny algae synthesized by light at the edges of tidepools a few million years ago) are already technical devices. Any material system is technological if it filters information useful to its survival, if it memorizes and processes that information and makes inferences based on the regulating effect of behaviour, that is, if it intervenes on and impact its environment so as to assure its perpetuation at least. (Lyotard 1991)

Thus, in response to the previous question, one answer could be the shift in the way we perceive technology. Following the assumption of Jean-François Lyotard, a post-structuralist French philosopher, technology is embedded in nature as well as in humans and, over the centuries, has perfected the principle of adaptation. Translating this principle in architecture, material systems can be intended as technological devices themselves; in addition to fighting climate change and adverse natural forces, we can design systems that are able to drive those forces towards new, desirable configurations. The role of the designer then becomes more creative by engaging active materials in a participative co-creation which involves matter, external conditions and the users. Indeed, new material systems can be designed in order to adapt, and therefore take advantage of those unfavourable conditions, which are triggering the adaptation process, while the user can tune the properties according to their needs. Moreover, digital fabrication techniques allow designers to have a direct relationship with matter, almost like traditional craftmanship, as well as to customize tools with endless possibilities (Picon 2019).

5.3 Material as Substance Versus Material as Action

Matter can be perceived as an active generator of architecture, active materiality possess morphogenetic powers of its own (DeLanda 2015). Material systems themselves are able to sense environmental conditions and inform the construction process. New materials are driving innovation in the construction field, disrupting standards by establishing new functions and new requirements. For instance, they can enhance structural performances and safety (e.g. self-healing concrete), durability (fibre reinforced composites), users comfort (shape memory materials employed for kinetic systems), energy efficiency (aerogel as super insulative material). Therefore, the research on emerging complex material systems encompasses the definition of new tectonics paradigms and fabrication techniques, with their personal set of regulations (Albag et al. 2020). As a result, virtuous case studies are dictating new laws while legislators struggle to keep up.

The last century has brought endless possibility for new features and functions, shifting its attention to performance, especially on the mechanical properties, and the "active" features (such as sensing, actuating), overturning the static traditional conception of matter fundamentally embedded in the syntax of design.

For millennia, we have been familiar with very few families of materials. The very first ones, such as wood, clay, iron and leather, are still part of our everyday lives and have created an array of memories of how do we sense and perceive those materials. Did our relationship with materials change?

The later twentieth century has seen the full blossoming of the idea of isotropic plasticity and homogeneity. The popularity of industrial or processed materials such as plastics, concrete, steel or plywood, has arisen from the idea that managing anisotropy means high costs, slow manufacturing rate and difficult performance prediction. In the past, the tactile relationship of the craftsperson and the material was based on a strong understanding of grain or anisotropy. Mainly thanks to digital fabrication techniques, the current moment may be largely seen as a rediscovery of the tactility of matter in its heterogeneity.

New emergent materials are challenging us with a new understanding, we don't know their properties a priori, nor have we endowed them with a cultural meaning (Manzini and Cau 1989). We usually describe materials by their visual, tactile or mechanical characteristics, while in the last years we have been focusing on their performance, especially for 'super-materials' such as aerogel which is transparent and high-insulative, or graphene which is extremely thin but incredibly tough and conductive. Furthermore, responsive materials are generating a new kind of experience for the users. For instance, recently many airplanes have been equipped with an interactive window system: the window dimming is activated through a button that allows different gradients of opacity directly in the glass. This technology (developed by PPG Aerospace under the name Alteos™) works through an electrochromic gel embedded in the glass that respond to electricity. We can say that the material is perceived as the function it has, it is identified by 'what it does' instead of 'what it is', we would refer to it as a smart shading material. Nevertheless, in the case of stimulus-responsive materials the 'what it does' feature is already embedded in their definition: the word 'electrochromic' contains the double notion of 'responsive to electricity' and 'colour changing'.

5.4 Stimuli-Responsive Materials (SRMs)

Stimuli-responsive materials (SRMs) are endowed with the innate ability to react to external conditions. They can be activated through the achievement of a determined threshold of temperature or humidity for instance, and the response can enact different reactions such as colour or shape changing. Both their micro and macro structure can be designed and programmed in order to respond in an expected fashion.

The Encyclopedia of Chemical Technology states that: *"smart materials and structures are those objects that sense environmental events, process that sensory information, and then act on the environment."*(Perry 1961) Hence smart materials can implement different smart behaviours like: shape-memory, self-assembly, self-healing, self-sensing, self-actuating (Li et al. 2017).

According to Addington and Shodeck,[1] (Addington and Schodek 2005) smart materials exhibit the following characteristics:

- immediacy, the response is in real-time
- transiency, the response happens to more than one environmental state

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[1] Authors of the book "Smart Materials and New Technologies for architecture and design profession". Michelle Addington is currently dean of The University of Texas at Austin School of Architecture and had previously taught at GSD (Graduate School of Design) Harvard. Daniel L. Shodeck was emeritus professor at GSD Harvard where he taught for more than 35 years in the architecture department.

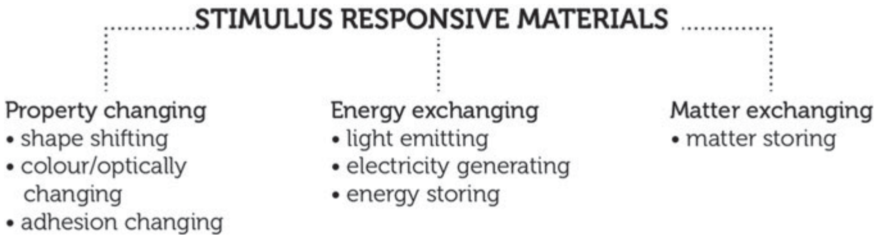

Fig. 5.1 Classification of stimulus-responsive materials

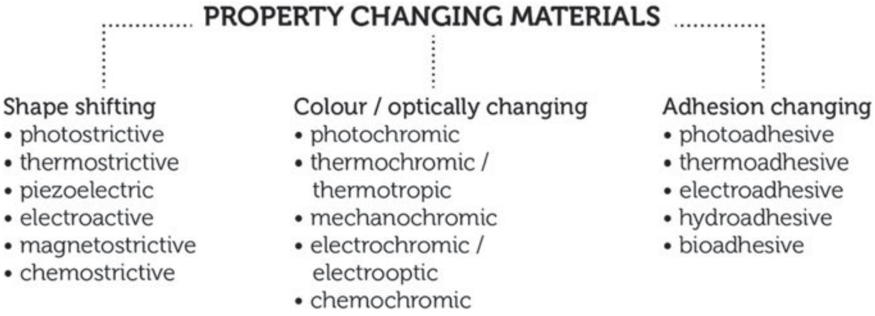

Fig. 5.2 Classification of property changing materials

- self-actuation, intelligence is internal to the ‘material’
- selectivity, the response is discrete and predictable
- directness, the response is local to the ‘activating’ event.

Thus, they possess the ability to change their physical properties in a specific manner in response to a stimulus input which could be light, pressure, temperature, electric and magnetic fields and their chemical environment. The associated changeable physical properties could be shape, stiffness, viscosity and conductivity.

According to Ritter (2007)[2] SRMs can be classified, on the basis of the effect produced by the stimulus, as: property changing, energy exchanging and matter exchanging (Fig. 5.1).

Property changing materials can be divided in shape shifting, colour/optically changing and adhesion changing (Fig. 5.2). Shape-shifting materials are considered the most attractive for the architectural field, especially thermostrictive and electroactive. Matter exchanging materials can be considered also as property changing shape-shifting materials, since the storage of matter has induced them to change shape.

As shown in Fig. 5.2 Ritter differentiates shape shifting materials according to their triggering stimuli:

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[2] Axel Ritter, author of the book “Smart Materials in architecture, interior architecture and design” is an expert on smart materials and structures and their use in the field of kinetic architecture.

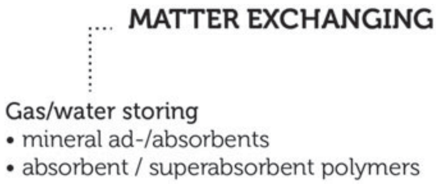

Fig. 5.3 Classification of matter exchanging materials

- photostrictive are excited by the effect of light
- thermostrictive are excited by the effect of temperature
- piezoelectric are excited by the effect of pressure or tension
- electroactive are excited by the effect of an electric field
- chemostrictive are excited by the effect of a chemical environment.

Thermostrictive materials are those of greater interest due to their availability and predicted long-term stability, for instance shape memory alloy (SMA) and shape memory polymer (SMP) belong to this category.

As shown in Fig. 5.3, matter exchanging materials can be divided into gas and/or water storing and particle storing.

Gas or water storing are excited by gas and/or water, in the form of water vapor, water or aqueous solutions, to adsorb (attaching them to the inner surfaces) or absorb them (taking them into their volume). Absorbent polymers belong to this class, they are synthetic hydrophilic three-dimensionally cross-linked polymers with the ability to absorb liquid components onto their internal surfaces and take them into their volume, hydrogels are pointed out as the most promising in 4D printing (Bakarich et al. 2015).

Nevertheless, this stimuli-responsive material classification operated by Ritter does not exactly reflect and describe the reality of smart materials properties because they are interwoven in a more complex system including materials that can react to different stimuli (such as shape memory polymers) or that enable different effects (such as hydrogel).

5.5 4D Printing

4D printing, introduced by the Self-Assembly Lab in 2013, was defined as 3D printing with the addition of time, meaning objects are printed that can transform after their creation (Tibbits et al. 2014). While mostly 3D printed products are static and inanimate, 4D printing involves carefully designed geometries with precisely controlled deposition of different materials that can change shape when subject to external stimuli.

According to Pei (2014), 4D printing is composed of three main elements. The first is the use of stimuli-responsive composite materials, the second is the stimulus that will act on the material, the last is the amount of time for the interaction to occur, where the final result is intended to be the change of state of the object.

Developments in 4D printing are largely made possible due to the recent advancements in multi-material printing. Additionally, mathematical models are of fundamental importance in order to design the material distribution and structure needed to achieve the desired change in shape, property, or functionality. In accordance to Sydney Gladman et al. (2016) the mathematic approach adopted to describe and simulate the process can be divided into the forward and the inverse design problem, and most of current predictive models are not able to tackle both of them. The forward problem consists in the determination of the final desired shape (e.g. resulting curvatures values of the target surface) given printing paths (directions of printing lines), material properties (accounting for anisotropic swelling), and interfilament spacing. The inverse problem is the determination of the printing paths and nozzle sizes given the final desired shape (target surface).

5.6 Shape Shifting Behaviours

At MIT's Self-Assembly Lab, a variety of 4D printed structures that exhibit shape shifting behaviours have been fabricated. The tests conducted demonstrate the ability of those structures to perform the followings:

- 1D to 2D bending, folding
- 1D to 3D folding
- 2D to 3D bending, folding, twisting, surface curling, surface topographical change.

These experiments have been created using Stratasys's Connex multi-material printer and the stimulus responsive material involved was a moisture-swelling hydrogel which can be considered as a shape-shifting material (matter storing).

5.6.1 1D to 2D

Figure 5.4a consist of an assembly of rigid disks with expanding active hydrogel in between, where the disks in the centre act as stoppers (Raviv et al. 2014). After the structure is immersed in water, the hydrogel parts will swell while the rigid discs remain in the same shape. This stress mismatch enables the overall shape to transform by adjusting the distances between the stoppers (central discs) which determine the final folding angle. With the same technique, a more complex self-folding structure (Fig. 5.4b) was demonstrated by printing a single 30 cm strand that, can arrange into letters MIT (Tibbits 2014).

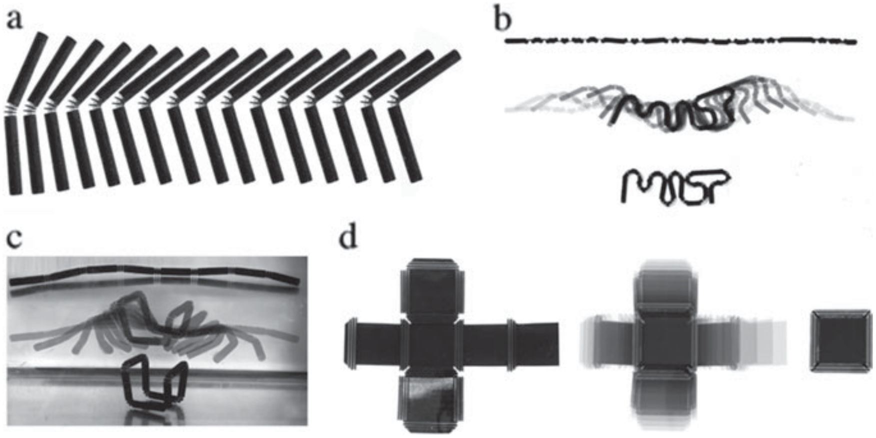

Fig. 5.4 Examples of shape shifting behaviours achieved by 4D printing. *Credits* Self-Assembly Lab, MIT + Stratasys ltd. + Autodesk inc.

5.6.2 1D to 3D

In Fig. 5.4c for each wireframe hinge, two rigid discs are embedded in the hydrogel part, which connects the two rigid strands allowing three-dimensional self-folding structure. Here as well, the rigid discs act as angle limiters, forcing the strand to stop at 90° when touching one another.

5.6.3 2D to 3D

The same logic has been applied to a 2D flat plane (Fig. 5.4d) which can be self-folded into a closed-surface cube. Additional interesting 2D to 3D behaviors investigated under this research include surface topographical change and surface curling.

5.7 Future Developments: Rapid Liquid Printing

The first noticeable limit of the so far 4D printed objects is the scale. Multi-material printers and especially printing methods that involve post processing, such as curing, are usually extremely accurate but limited in scale, due to the complex equipment and often are time consuming processes. A novel technique, Rapid Liquid Printing (RLP) has been developed, that encompasses the deposition of a variety of materials within a suspension of gel (Fig. 5.5), avoiding the need for scaffolding for complex geometries, therefore allowing spatial printing (Hajash et al. 2017). RLP collapses

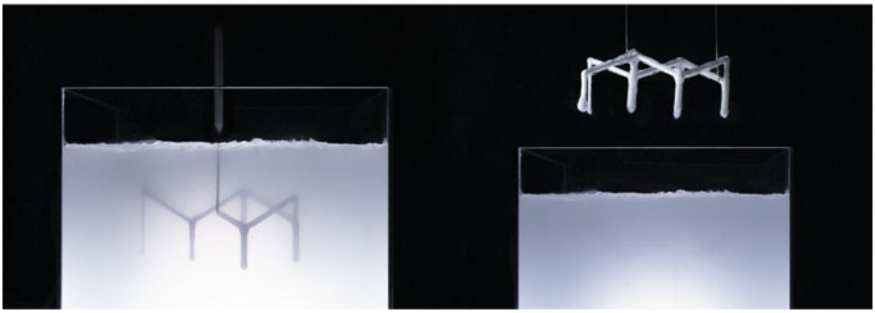

Fig. 5.5 Rapid liquid printing. *Credits* Self-Assembly Lab, MIT + Christophe Guberan + Steelcase

additive manufacturing and industrial-grade materials into a cohesive fast production method of small- to large-scale objects. Moreover, it opens to a wider array or materials, from UV curable resins to very flexible two-parts silicones, foams, plastics or even concrete.

Most 3D printing techniques are anisotropic processes, leading to a directionality in the mechanical material properties, furthermore they often involve the deposition of fused material causing residual stresses, warping and layer delamination (Wang et al. 2007).

RLP synthesizes an additive process, able to accommodate the traditional layer-by-layer deposition or multi-axis deposition through a nozzle, and typical casting characteristics, such as isotropic material properties and smooth finish. Contrary to other AM methods that rely on specific materials based on the printing process, compliant materials for RLP include all sort of well tested, industrially produced liquid compounds. Just to name a few, rubbers, urethane plastics, silicone, acrylics and epoxy and their properties include a large range of different Shore hardness, elongation break, porosity and curing methods, offering options for a variety of applications.

The machine setup consists of a multi-axis control platform, the deposition system and a tank with granular gel. The control platform manages the movement of the nozzle, it can be customized to achieve the desired dimensions and geometric freedom, e.g. it can be comprised of a multi-axis CNC as well as a 6-axis robotic arm. The deposition system, attached to the control platform, is composed by a pneumatic system that pushes the material from the cartridges into a static mixer, for fully blending 2-part materials, and finally into the nozzle. By tuning speed, pressure and nozzle size, it is possible to control the line spacing and the wall thickness of the printed object.

RLP has already proven well suited for the fabrication of product design objects. Furthermore, by increasing the tank dimensions it would be possible to manufacture building components directly ready to be assembled. Thanks to its flexibility, the pneumatic dispensing system can be equipped with multiple cartridges allowing for multi-material printing, while the gel can be reused multiple times. This technique can offer the fundamental potential of functionally graded and highly tunable structures.

Moreover, it may allow printed structures with stimuli-responsive materials that otherwise would be difficult or impossible to print, especially at the large scales. For instance, liquid materials such as hydrogel/resin/silicone can serve as a base for the compound in order to form an ink-like paste that can be extruded by applying a certain pressure. Thanks to the gel, the structures can grow in height being supported while curing. Thermostrictives such as thermo-responsive hydrogels (Sydney Gladman et al. 2016) and liquid crystal elastomers (LCE) (Kotikian et al. 2018) have been already printed but only small-scale. Piezoelectrics like Polyvinylidene fluoride (PVDF), electroactives like Polypyrrole (PPy) or thermostrictive phase-changing materials such as paraffine and ethanol can be mixed with gels or silicones in a composite solution.

Many researches on 4D printing have been constrained by the use of printers that would allow to print only their own brand materials, which have been perfectly engineered, but do not enable experimental tests. RLP, combined with a research on materials and their feasibility for being extruded, can allow a wide array of new smart materials to be printed.

In the construction sector, as 4D printed constructs, we can imagine responsive systems such as adaptive façade components that react to the environment, activating shading systems through heat responsive materials or self-deployable structures that self-assembly thanks to hinges-swelling due to water absorption.

In the final analysis, RLP coupled with responsive materials can pave the way for applications of 4D printing in multiple fields, ensuring flexibility of design (as for scale and complexity), versatility in terms of materials, competitiveness on the market.

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Chapter 6
Auxetic Materials

Ofir Elazar Albag

Abstract Auxetic materials are characterized by the uncommon capacity of extending sideways when pulled longitudinally, while contracting laterally under compressive action. This particular property enables auxetic materials and metamaterials to have special capabilities such as variable permeability, energy absorption, resistance to fracture, the ability to adapt to a bending force and resistance to failure due to shear load. Thanks to these features, auxetic materials have found promising applications in many performative environments, including crash protection, body armor, fasteners, medical devices, sports equipment and aerospace technologies. The special characteristics of auxetic materials have opened new leads for exploration in many design fields including fashion design, product design and architecture, creating new aesthetic languages and functional standards. The chapter gives an overview of how the auxetic principle works, its current applications in various design disciplines and a vision of what could come next in future scenarios regarding auxetics.

Keywords Auxetic materials · Negative Poisson's ratio · Metamaterials · Applications · Patterns · Material science

6.1 Introduction to Auxetics

6.1.1 What Are Auxetics

The term auxetics was first used in 1991 by Ken Evans to label materials previously referred to as dilational and originated from the Greek word for "tending to increase" (Carneiro et al. 2013). Auxetic materials are materials with unique properties: while common materials stretch thinner in the perpendicular direction to an applied tension force, auxetic materials, on the other hand, expand or shrink equally in all directions

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when stretched or compressed, respectively. This behavior is also called the Poisson effect and is measured by Poisson's ratio, which is the negative of the ratio between transversal and longitudinal strain. In fact, most materials shrink transversally when pulled longitudinally, which results in a negative strain ratio, but in turn produces a positive Poisson's ratio. Auxetic materials do the opposite and they are often referred to as materials with a negative Poisson's ratio. This could come as a result of the micro-structure of the material at an atomic level, as well as from a meso- or macro-scale geometric arrangement of material, which is why there are some typical patterns that are commonly associated to auxetics (Strek et al. 2018).

6.1.2 Brief History of Auxetics

The discovery of auxetics dates back to the beginning of the twentieth century and is credited to German physicist Woldemar Voigt, who examined iron pyrite minerals and observed how the crystals grew thicker laterally when under longitudinal tension. However, Voigt could not come up with an explanation to this behavior and the phenomenon was disregarded for decades. The topic was picked up only in the '70s, when more interest started to spread among researchers and many materials, such as ferromagnetic films (Popereka and Balagurov 1970) and fcc crystals (Milstein and Huang 1979), were confirmed to have a negative Poisson's ratio.

The biggest breakthroughs came in the late '80s, starting from the emergence of mechanical and thermodynamic models for the analysis of deformation in auxetic cellular grids (Gibson and Ashby 1988), to the discovery of materials with extreme Poisson's ratios, reaching up to -12 (Caddock and Evans 1989). But perhaps the biggest step forward was moving on from naturally-occurring auxetic rocks and minerals, to the first artificial auxetic materials. Roderic Lakes produced the first foam with a negative Poisson's ratio by manipulating the configuration of a regular foam with a sequence of compression, moulding and heating actions, a process that altered the arrangement of its cell structures into a reentrant disposition (Lakes 1987). This proved that the true potential of auxetic behavior lies in the ability of ingraining it in existing materials by means of strategic geometric design, which made way to an array of innovative applications.

6.2 Applied Auxetics

6.2.1 Applications Across Disciplines

Ever since the rise of interest in auxetics 30 years ago, the principle has found many types and fields of application, including the army, aerospace, maritime, biomedical, sportswear and apparel sectors. In aerospace, the high thermal filtering capacity of auxetic materials has been used to provide high-performing insulation. The defense sector is currently investing in having lighter protective gear that uses the auxetic property of global compacting under compression to produce materials with stronger resistance against ballistic impact, regardless of lower mass (Liu 2006). In biomedical applications, auxetic materials are used in making prostheses that provide higher comfort and better recovery for patients, for example in artificial intervertebral disks, cushion pads for knee prosthetics or tools for repairing cardiac valves (Scarpa 2008).

Furniture design is another promising field for the application of auxetic materials. For example, auxetic surfaces that can react to forces by local expansion enable the design of chairs that precisely adapt to the posture, body shape and weight of the user. At a larger scale, auxetic materials can be used to create flat-packed complex structures that can be easily deployed on-site. This is possible thanks to auxetic materials' capability to be elastically deformed into synclastic surfaces starting from a flat format (Papadopoulou et al. 2017).

Auxetic fibers are also being used in construction to produce better reinforced composites, since their non-shrinking behavior when subjected to tension could contribute to reducing cracks. On the other hand, the fashion industry is exploiting the ability of auxetics to easily adapt into desired geometries by closely conforming to complex shapes. This adaptability could potentially enable a manufacturer to produce one-size-fits-all shoes or garments, or even multi-age children apparel, and thus promote great savings in both costs of production as well as resulting waste, while maintaining the highest standards of comfort for the user. That is why designers in many fields are becoming increasingly acquainted with various auxetic patterns and using their potential in compelling designs.

6.2.2 Auxetics in Fashion

The promising characteristics of materials with negative Poisson's ratio allowed for the investigation of new paradigms in an array of fields concerned with improved performance and comfort, expanding their aesthetic and functional offer. The apparel industry already seemed to recognize the advantage auxetic patterns give in enhancing a usual sheet of material into an adaptive one that closely fits the wearer's body and provides unprecedented comfort. Under Armour uses an auxetic layer on the upper part of the shoe to provide extra breathability (Toronjo 2014), whereas Nike has applied the principle of auxetics to its soles, which provide for increased flexibility, comfort and grip, while reducing the impact of the foot hitting the ground (Cross 2016). That same adaptability could also allow producers to create one-size pieces of clothing which adapt to all possible measures and thus eliminate the need for expensive and wasteful different sizes. This unique property is fully exploited in Petit Pli's auxetic children's apparel, which developed a sustainable alternative for children's fast-changing clothing using garments that "grow" by the application of a zigzag auxetic folding pattern (Yasin 2018). In this way, they could offer functional children's fashion that lasts for longer and results in less waste (Fig. 6.1).

Fig. 6.1 Auxetic materials used by Petit Pli to produce adaptive clothing for kids: the trousers can almost double in size due to the auxetic principle (courtesy of Petit Pli, photo credits: Ryan Mario Yasin, Mollie Rose)

Fashion designer Danit Peleg, who is credited as the first person to print her entire collection on home 3D printers (Grain 2016), uses auxetic patterns in her garments not only due to their ability to adapt to all bodies, but also to create more fabric-like behavior out of the commonly rigid outcomes of FDM printing. Her auxetic 3D-printed fabrics have a natural way of draping that is similar to the shape that a knitted textile would follow, due to their ability to adapt to complex doubly-curved surfaces. In addition, the auxetic macro-patterns provide an extra bouncing quality to Peleg's clothing, which is why they were used in several occasions involving dancing performances. In this case, auxetics provide an experience that was previously unimaginable (Fig. 6.2).

6.2.3 Auxetics in Architecture

The auxetic-specific ability to follow complex synclastic and anticlastic surfaces has been explored also in architecture, an industry in which the manufacturing of doubly curved elements has struggled to keep up with the architects' novel designs, that have come due to the revolution in advanced digital 3D modelling. The current widespread techniques of producing doubly curved panels often involve at least one step of moulding, which results in very high manufacturing costs and slow rates of production.

Architects at ZHA challenged the status-quo of the construction industry in this aspect in their Volu dining pavilion. They applied an auxetic cutting pattern to 2 mm

Fig. 6.2 A skirt by Danit Peleg that uses the stretchiness and bounciness of auxetic materials (courtesy of Danit Peleg, photo credits: Daria Ratiner)

steel plates in order to kerf bend them into doubly-curved panels that closely followed the flowy design of the pavilion (Louth et al. 2017). Kerfing is a method of providing curvature in a flat rigid material by cutting through it or by making incisions, but it's usually limited to unidirectional flexibility and thus developable surfaces. By using an auxetic pattern, architects at ZHA were able to take kurfing one step further (Fig. 6.3).

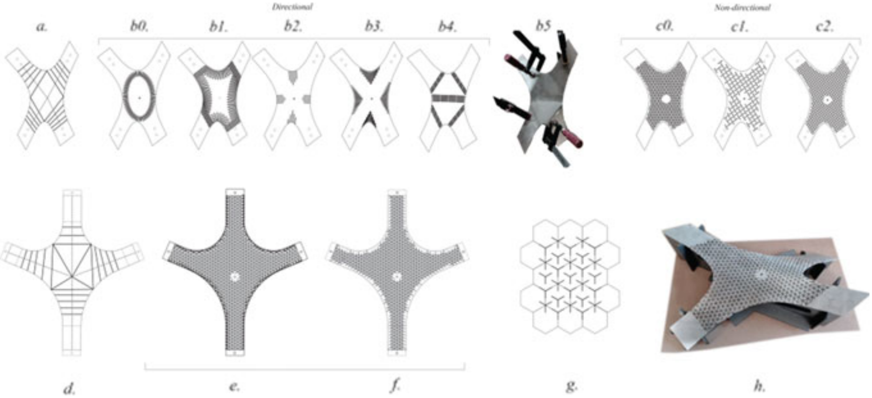

Fig. 6.3 Auxetic pattern used by ZHA to cut custom doubly curved pieces for the Volu pavilion (courtesy of Zaha Hadid Architects)

Another direction architecture is currently moving towards is the exploration of adaptive spaces, so the interior quality of auxetic patterns is being used to create functionally graded barriers that provide adapted visual and acoustic comfort. In this way, auxetics are making their way into the list of advanced programmable materials. In addition to interior-exclusive uses, auxetics can be also applied in systems regulating exterior to interior filtering, such as the case of shading systems using bilayer heat-activated polymers with designed intertwining patterns (Papadopoulou et al. 2017). However, these climate regulation systems remain in their first steps towards a widely applied solution.

6.3 The Future of Auxetics/Promising Scenarios for Auxetics

6.3.1 Construction of Doubly Curved Surfaces

As shown in the case of the Volu pavilion by Zaha Hadid Architects, one of the emerging applications of auxetics is the fabrication of doubly curved surfaces. The issue of manufacturing 3D objects with positive Gaussian curves has increasingly been dealt with in recent years, as computational tools provide the possibility of designing ever more complex and sophisticated geometries. Despite recent efforts in making doubly curved panels more accessible, the common prominent practice in architecture still remains approximating most of the shapes to developable surfaces or, in other words, curved surfaces that can be produced out of bending a flat, inextensible sheet of material. The problem with this approach is that it often requires a thorough and careful reconstruction of the design which often diverges too much from the original and requires more paneling, hence reducing the continuity of the surface's appearance.

A promising alternative to tackle this problem is proposed by a recent paper that goes beyond the developable approach and rationalizes surfaces by using auxetic principles. This method harnesses the enhanced plastic behavior created by the application of auxetic cut patterns into an inherently inextensible material (such as metal sheets) to cheaply and easily approximate a wide array of complex, doubly curved objects. Elements formed through this cutting process exhibit small local rotations that allow the material to gain extreme stretching properties and consequently provide a result that closely wraps the target surface (Konaković et al. 2016). By employing constraints and optimization criteria, the researchers propose a computational workflow to the approximation of complex surfaces, which would not be possible using traditional auxetic design methodologies. However, there are a few limits to this method, namely the extent of the gaussian curvature it can approximate (for example it will never be able to create a whole sphere from a single sheet) and the complicated geometric calculations that have to take place in order to determine the right auxetic cut pattern and its sizing across the material. Nevertheless, the method could improve current best practices by considerably reducing the paneling of complex surfaces in construction.

6.3.2 Shape-Shifting Architecture

Shape-shifting architecture takes adaptive architecture one step further, from static functionally graded architectural elements, to dynamic architectural skins and even moving skeletons, that adapt to the user's needs by means of literal encapsulation or protrusion. These scenarios of futuristic architecture often target changing levels of privacy or isolation and aim to give a seamless sensation in the changes happening in one's work life at the office or leisure time at home. A group of students at Hyperbody proposed an auxetic wall that could shift between several configurations desired by inhabitants of student dorms. The wall uses a differentiated auxetic pattern to guide the shape of the wall, which controls the levels of privacy around an individual or a group of people (Fig. 6.4). The pattern made it possible to have functional furniture embedded in the wall, which pops out due to the material's geometric morphology (Kolo et al. 2017).

Fig. 6.4 Parametrically designed auxetic pattern used for a shape-shifting wall at Hyperbody, in which a bench is designed to flush with the wall in certain configurations but pop out in others (courtesy of Elpiza Kolo)

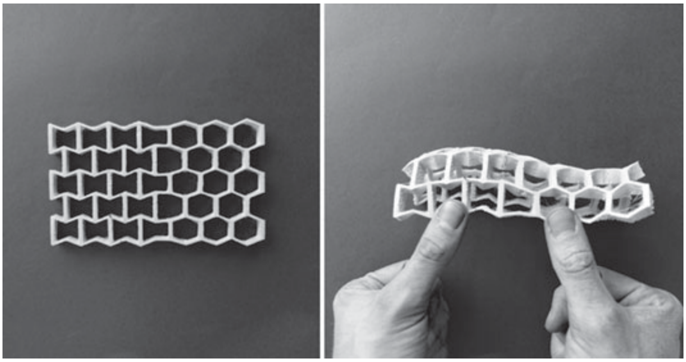

Fig. 6.5 In the prototype designed by Mirante the alternation between auxetic and hexagonal patterns makes the grid bend in non-uniform ways to achieve more curvature in auxetic areas (courtesy of Lorenzo Mirante)

Shape-shifting architecture also has the potential to facilitate construction processes and make the transportation of curved prefabricated elements to the building site easier, by starting out from flat sheets. A project by Mirante uses auxetic patterns to optimize bending-active structures that can be activated on site by compression forces and reach complex shapes starting from completely flat grids (Fig. 6.5). Differently from typical bending-active grids, that start from flat spatial arrangements to reach uniformly curved vaults or domes, this solution uses auxetics to envision surfaces with variable curvatures and proposes a computational workflow for their design (Mirante 2015). Another promising construction technique is the practice of pre-buckling 3D lattices to turn them into auxetic ones, thus achieving stiffer and more resistant structures, a principle that has recently been explored by material scientists. Applying loads to 3D auxetic lattices in the direction in which they possess more rigidity was proven to optimize their crashworthiness (Albertini et al. 2019).

6.3.3 *Smart Auxetics*

Recent developments in material science have infiltrated and pushed the field even further by producing active auxetic structures, made of smart materials that respond to specific environmental stimuli such as heat, moisture or air pressure. Active auxetic materials offer even greater adaptability and functionality as they can self-transform and adapt to environmental conditions and user needs. For example, temperature-active clothing can be made by using bilayer polymers composites with different coefficients of thermal expansion, properties emerging from their auxetic nature (Papadopoulou et al. 2017). The construction sector can also benefit from the application of auxetics in bilayer materials, since they hold the potential of adjusting the stiffness of bent plates without changing their geometry. Such plates can exhibit a linear behavior even in cases of extreme displacements, which makes otherwise unaltered elements much safer when approaching failure (Brighenti 2014).

Using active auxetic materials increases the potential range of application by replacing the need for external, mechanical stimuli with an intrinsic one that drives the auxetic behavior on the material level. We can now imagine applications of self-adapting auxetic materials in our every-day environment: from compressed-state shipping of disaster relief shelters that transform by exposure to specific environmental conditions, to apparel and other products that simply provide custom fit as well as adaptive breathability, waterproofing and self-optimization.

6.4 Conclusion

The vast possibilities offered by the combination of smart materials and auxetic geometries blends the boundaries between the disciplines of design and material science, providing new visions for the design of highly adaptive, performance-driven products that carry the promise of improved well-being with a lower environmental cost. When it comes to architecture, whether this technology will be used to improve construction processes or a building's structural stiffness, auxetic materials seem to hold the potential to transform our built environment for the better and for the safer.

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Chapter 7
Bespoke Knitted Textiles for Large-Scale Architectural Projects

Maria Anishchenko

Abstract Textiles are important materials in modern architectural technology. They enable lightweight shell structures with specific inhomogeneous textures and complicated geometries to be constructed. The traditional method of constructing a bespoke textile composition and geometry includes patterning, sewing, and welding. This is wasteful because it consists of several production stages which significantly increase the time and the cost of production. Meanwhile, modern knitting machines are capable to produce complex, seamless three-dimensional shapes in a fast and waste-free manner. This new technique, under the current study, may be an alternative to 3d-printing in the production of large-scale bespoke shapes. This chapter presents the initial results of the research focused on understanding how different fabric structures influence the perception and characteristics of textiles for large-scale architectural applications and how they can be produced. It starts with an introduction to the topic of knitting technology, concentrating on the automatization of the production of the bespoke inhomogeneous knitted textiles, covers the topics of sustainability and safety of textiles. The chapter includes a case study that investigates the architectural characteristics of knitted textiles on the scale of a wall. It finishes with the analysis of the study and observation of future directions of the research.

Keywords Knitting · Digital knitting · Sustainable textiles · Three-dimensional knitting · Characteristics of textiles · Advanced textiles

7.1 Introduction

Textiles have a long-lasting tradition in architecture being used in bending-active structures since the works of Frei Otto (Thomsen and Hicks 2008). Recently they were proven to be as well a feasible solution for the creation of resource-efficient formwork (Brennan Ba et al. 2013) or reinforcement for complex concrete geometries

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(Popescu et al. 2018). Besides large-scale applications, textiles are widely used in interior design. Introducing fabric to the interior space influences the acoustics creates solar screens and light reflectors, helps to define a space and increases the comfort level.

Knitted textiles in architecture is a very young and underexplored field. Nowadays, they are mostly used in tensile structures, though in most applications their complete potential is not used. Moreover, most of the knitted fabrics are produced as uniform flat sheet material (Popescu et al. 2017). This way the main advantages of the technology of knitting are not used, as the fabrics still need to be cut, welded or sewed. These are wasteful processes that increase labor hours and require a lot of different processes of work.

Meanwhile, modern knitting machines with computer numerical control (CNC) are capable of quickly produce textiles with complicated texture and shape with minimum human intervention. This permits complex, seamless three-dimensional shapes to be created in a fast and waste-free manner. Besides, the seamless structure allows concentrating on force distribution inside the material without having connections as weak points (Underwood 2009).

7.2 Production of Bespoke Knitted Textiles

Industrial flatbed CNC knitting machines are programmable and built for industrial manufacturing. They are mostly used in the fashion industry to produce garments and shoes. In recent years an interest in the advanced CNC knitting machines has grown up also in other fields like engineering and construction. This is thanks to the advances in the knitting technology that allow us to produce textiles on-demand and integrate the special fibers directly into the fabrics.

Knitted textile is a mechanically flexible structure that can be customized on the levels of material structure, yarn type, and stitch composition. Using CNC knitting, where the qualities of the fiber and the manipulation of a knit structure are utilized to satisfy structural needs and explore spatial qualities, the textile can be transformed into a highly heterogeneous structure (Ahlquist 2016). It means that one seamless piece of the textile may contain several different patterns, differentiated material composition, and bespoke geometrics computed and programmed to have a specific shape, structural and physical properties. These new possibilities of traditional technology, being on a very early stage of development have growth opportunities and can scale up considerably in terms of innovation.

Flatbed knitting machines are designed to seamlessly produce three-dimensional volumes, operate in high capacity with little human intervention. However, when changing knitting programs, they usually require manual intervention by highly skilled technicians (Simonis et al. 2016). It limits the results to the skills and experience of the knitting engineers. The development of the machine code to produce the knit requires an extensive understanding of the knitting process in the weft knitting machine, which further includes nuanced control of stitch length, machine speed, and fabric take-down values—all of which varied according to the material types and stitch structure (Karmon et al. 2018).

Complex knitted structures are achieved by electronically controlling specific needles, which can transfer, skip and cross yarns between needles and across needle beds. Different combinations of these basic operations result in different patterns. The fabrics of different patterns have different appearance, density, different elastic and stress-resistant properties.

Customization of knitted fabrics is, therefore, possible through digital, mechanical and material control of every stitch combination within the fabric. The main variables that can control the variation of stitch structure are material types, the density of the material, combination of stitches, composition of yarns, layers and three-dimensional elements.

7.3 Safety and Perception of Textiles in Architecture

Textile environments can be a sustainable alternative to the conventional construction materials only under the condition, that they can satisfy the aspects of safety and architectural comfort. Both can be controlled on the levels of fiber composition and the way of textile production.

Fiber engineers work and have already achieved significant results in improving the resistance to fire, ultraviolet rays, moisture, and other aspects that should be considered according to construction regulations. Through manipulation of the yarn composition, the modern textiles can be used both inside and outside without worsening of their structural and aesthetic qualities with time.

The aspects of architectural comfort can be also controlled on the level of yarn composition. For example, special hollow-core fibers by Italian company Sinterama can absorb noise and improve acoustic properties thanks to its hollow core which creates an additional internal surface that can absorb more sound waves.

On another hand, the way of fabric production, density, and thickness of the material also plays a significant role in the perception of architectural textiles and their role in architectural comfort. All these characteristics influence the way we perceive the textiles and their capacity to distribute light and air, its insulation characteristics and structural resistance. From this point of view, knitting has advantages at the production stage. It enables a high variety of patterns with inhomogeneous distribution and material composition to be achieved, thought this question is not studied well yet.

7.4 Sustainability of Fibres

Textiles, in general, are not sustainable. Textile waste occupies nearly 5% of all landfill space and synthetic clothing may take hundreds of years to decompose. The sustainability of textiles can be evaluated from multiple sides: the amount of material, kind of materials used, amount of waste, type of fibers and yarns production, way of dying, etc.

Nevertheless, multiple companies all over the world work on inventing new ways of sustainable textiles production doing yarns of recycled fabrics, the wood pulp of trees, plastics. For example, Italian company Sinterama and American company Parley is creating yarns, 100% recycled from used plastic bottles. It is an ecologic product that allows cleaning the planet from plastic waste transforming it into fabrics. While usage of these novel materials does not have yet a wide popularity for the Garment industry for the psychological perception of the idea of wearing garbage, it is finding its niche in the product design and construction industry.

Another important aspect of the sustainability of textiles is waste. Normally textiles are produced as one plain piece and then are cut to obtain required shape. It generates most waste by comparison with the other production stages. As a bespoke technology, knitting permits the production of knitted textiles without the need for cutting and connecting the pieces of fabrics. It allows for creating nearly zero-waste production.

7.5 Case Study: Senseknit Pavilion

The Senseknit Pavilion was designed and built as a response to a question of how to design textiles for architecture satisfying the primary comfort needs, making them at the same time reliable and safe. To achieve that the recycled engineered fibers and the advanced technology of digital knitting were used.

The pavilion is designed as a single curved wall. The base structure is done with woodcuts with the CNC machine and assembled in 22 single panels that are easy to transport and assemble. The entire structure is covered with 90 mq of knitted textiles, optimized with the technology of digital knitting. All the textiles were produced of the polyester 100% recycled from plastic bottles.

Bending and curving the wall is forming four partly closed areas. Each area corresponds to the different aspects of architectural comfort: acoustic, structure, light and air distribution. The textiles for each area were developed and produced on demand to meet the planned scenario (Fig. 7.1).

Acoustic comfort is one of the primary needs of the contemporary space. Textiles soften sound by absorbing and reducing reflection, thus increasing the acoustic comfort. The absorbance characteristics depend on the area of the material exposed to noise. For this reason, the acoustic effect increases when the material is fibrous, rough and three-dimensionally shaped. The acoustic part of the pavilion is done with a textile made of special noise absorbing fibers with a hollow core. The hollow core increases the absorbing area of the fiber, helping to catch more sound. The textiles are formed in a 3D pattern, which also increases the area of the surface, thus improving the acoustic performance (Fig. 7.2a).

The structural stability of any architectural object is the main prerequisite for safety. Textiles themselves are not structural but combined properly with structural

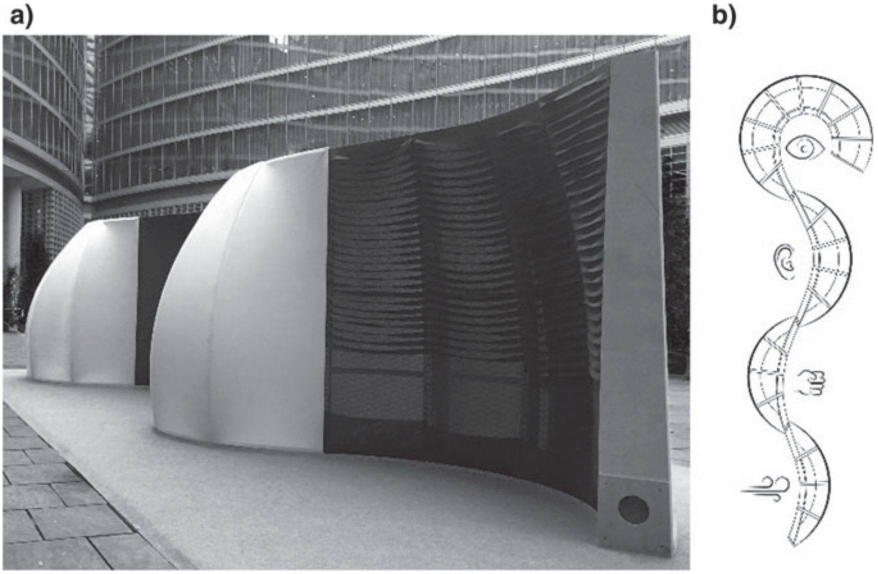

Fig. 7.1 Picture of the Senseknit pavilion exposed during the "Design week 2019" (**a**) and plan of the pavilion (**b**)

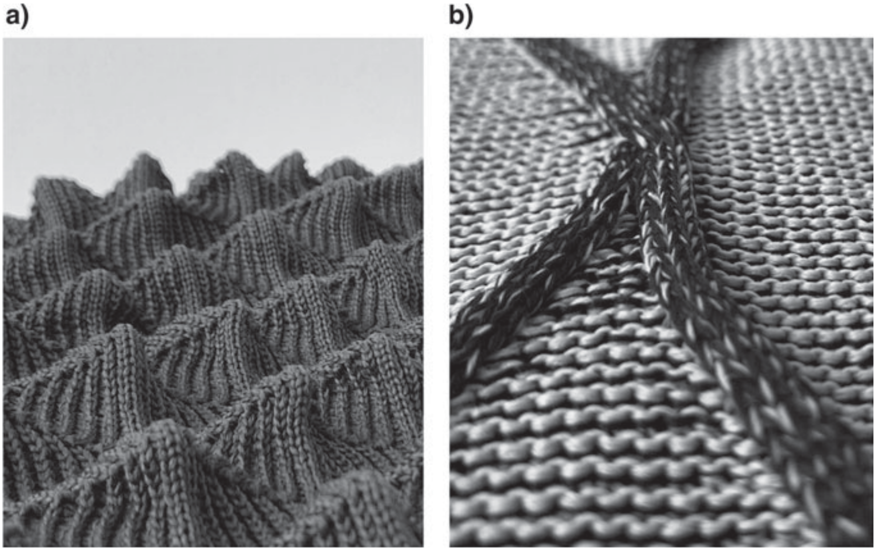

Fig. 7.2 Fabric with three-dimensional pattern for higher acoustic absorbance (**a**) and fabric with "reinforced" areas for the structural stability (**b**)

elements, they get the capacity to bear loads and sustain forces. The load-bearing capacity of textiles is defined by the strength of the fibers, pattern, and density. The denser fabrics are capable to bear more load, but at the same time, they have a bigger weight and thus require more material and structure. Nevertheless, the load distribution inside the textiles is not homogeneous. Thus, to optimize the density of the textiles, the denser textiles should be placed in areas that are more exposed to loads, while the rest can stay light, without affecting the load-bearing capacity. To achieve that the directions of the highest stress flows were identified and "reinforced" with the higher density fabric. This creates a lighter structure, with reinforcement only where needed, thus satisfying the principle "Build more with less" (Fig. 7.2b).

In the climatic area, textiles are used to control air movement to obtain a distributed flow. The idea of distributing air with fabric is not new. Air-permeable fabric pipes do exist on the market both for industrial and private applications. Among their main benefits is the possibility to control the air direction and force controlling the density of the fabrics. Textiles with differentiated density distribution help to block or free the airflow to obtain the desired effect. Distributing the air through a fabric wall can be a new step to air-conditioning of a space (Fig. 7.3).

In the visual area, the openness of the textiles helps to control the level of light and to create desired visual effects, filtering the light in different modes and intensity. For the pavilion, the LED lights were installed inside the wooden structure. Passing through the textiles the light was distributed creating an effect of an illuminated wall (Fig. 7.4a).

For this part of the pavilion were used special light-sensitive fiber Lumen by LineaPiù Italia. These fibers are coated with photosensitive pigments, transparent to the normal light, but can change color when exposed to ultraviolet light. They create

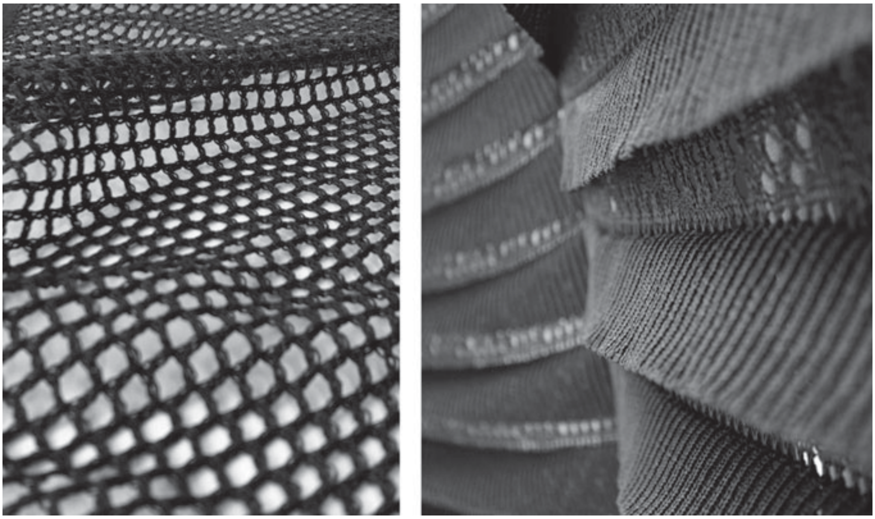

Fig. 7.3 Fabric with differentiated density and openness for the control of the air distribution

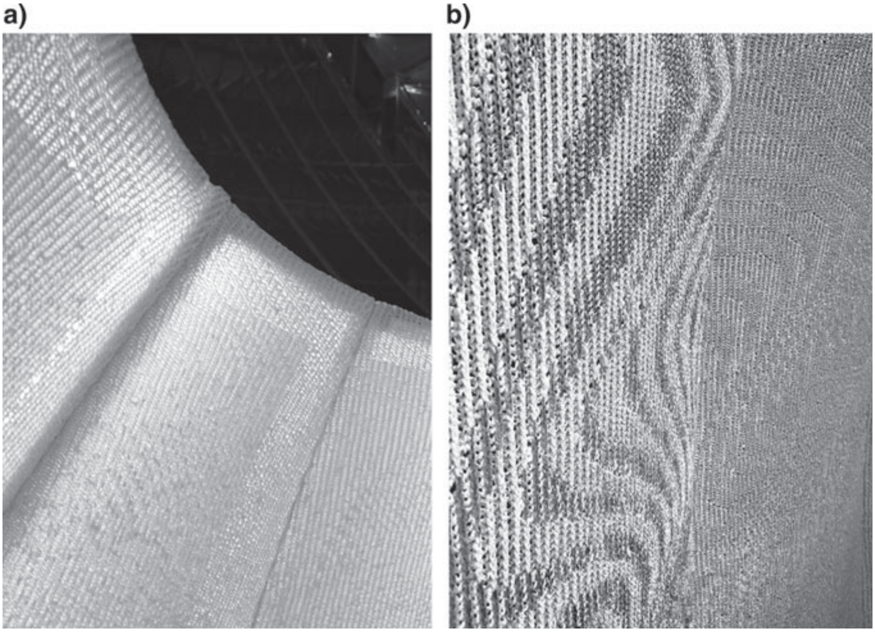

Fig. 7.4 The visual part of the Senseknit pavilion, illuminated at night (**a**); the optical effect of the visual part of the pavilion, exposed to the sunlight (**b**)

an optical effect and change color when exposed to the sun-light (Fig. 7.4b). Thus, the visual effects were achieved both for the dark and light time of the day.

7.6 Results and Discussion

The scenarios presented in the case study demonstrated the advantages of textiles for the architectural application. Besides the aesthetics and low weight, they can have integrated functions that may change the perception of the textiles for large-scale applications.

All the textiles for the pavilion were customized depending on their designed functions and produced on demand with the industrial flatbed knitting machines. However, due to the scarcity of time and resources, the choice of patterns and density of textiles were done mostly in an intuitive manner. Though the textiles in all the parts of the pavilion have proved their usability to influence the aspects of architectural comfort, a deeper study of their characteristics is required.

The next step of the research of textiles for architectural large-scale applications is in understanding the real potentiality of the material and making analysis to predict and control the real effect. These future steps of the research will be done with a series of experiments that will unveil the main driving factors that do influence different architectural characteristics of textiles.

An important step for future research is customization of the knit programming software and its integration with 3d-modeling and tensile behavior simulation programs. Together with a database of driving factors influencing the characteristics of textiles, it will bring the bespoke textiles for architectural applications on a new level. In the perspective, the development of knitting technology may result in new applications, improvement of performance and optimization of the structure and density of the material.

Acknowledgements The Senseknit pavilion was created with the help and support of several academic groups of Politecnico di Milano and external companies. From the Material Balance Research Group, the project was carried by professor Ingrid Paoletti, Ph.D. candidates Maria Anishchenko and Samir Al-Azri. The Textileshub of the Department of Architecture, building environment, and construction engineering, was represented by professor Alessandra Zanelli and architect Elpiza Kolo. The experience of work with textiles was provided by the Design department: Professor Giovanni Maria Conti, Martina Motta, and Charlotta Bellissimo. The fibers recycled from the plastic bottles as well as support during the design process were provided by a company Sinterama. The light-sensitive fibres were provided by LineaPiù. The knitted textiles were programmed and produced by a company Kn-hit on the Stoll knitting machines.

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Chapter 8
Future Façade Systems. Technological Culture and Experimental Perspectives

Massimiliano Nastri

Abstract The study examines the contents and the methodological and systemic guidelines concerning building façades, which are expressed in terms of morpho-typological, environmental, interactive and energy characters, according to the procedures of integrated operations with regard to the interaction with environmental, climatic and energy loads. In this respect, the study focuses on the dynamic and reactive behavior, mediation and interchange practices in relation to the control and conveyance of thermal, light and air flows, along with the calibration of components according to energy performances. The study is developed in accordance with the procedures of dematerialization, interconnection and permeability of building façades, by deepening the constituent practices of textures aimed at spatial, perceptual and evocative connections. The examination of façades relates to conceptual and experimental practices according to the development of plastic, organic and kinematic morpho-genetic processes, extended to a three-dimensional digital modeling and topology optimization aimed at calibrating performances and physical and geometric characteristics. In addition, this research considers the development of façade surfaces in communicative and interactive form as a medium for visual and mediatic transmission.

Keywords Building envelope and façade systems · Environmental and energy design of façade systems · Dematerialization and interconnection of façade systems · Computational design of façade systems · Topology optimization of façade systems · Mediatic and communicative design of façade systems

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8.1 Morpho-Typological, Productive and Constructive Constitution of Advanced Façade Components

The design, production and manufacturing of building envelope systems, aimed at performing morpho-typological, perceptual, physical and environmental functions within the *Material Balance Research*, are dealt with the evolved *curtain wall* configuration (known as "outer curtain") and with the geometric and material continuity of "light façades" (or "curtain walls"), located outside the main structural apparatus (Giordanino et al. 1963, tr. it. 1967; Nardi 1961, 1976; Schaal 1961; Nastri 2008a, b, c). The evolved configuration of *curtain wall* is achieved according to the conditions arising from the widespread "technical opening" offered by the contemporary industrial production of façade systems (already defined by *components approach* or *componenting* processes, using "aggregation rules" for the assembly of "pieces"), which identifies an area characterized both by the multiplicity of combinations and by synergies between technical and material elements of different productive origin (Murray 2009; Nastri 2017).[1] This supports the "flexible" relationship criteria between structural and envelope elements, connection and functional devices and assembly modes (Daniels 2003; Herzog et al. 2008) (Fig. 8.1).

In general, the technical and executive design of façade systems focuses on the selective and "customized" use of the results derived from the current production and performance offer. This is done considering the opportunities of choosing between "series solutions" and "prototype solutions". In this respect, the convergence between design culture and industrial culture is defined by the versatility of production lines, the innovation aimed at the flexibility (but also to the specialization) of products and the offer of new performances, while considering the purpose of "multi-material" relationship and specialized stratification (Herzog et al. 2004, tr. it. 2005). This determines the development of functions according to specific needs and of products showing morphological neutrality and variety of use, articulation and joining procedures (Boswell 2013) (Fig. 8.2).

Within the design, productive and constructive scenario, the study considers the building envelope systems in relation to:

- the role of "transition" between internal spaces and external spaces, in an autonomous (morpho-typological) way towards the intended uses and in combination between performance contents (such as *useful skin*) and external aspects (such as *ornamental packaging skin*);
- the "integrated" constitution of components, characterized by "specialization" processes aimed at taking overall quality at different levels, in accordance with structural and connective, geometric and dimensional coordination procedures, to

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[1] The scientific framework of this subject is dealt within the training course: Nastri M, «I sistemi di involucro. Facciate continue» (Tecniche Nuove S.p.A., Training and Retraining Division). Website (online course): http://www.tecnichenuove.com/argomenti/edilizia-e-architettura/i-sistemi-di-involucro-facciate-continue-12030.html.

Fig. 8.1 Selective and "customized" use of "series solutions" and "prototype solutions", according to specific needs and products showing morphological neutrality. Building Design Partnership, Marks & Spencer Building, Manchester © Courtesy of Focchi S.p.A.

allow both the application to multiple construction types and mechanical assembly modes (Watts 2010) (Fig. 8.3).

In accordance with this approach, the study examines the composition of building envelope systems (complying with the use of planar, modular or "customized" elements) by:

- the use of morpho-typological "rules" through prefabricated components, where their connection modes determine both the expressive and executive correlation strategy (Gulinello 2010);

Fig. 8.2 Role of “transition”, in combination between performance contents and external aspects, and “integrated” constitution of components, characterized by “specialization” processes. Sidell Gibson Architects, One Snow Hill Building, Birmingham © Courtesy of Focchi S.p.A.

- the “construction poetry” finalized to define the semantic criteria of frames and envelopes in accordance with the expression of principles and modes of relationship between the pieces and the materials (Knaack et al. 2007).[2]

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[2] The design of building envelope systems, in relation to the references of morpho-typological and traditional connective composition, considers:

• the tendency of rationalization and “reinvention” of both components and technical interfaces, in an integrated way according to the variety of expressive possibilities;

• the hybridization of traditional materials, in order to legitimize the “solid” and “massive” presence, within the growing “virtuality” and the ephemeral, dynamic and “metamorphic” configuration of façade curtains (Schittich 2001, tr. it. 2003).

Fig. 8.3 Use of morpho-typological "rules" through prefabricated components and "construction poetry" finalized to define the semantic criteria of frames and envelopes. Goring and Straja Architects, Perseo District, Pero, Milan © Courtesy of AGC Glass Italia

8.2 Environmental, Functional and Integrated Design of Building Envelope Systems

The study of building envelope systems, within the *Material Balance Research*, is defined by the constitution of integrated functional components with the purpose of receiving, guiding and selecting environmental loads in order to achieve ergonomically "calibrated" conditions for internal spaces. The definition of building envelope systems considers the analogy with the concept of "machine-envelope" as a support and as an integrator of functional elements (Banham 1976, tr. it. 1980), expressed in formal, perceptual and performance terms: façade components are composed as "mechanical bodies", "active diaphragms" and membranes which foster or prevent heat, light, acoustic and aerial flow transfer with the external environment, playing a visual and energy adjustment role (Schittich 2001, tr. it. 2003). The examination focuses on the development of the *engineering performances* (in particular, intended as a combination of multiple "environmental performances"), of the *environmentally responsive walls* (which actively "react" to the environmental loads through the perceptual and "organic" contact with weather conditions), and of the *engineered walls* (intended as mechanical equipments) which regulate thermal, light and air flow transmission, together with the mitigation of wind and acoustic loads (Daniels 1994; Syed 2012). On this basis, the analysis considers:

- the specialization and combination of "passive" and "active" functioning procedures leading to "self-regulating" building envelope systems sensitive both to external weather changes and to the need for thermal and light, air and acoustic comfort in internal spaces (Wigginton and Harris 2002);
- the environmental and "adaptive" strategy aimed at developing building envelope systems according to their metabolic efficiency and "instinctive" reactive capacity, as *intelligent skins* with "automatic" performances (using functional "autonomous adjustment" criteria) and as membranes defined as *biological skins* (effective towards external agents, by activating some "sensors" and protective devices). The biological reference identifies, inside the regulatory systems (such as the *computerized management systems*, *BMS*) and their environmental integration, protection and shading possibilities, the "hypothalamic" function able to react to external and internal loads (Atkin 1988) (Fig. 8.4).

8.2.1 Study of Dynamic Interaction Procedures

The examination explains the building envelope systems considered as "organic" compounds, adaptable and adjustable as *biological skins* and as *multifunctional skins*, that is as absorbent, radiant, reflecting, filtering and transferring devices (of thermal, light and air flows; Romano 2011). In particular, the use of dynamic and "reactive" elements takes the form of solar radiation control surfaces consisting of filtering or shielding sections capable of adjusting their transparency according to the level and distribution of natural brightness required in the interiors. The design of systems exposes the "technorganic" qualities (Welsh 1994), by interpreting and assimilating the environmental conditions in combination with the use of advanced techniques (in *organitech* form; Jencks 1995). This way, the study includes the experimentation concerning "artificial" (or "organic") systems integrated with "natural" systems, such as storage and conveyance, protection and calibration of "passive energies" devices that can provide buildings with heating, conditioning and ventilation. In this scenario, the study investigates:

- the development of building envelope systems intended as "dynamic interfaces", that is as a mediating and interchanging structure between the environmental

Fig. 8.4 Specialization and combination of “passive” and “active” functioning procedures, environmental and “adaptive” strategy according to metabolic efficiency and “instinctive” reactive capacity of the intelligent skins. Studio 44, Federal Almazov Heart, Blood and Endocrinology Centre, Almazova Medical Centre, Saint Petersburg © Courtesy of Lilli Systems

loads and the needs of indoor spaces, with “evolutive plasticity” and “adaptive” properties to environmentally differentiated loads (Altomonte 2004);

- the experimentation of advanced building envelope systems in order to integrate the climate conditions and convey them to indoor spaces, according to established procedures and levels, and to build components in the form of “biomechanical prototypes” where different parts specialize in a specific function (Hausladen et al. 2008) (Fig. 8.5).

8.2.2 *Study of Functional and Energy Formulation Procedures*

The examination defines building envelope systems as a means of mediation and response to external loads, in conjunction with the calibration of energy properties and performances (according to a *selective approach*), with the contribution of technical design and the consistent application to settlement requirements (as *environmentally*

Fig. 8.5 Development of "dynamic interfaces" as storage and conveyance, protection and calibration of "passive energies" devices that can provide heating, conditioning and ventilation. Schneider + Schumacher, Braun AG Building, Kronberg, Frankfurt am Main © Schneider + Schumacher

conscious design activity).[3] The performances of building envelope systems are processed in relation to "single-layer" systems (as *single-skin façades*) and "multi-layer" systems (as *multiple-skin façades*), whereby the fitting of planar surfaces generates "greenhouse effect", "chimney effect" and natural ventilation devices (in the form of *double skin façades*; Oesterle et al. 2001) (Fig. 8.6).

Moreover, performances are based on thermal, chemical and surface treatments, on stratification and cladding treatments (acting on the transmission of visible, solar and thermal radiation, especially in relation to the spectral field of infrared), on

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[3] The study of façade elements focuses on the physicality of the combined and multi-layered surfaces, which the experimental research tends to transform into something "thick" and into an "interface of intelligent systems" (Altomonte 2004, p. 42). The main materials of external surfaces are composed in relation to their change processes from "stable entities" into "plannable entities" according to a particular "performance program" (ibid.). Their application is structured in relation to the outcomes of solutions where the functions tend to become "complex" (in "controlled" and "managed" ways) and articulated between them (in a *solid state* form).

Fig. 8.6 Examination of "multi-layer" systems in order to generate "greenhouse effect", "chimney effect" and natural ventilation devices in the form of double skin façades. Progetto CMR, Garibaldi Business Centre, Milan © Courtesy of Progetto CMR

coloring and deposition treatments in relation to the enclosure (Konis and Selkowitz 2017). In this scenario, the study investigates:

- the physical, material and performance contents of building envelope systems developed according to criteria of efficiency considering both energy and environmental conditions and ergonomic conditions through the reflection, collection and diffusion of external or internal loads. This is achieved by "passive" procedures, which are intended to accumulate and distribute the energy produced by solar radiation without the use of implantation equipment, or by "active" procedures, with the addition of technical devices (in the form of "collectors") aimed at integrating and conveying heat, natural light or convection in relation to air flows (Argiolas 2005; Aksamija 2013);
- the technologies related to building envelope components and devices able to activate the processes of "eco-efficient interaction" and "permeability" in relation to the thermo-hygrometric, light and air loads (by determining the energy and environmental control of "selective" and dynamic criteria), with the possibility of adjusting their flows and conveying them into overall functioning (Lovell 2010).

8.3 Permeable and Diaphragmatic Design of Building Envelope Systems

The study of building envelope systems examines the development of façade curtains in accordance with “dematerialization” and “interconnection” procedures, considering external, light-constitution surfaces, aimed at defining the relationships that support environmental and spatial interaction. The “dematerialization” procedures, which involve the application of “differences” of density and of “diaphragmatic porosity”, are part of the contemporary design, productive and constructive experimentation, which takes, as a field of research and poetic development, the criteria, exercises and paradigms of “fusion” between architecture and context. The study of building envelope systems examines, in particular:

- the application of vertical enclosures according to the environmental and spatial “dissolution” of “boundaries” (considering them as losing their meaning of border between that which is “contained” and “external” spaces). This is done through the “dematerialization” of façade and cladding components (open to spatial, perceptual and evocative flows), by means of “filters”, “diaphragms” and “mediated transparencies” (Premier 2012);
- the examination of physical and material characters of surfaces in relation to the “loss” of their tectonic consistency, expressing their permeability conditions, both functional and related to their use, and towards the random articulation inside the conceptual and visual steps.

The analysis focuses on the development of vertical enclosures which, in carrying out their purpose of enveloping and delimiting, are conceived as “revocable sheets”, such as “intangible” and “movable” elements, in order to generate the dialectical relationships between internal spaces and the external context, and to emphasize the interactive and “organic” logic of architecture. In particular, the enveloping apparatus shall be determined by means of differentiated or calibrated “densities”, according to the “cross-linking” principle by using “cuts”, pixels and openings, inscribed and interposed on the curtain wall (Fig. 8.7).

8.3.1 Study of Perceptual and Connective Articulation Procedures

The field of interest, which includes the management of symbiosis practices in an “incorporeal” and “intangible” way applied to the context, entrusting to the fluidity of perceptual instances and external membranes the “loss” of texture and the enhancement of the diaphanous character (according to the detection of morphological, functional and visual permeability), defines:

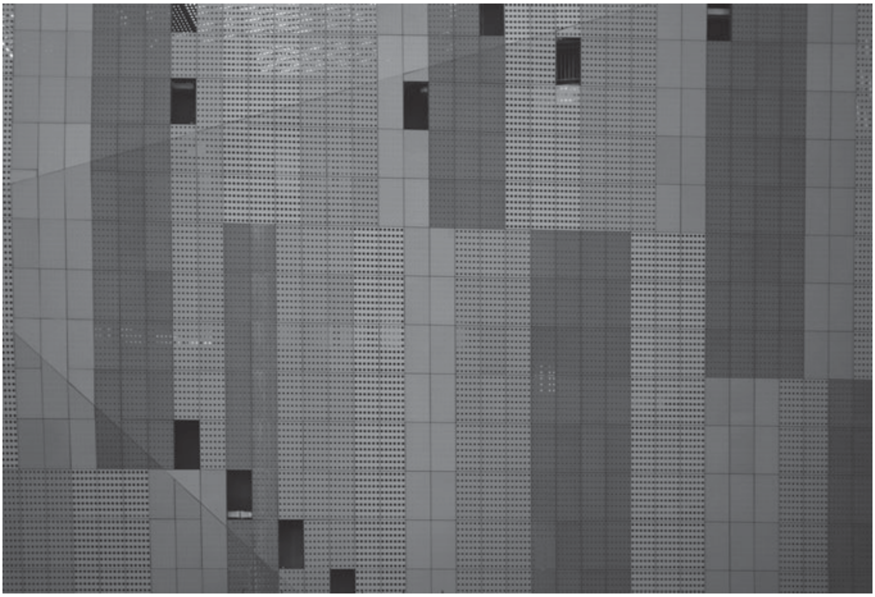

Fig. 8.7 “Dematerialization” and “interconnection” procedures with application of “differences” of density and of “diaphragmatic porosity”, according to the environmental and spatial “dissolution” to generate dialectical relationships between internal spaces and external context. Cino Zucchi Architetti + Park Associati, Salewa-Oberalp Headquarters, Bolzano © Courtesy of Park Associati

- the concept of “deformed” and “impalpable”, “metamorphic” and “unstable” surfaces, in relation to their properties of transparency, reflection and opacity (Prina 2008);
- the procedures of “organic deformation”, aimed at defining the façade curtains as “fabrics” that pierce space through their “porous” and “vibrant”, sensitive and interactive constitution, adaptable to the urban and “immaterial” context (Fortmeyer and Linn 2014) (Fig. 8.8).

Moreover, the analysis focuses on the composition of building envelope systems according to the ethereal constitution, such as a light and “impalpable”, “metamorphic” and “unstable” simulacrum (within environmental, interactive and perceptual variations) by differentiated or calibrated “porosities” defined by:

- the application of rules aimed at considering building envelope systems as an “overlapping landscape”, in a tension-sensitive relationship with the tectonics structures and the spaces. This is achieved by formulating a balance and a combined syntax between the specific characters of the context and the architecture (carried out as a “provisional” and “immersive” expression; Murray 2013);
- the work on the curtain wall according to the appropriate compositive and functional intents for the constitution of “diaphragmatic textures” (with the possibility

Fig. 8.8 Constitution of "deformed" and "impalpable", "metamorphic" and "unstable" surfaces, according to the procedures of "organic deformation" of the façade curtains adaptable to the urban and "immaterial" context. Cino Zucchi Architetti, U15 Building, Assago, Milan © Courtesy of Cino Zucchi Architetti

of grading and modulating the façades), in order to emphasize the "temporary" and ephemeral aspect including the "hypermedial perception" characters (by reference to languages aimed at interacting with the complex realm of sensoriality) (Fig. 8.9).

8.4 Complex and Optimized Morphology Surfaces Design

The study of building envelope systems examines the organization of two-dimensional and three-dimensional geometric structures in accordance with plastic, organic and kinematic morpho-genetic processes resulting both from "dynamic balance" levels and from constant fluctuations and mutations. The study is associated with the experimental design of *architectural compounds* where the combination of "tension" and "distortion" stimulation determines the spatial and volumetric configuration. This field of study considers the façade surfaces shaped as continuous

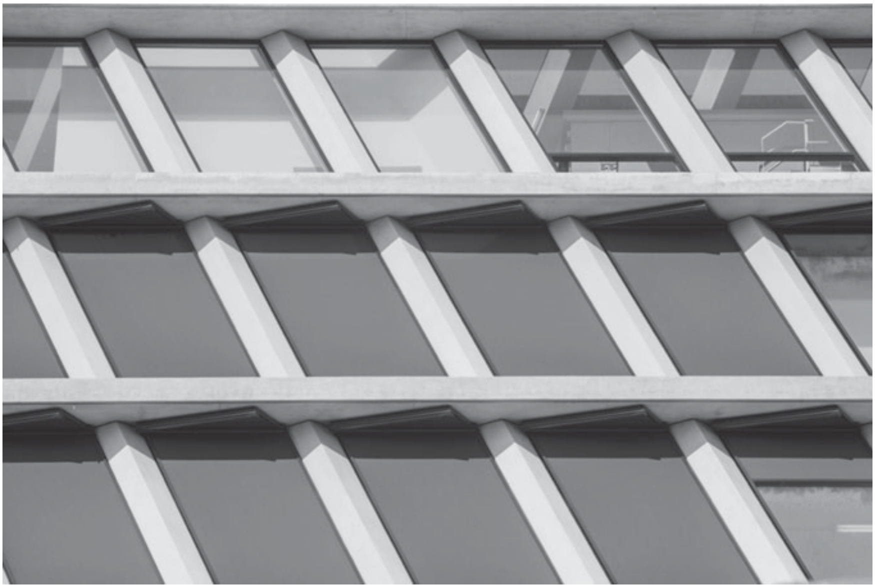

Fig. 8.9 Constitution as light and “impalpable”, “metamorphic” and “unstable” simulacrum by differentiated or calibrated “porosities”, as “provisional”, “immersive” and “diaphragmatic textures”. Jacques Herzog and Pierre de Meuron, Giangiacomo Feltrinelli Foundation, Milan © Courtesy of Resstende s.r.l.

“masses” or as intersections and transitions, according to “indeterminate” and relational forms (Block et al. 2015). Specifically, the study observes the composition of curtain walls (whereby the frames create the “sculptural” conception of the three-dimensional model, determining the rules of the “morphological configuration”) through:

- the generative tension aimed at destructuring the “multi-linear” morphologies (capable of incorporating multiple variations and directions) and producing the prospective distortions geared towards multiple focal and functional points;
- the kinematic, permeable and osmotic organization in relation to the environmental, urban and perceptual conditions, in order to allow a multi-directional integration with the context;
- the constitution of metaphorical, analogical and dynamic morphologies, defined by the transfiguration and articulation of *flows* and *networks*, the view of “force-fields” of urban and “intangible” spaces (where the surfaces achieve the “connection-transition” ratio between the built-up densities and the external, environmental and urban spaces; Nastri 2009) (Fig. 8.10).

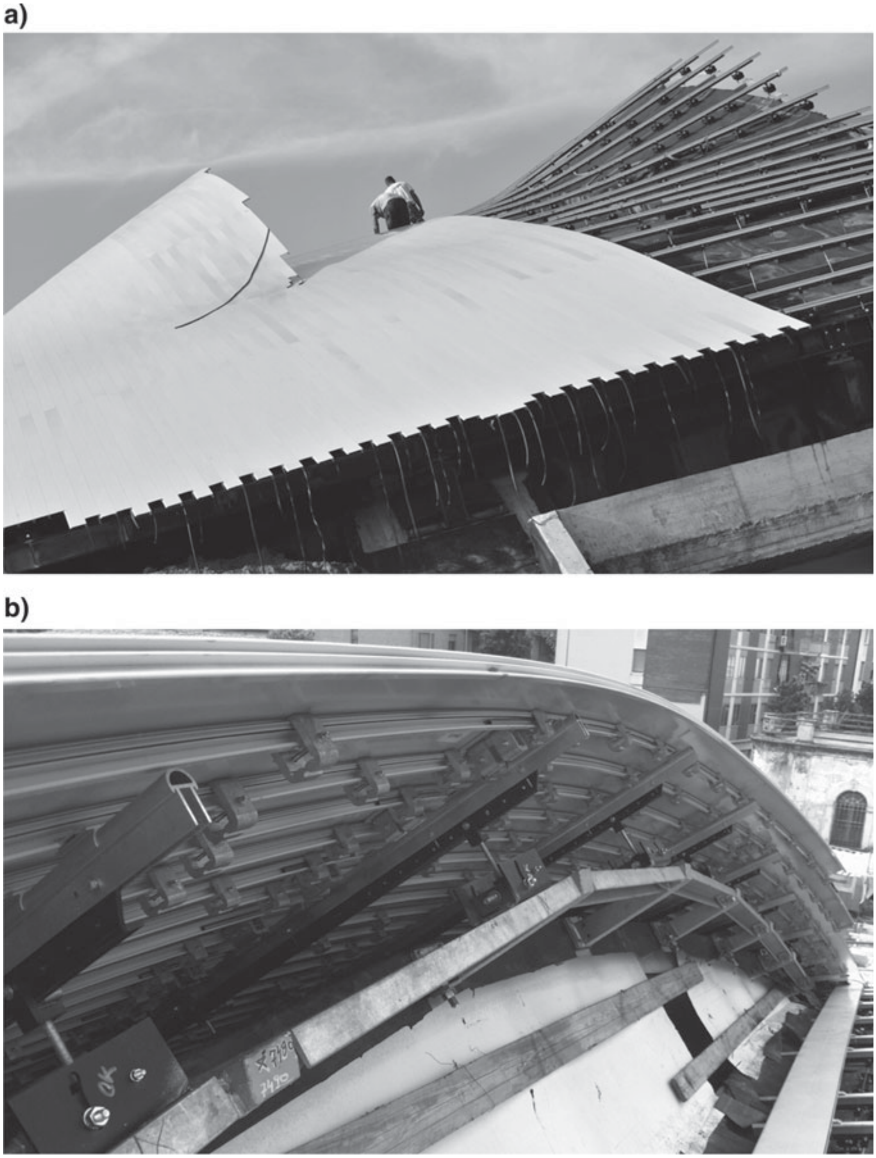

Fig. 8.10 Plastic, organic and kinematic morpho-genetic processes through the generative tension aimed at destructuring the “multi-linear” morphologies (**a**) in order to build the façade surfaces shaped as intersections and transitions (**b**). Future Systems and Andrea Morgante, Enzo Ferrari Museum, Modena © Courtesy of Cooperativa di Costruzioni di Modena

8.4.1 Study of Calibrated and Multi-dimensional Composition Procedures

The study of building envelope systems is part of the research regarding the application of *Automotive Manufacturing* procedures into the experimental design, production and construction scenario, aimed at the constitution of complex architectures defined by the overcoming of limits related to geometric, structural and connecting feasibility conditions. The study, using the operating methodologies acquired and transferred from the industrial sectors with the support of advanced technologies (such as automotive, aerospace and medical), in the expression of computational design practices, considers the cognitive and application guidelines for the implementation of multi-dimensional technical solutions, according to:

- the development of the three-dimensional digital configuration, the subsequent optimization related to the requirements and the physical printing (as *3D printing*), often reducing post-production and finishing phases;
- the geometric and physical, chemical and material calibration, determined in relation to the performances needed (by simulation and virtual modeling);
- the development of complex geometry integrated components, avoiding the critical issues caused by the combination of elements and joining devices according to traditional solutions (Naboni and Paoletti 2015) (Fig. 8.11).

8.4.2 Study of Topology Optimization Procedures

The study of advanced building envelope systems considers the experimental design, productive and constructive procedures aimed at the *topology optimization* processes focused on components and technical interfaces, according to:

- the method of shaping the geometric, structural and physical constitution in accordance with the desired performances in terms of strength (mainly mechanical) and material distribution related to the lowest possible weight, considering the feasibility constraints and thus complementing it with additive production practices (which can also foresee the extension of customized solutions into serial solutions; Bendsøe and Sigmund 2003);
- the method aimed at a “calculable” and “manipulable” constitution of components, the subsequent “empirical education” and “executive materialization” of data, through processes related to geometric, structural and parametric “calibration” of functions (as *shape-size-structural optimization* activities)[4] (Fig. 8.12).

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[4] The analysis concerns the contents of the lecture: Paoletti I, Nastri M, Adaptive Façades and Topology Optimization, Conference Façade 2018—Adaptive, COST TU1403, Adaptive Facades Network. Lucerne University of Applied Sciences and Arts (Lucerne, 27.11.2018). Published in Luible A, Gosztonyi S, Ed. (2018) Façade 2018—Adaptive, Proceedings of the COST TU1403 Adaptive Facades Network. Lucerne University of Applied Sciences and Arts, TU Delft Open, Delft, 2018, pp. 473–485.

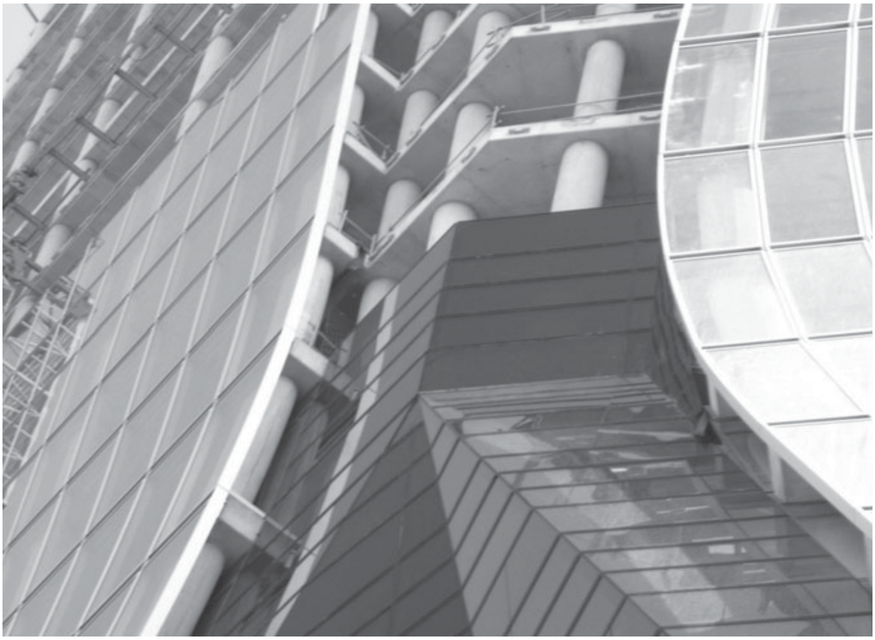

Fig. 8.11 Computational design practices of multi-dimensional technical solutions, with the development of complex geometry integrated components and joining devices. Zaha Hadid Architects, CMA-CGM Building, Marseille © Courtesy of Metalsigma Tunesi S.p.A.

8.5 "Mediatic" and "Communicative" Design of Building Envelope Systems

The study of building envelope systems is based on a part of contemporary architecture that displays, through its external skins, a desire of greater effectiveness in communication, establishing itself in a position of "discontinuity" compared to the urban context. The interactive façade design examines the composition of external surfaces considered as supports for information and as "irradiating macro-objects", as interactive choreographic tools at "infrastructural" scale (Gasparini 2009, 2012). The composition of building envelope systems is demonstrated by the acquisition of new visual and "virtual" potentials, which transcend material aspects and aim at the metamorphosis of curtains (which stand out as "bodywork" and "communicative devices") (Fig. 8.13).

Within this scenario, the composition of façades is determined both by the loss of prospective "stability" (along with the progressive "intangible" transformation of architecture) and by the emphasis on their constitution as "membranes" and "programmable surfaces". The combination of the expressive and performance possibilities, the processing methods and the morphological experiments supports the evolution of the compositive characters, according to:

Fig. 8.12 Topology optimization processes focused on components and technical interfaces, through shaping the geometric, structural and physical constitution in accordance with the desired performances and parametric “calibration” of functions. Massimiliano and Doriana Fuksas, Former Unione Militare Building, Rome © Gianni Basso; Courtesy of Stahlbau Pichler

- the constitution of scenographic and “catalyst mechanisms”, open to multiple expressive and functional solutions, such as “accumulators” of images and as urban “transmitters”, by assigning to the “decorative curtains” (already theorized by Robert Venturi) the function of communicative support (from internal spaces and context) and by exposing itself to the interactive perception at an “infrastructural” scale (Henket and Heynen 2002);
- the development of *conceptual installations*, through which the temporary, ephemeral and evocative content of the visual involvement is detected, where the surfaces take on the stimulations from the mediatic culture by asserting themselves as *media façades* (i.e. as a “mediatized façades”) or *hypersurfaces* (i.e. as media’s expressive potential supports; Haeusler 2009, 2010);
- the way of interaction and “fusion” between the architecture and the context, by developing surfaces with fluid and dynamic morphologies, where the façade curtains are examined in the form of “active membranes” in relation to the paradigms of “immediacy” (Haeusler et al. 2012) (Fig. 8.14).

The interactive design of building envelope systems concerns the “dematerialization” of “containers”, so that the surfaces are manifested as “mediatic skins”, as “sensors” capable of reporting the reality and information instances, according to:

- the contribution of digital processing, which allows to represent the “organic”, “dynamic” and “metamorphic” aspects of the “virtualization” of façade curtains;

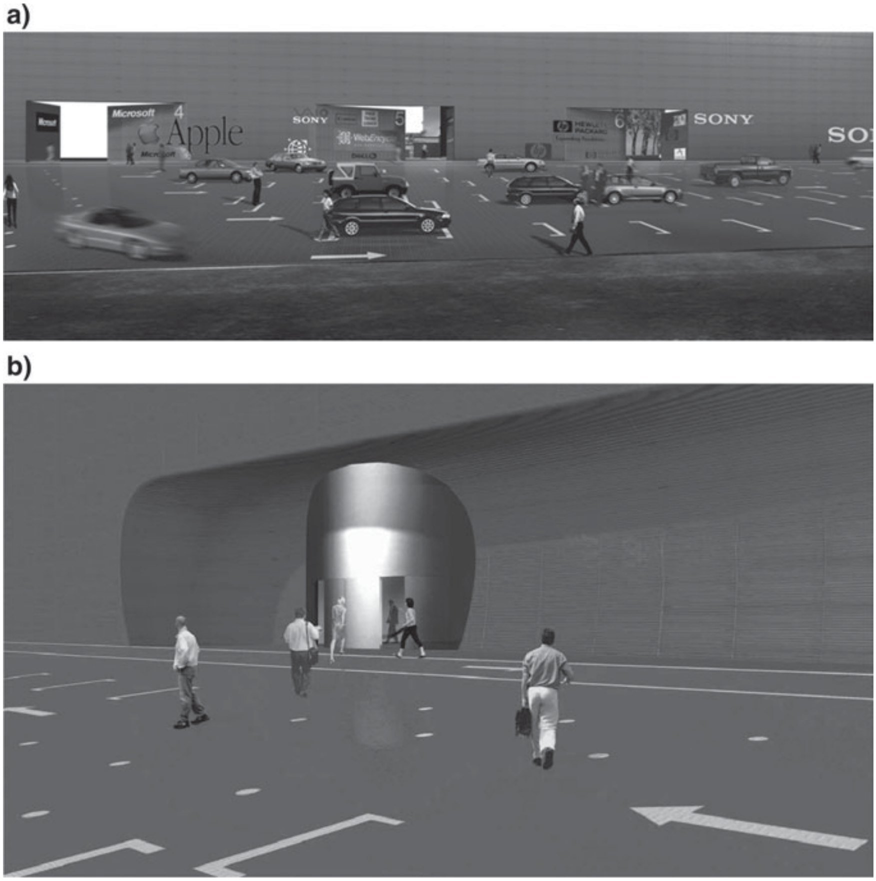

Fig. 8.13 Interactive façades as supports for information and as "irradiating macro-objects", characterized both by scenographic and "catalyst mechanisms" (**a**) and as conceptual installations or media façades (**b**). Atelier Jean Nouvel + Studio Blast, Kilometro Rosso, Scientific and Technological Park, Stezzano, Bergamo © Courtesy of Studio Blast

- the development of criteria of "hypermediate perception", aimed at intellectual, emotional and sensorial reactivity;
- the plastic tension of façade curtains brought to the extreme of its functions so that the closing "barriers" are exceeded by the inclusion and dilution of visual transitions (Moloney 2011).

Fig. 8.14 Interactive surfaces as "mediatic skins" according to the development of criteria of "hypermediate perception" and to the inclusion and dilution of visual transitions. Gianandrea Barreca and Giovanni La Varra, RCS Media Group Headquarters, "B5" Building, Milan © Courtesy of Focchi S.p.A.

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Chapter 9
Nature Reloaded. Microalgae as Future Landscape Ecology

Olga Beatrice Carcassi

Abstract Current design discourses incite the definition of a new ecology, which is the intercommunications among organisms and their environment (Haeckel Ernst 1866). At this regard, Microalgae are getting momentum due to their abilities to be used as a form of nutrient-rich food and other products, in the development of biofuels, as a way to reduce carbon dioxide and other greenhouse gases from the atmosphere, and as a method of treating industrial and urban wastewater. In fact, architectural applications using these microorganisms aim at reducing our impact on the planet by employing biology to solve some of the world's biggest problems. In these chapter we try to review and understand their needs as living systems and the possible utilization in urban contexts.

Keywords Microalgae · Landscape ecology · Bio-fabrication · Wastewater treatment · Bioplastic

9.1 Introduction Landscape Ecology

9.1.1 What Is Landscape Ecology

Humans have brought about unprecedented changes to environments worldwide (Wong and Candolin 2015). For many species, behavioural adjustments represent the first response to altered conditions. In an evolving anthropocentric perspective, where we are the protagonists of these alterations, the role of landscape ecology is to incite new symbiotic relationships between humans, technology and nature.

Modern cities are complex sets of social and economic interactions, public and private spaces and natural and artificial environments continually evolving. Hence, at a human scale the landscape ecology can be considered as a parameter that affects

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the interaction between living species and their urban environments. Through the proposition of spatial attributes and arrangements of landscape elements in the cities' ambience, we can act on climate conditions and the consequences created by the urbanization itself.

"*The way biological systems solve problems is pretty different from the way engineered systems solve problems*," says Peter Niewiarowski, biologist at the University of Akron and its Biomimicry Research and Innovation Center (Mortice 2016). Human technical solutions use more materials or energy to accelerate reactions, whereas natural processes instead lean on unique geometry and material properties. For this reason, our aim is to detect biological systems that are naturally disposed to take advantages of the current perturbed situation (e.g. high CO_2 emissions, temperature rise, water pollution, etc.) and "solve" these criticisms. By infusing sustainability concepts into human habits, designers, architects and engineers have thus the opportunity to guide these behavioural adjustments through the products and processes they conceived.

9.1.2 Nature Reloaded

But, what exactly are these sustainable concepts? By defining natural mechanisms that can be inserted in urban contexts as punctual, adaptable and scalable solutions, this chapter tries to analyse alternatives in current design paradigms where technology and the biosphere found new synergies in the translation of a contemporary ecology. This approach is here defined as "Nature Reloaded".

Nowadays, the technological innovations could serve these solutions integrating and supporting nature resources, and not in an exploitation logic. In fact, according to many researchers, the unique benefits of biological elements through the combination of the technical and biological cycles within cities' skins, inaugurate an innovative approach to sustainability by incorporating to their surfaces environmental, energetic, and social values (Elrayies 2018). Among these, examples exploiting photosynthetic living microorganisms, as microalgae, has been implemented in order to answer to these major issues.

9.2 Microalgae as Application of Landscape Ecology

By generating both small-scale and larger scale applications within a highly distributed network of algae production, these microorganisms can offer a complimentary urban system at multiple levels aiming at enhancing the habitability of cities while reconnecting them with natural systems. In order to operate this reconnection, it is essential to fully understand the microorganisms at issue, how they live and what they need to prosper and grow. Ergo, in the next paragraphs we try to explained both their biological characteristics and architectural potentials.

9.2.1 Microalgae

Microalgae are biological microorganisms able to capture carbon dioxide through photosynthesis. Their biomass have the ability to respond to future challenges in terms of availability, high growth and production rates, yield per unit area, not competing for arable land (Nasution et al. 2016) and being most suitable optimal sources for biofuels (Andersson et al. 2014; Shuba and Kifle 2018). In fact, the growth rate of microalgae is 5–10 times faster than conventional food crops (Zullaikah et al. 2019). Moreover, microalgae are able to produce more O_2 than plants can produce and are besides, directly responsible of almost the 50% of the photosynthesis on Earth (Sayre 2010). Together with the air purification, its biomass can also be used to prepare high quality food and for other multiple purposes, such as bioplastic and wastewater treatments. All of these characteristics make them quite interesting in this search towards the redefinition of the cities of tomorrow.

9.2.2 Main Species

Microalgae include a great variety of microorganisms. In fact, they are a large group composed of eukaryotic photoautotrophic protists and prokaryotic cyanobacteria (Correa et al. 2018). The word algae are referred to both macroalgae (multicellular algae) and a wide and various group of microorganism known as microalgae. The microalgae can be tiny, e.g. those of *Chlorella genus* with a diameter of 0.003 m, while some of the macroalgae can reach 100 m of length.

They account over 300,000 species out of which around 30,000 are documented (Mobin and Alam 2017). Only a small number of these varieties have been studied for possible beneficial use. They live in complex natural habitats and can adapt rapidly in extreme conditions (variable salinity, temperature, nutrients, UV–irradiation), such as in thermal and volcanic waters or in cold polar climates.

Typically, they grow suspended in a medium (usually water) and use photosynthesis from CO_2 and solar energy to produce sugars for their own metabolism and to release O_2, which partly is used in their respiration process, and partly is discharged in the medium in which they are inserted.

9.2.3 Elements for Microalgae Growth

The most important parameters regulating algal growth are: nutrient quantity and quality, light, pH, turbulence, salinity and temperature. However, temperature, light and carbon dioxide play a key role.

The carbon absorption can occur both naturally from atmospheric CO_2 or from the combustion fumes coming from other processes. Usually, to increase gas diffusion the

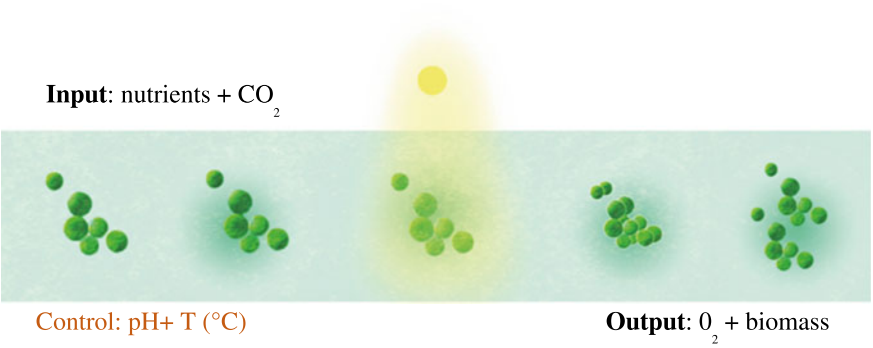

Fig. 9.1 Microalgae cultivation growth. By the author

cultivation systems are provided with a mixing structure (bubbling with air, paddle, etc.), either for prevent nutrient and light limitation effects. The light is therefore one of the assigning factor for algal cultures since photosynthesis only occurs if the cells get direct light radiations. Without a proper mixing, self-shading of phototrophic microorganisms and inhomogeneous illumination of PBRs cause heterogeneous light distributions, which subsequently induces the formation of heterogeneous cell populations. Moreover, the photosynthesis only occurs with the visible spectrum, with wavelength between 380 and 750 nm.

The temperature also regulates the microalgae growth and varies according to the species chosen. For the majority of species, the optimal value is between 20 and 30 °C, whereas for others the optimal value is 5 °C or even 70 °C.

For example, for the species Chlorella Vulgaris, the optimal temperature is around 25 °C, and from 1.8 kg of CO_2 can produce 1 kg of microalgae biomass.

If all these conditions are fulfilled, the microalgae grow through division (in average one time a day) doubling their biomass in a relatively short time (Fig. 9.1).

9.2.4 Cultivation Systems

In nature, microalgae can be found in the sea, in freshwater, in soil, on rocks, and even in snow. Whereas, a culture can be defined as an artificial environment in which the algae grow. Unlike terrestrial plants, they do not have a vascular system for the transport of nutrients and water, so they use a large external surface of exchange with the medium in which they are inserted. For instance, the medium is usually water but growth medium modifications with other gels have been tested (e.g. by encapsulating them within gel-based biomaterial such as hydrogel) (Estime et al. 2017).

In classical water systems, they can be cultivated in two different ways, namely in open pond systems (outdoor) and in closed ones (indoor), named photobioreactors (PBRs). The PBR is an engineered device able to provide an environment suitable to the spatially confined growth of biological organisms that can vary in size and shape. The outdoor systems exploit direct solar radiation and are less expensive than PBRs. For this reason, most of the algal cultivation is made in open ponds, even if technology potentials of the closed ones are higher in terms of productivity and controlled conditions of the cultivation solution. Diversely, the main PBR issues consist in the initial costs and in the design of the whole system (cultivation broth circulation and harvesting process). Indeed, by lowering the PBR cost, without affecting their performances, it will be possible to foster their diffuse distribution at a global scale. In fact, to meet the growing interest on microalgae renewable biomass, it is crucial to increase their production. However, obtaining energy efficient cultivation and harvesting technologies are necessary steps to improve their economic viability (Estime et al. 2017).

9.2.5 Products from Biomass

As a first consideration, it should be noted that biomass cannot be directly converted into final products within the production sites, tanks or photobioreactor. From the biomass obtained during the cultivation phase it is possible to obtain various types of products depending on the processes to which it is subjected. Moreover, each microalgae species has different contents of proteins, carbohydrates and lipids (Sen and Pal 2015). According to the final desired product, a species can be more suited in comparison to another due to its chemical composition.

The enormous variety of microalgae composition involve many areas of application with a high market potential in different sectors, such as: biofuel, food industry, pharmaceuticals, nutraceuticals, animal and fish feed, cosmetics, algae in pollution control and bioplastics. One of the way for reducing the cost is to derive multiple products in a single cycle (Biorefinery concept) (Bhalamurugan et al. 2018), so forth as nature where every element is seen as part of a bigger loop.

9.2.6 Wastewater Treatment

Another appealing micro-algae application is their performance as biological wastewater treatment. In the light of the population growth (United Nations Population Division 2019) leading to increased resource (water, food, chemicals and energy) demand, there is a growing awareness that the means that could be potentially recovered from used streams or wastes represent economic value and should not be lost. In wastewater-treatment facilities, microalgae can be used to clean and purify water (Shuba and Kifle 2018). Photosynthetic algae use CO_2 and nutrients ($NH4^+$, $NO3^-$ and PO_4^{3-}) for their growth, while producing oxygen. Indeed, these nutrients can be found in urban and industrial water as waste from their processes. Through the bioremediation of these waters, nutrients such as inorganic N and P to sustain growth as well as heavy metals and toxic compounds, are recovered in the form of biomass that can be used as a resource in other production cycles (Benedetti et al. 2018).

9.3 Microalgae in Architecture

The architectural examples found in literature, can be divided as medium-large scale, meaning building or urban scale, and as small scale, such as artifacts and everyday objects.

9.3.1 Medium-Large Scale Applications

The architectural examples at a medium-large scale focus on 3 objectives:

1. urban prototype for future garden focusing of the air purification and their potentials in food and energy production;
2. urban prototype focusing on their wastewater treatment potential;
3. façade panels integrated in the building systems.

The first group include PBRs installations as bio-digital gardening prototypes, where the urban space represents the synthesis of air purifier together with renewable energy and nutrients production for human needs, e.g. STRUNA by Politecnico of Milan (Paoletti 2019) (Fig. 9.2), H.O.R.T.U.S by ecoLogisStudio (2016) and the Algae Dome of Space 10 for IKEA (SPACE10 2019).

For the second group, the Bio-Integrated Design Lab at London's Bartlett School of Architecture (Parker et al. 2019) proposed a modular wall formed with tiles containing microalgae for clean water polluted with toxic dyes and heavy metals. Through the bioremediation phenomenon, these microorganisms remove pollutants from the water passing on it. By combining ceramic tiles and their potential of absorbing water with microalgae and a seaweed-based hydrogel, this wall can help in treat the contaminated water and make them run off clean and usable.

Thirdly, there are the PBRs as facade panels connected with the heating and wastewater systems of buildings. These are particularly interesting considering the improvement of the energy performance together with the active role attributed to building surfaces. By applying PBRs on building facades, they become bio-reactive facades exploiting microalgae as an energy source, making use of waste carbon and nutrients coming from local sewages and generating solar thermal energy in the process. Thus, the benefits of such an integration are:

- O_2 realising
- carbon dioxide sequestration
- cogeneration of heat and biomass with wastewater treatment

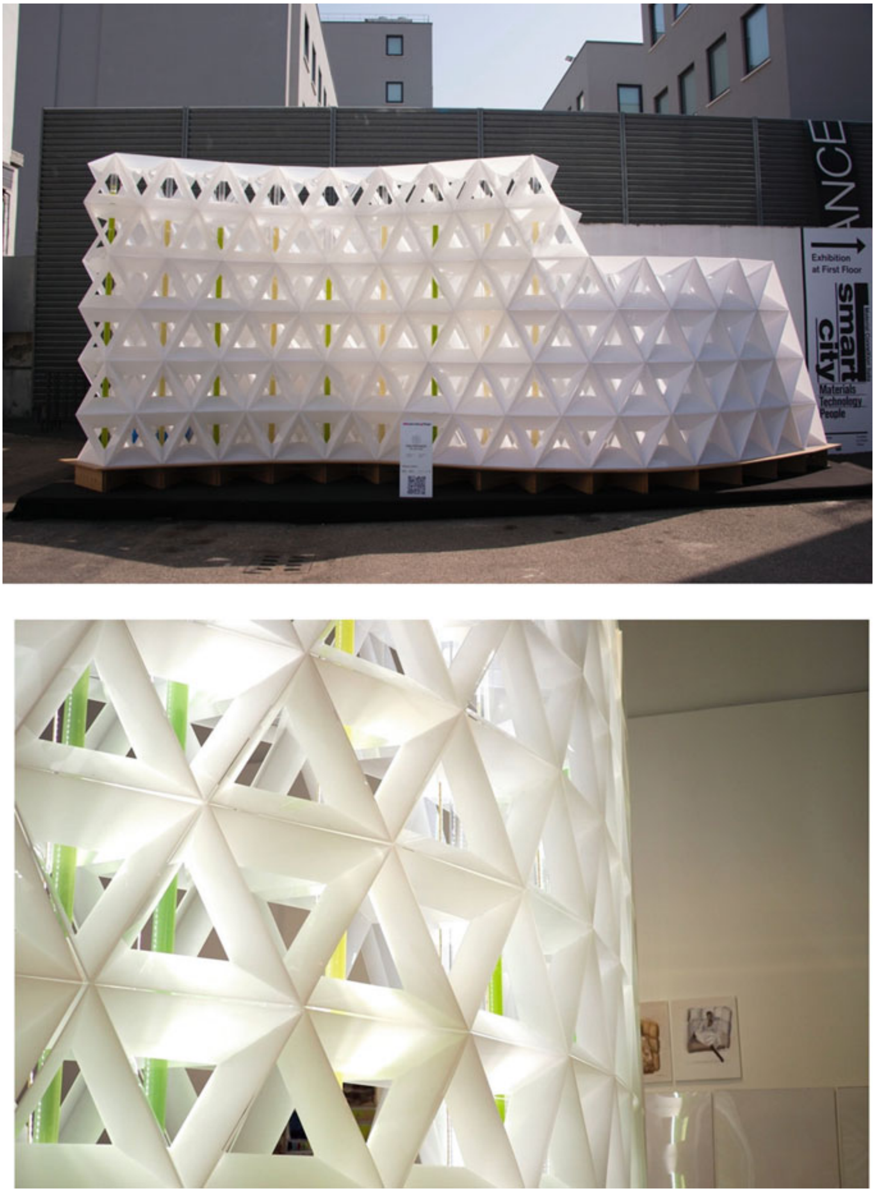

Fig. 9.2 SAPERLab by Politecnico of Milano (2018). STRUNA, Milan "La Triennale" exhibition "999. A collection of questions about contemporary living". Outdoor location (top). Indoor location (bottom)

- dynamic shading
- thermal and acoustic isolation.

Nowadays, the BIQ house in Hamburg, built by ARUP and a mixed group of architects and biologists, is the first and only existing and inhabited algae-powered building in the world. Despite the holistic energy and social concept, the inclusion of PBR façades alone doesn't make the building completely self-sufficient in terms of the energy needs, not justifying the high cost investment (BIQ is a 5 stores residential building that cost approximately € 5 million) (Elrayies 2018).

9.3.2 Small Scale Applications

At a small scale, in literature there are more than one objects combining light systems with photobioreactors, e.g. Bionic Chandelier (Julian Melchiorri 2017) or as device that can provide microalgae food as *Spirulina* directly in our home, e.g. Spitugrow (Bentur Srl 2017).

Furthermore, recent studies showed that the microalgae biomass is a well proven environmentally friend material. Once extracted fats and proteins, the microalgae biomass can be processed into high efficiency recyclable bioplastic that can be also used to 3D print objects. Some of these examples can be found in the works produced by Atelier Luma (2019). Here, the microalgae are mixed with biopolymers to produce a fully bio-based material proposing a new model for circular production through biofabrication that hopefully in the future will be able to substitute fossil-fuels plastic. Unfortunately, at the bioplastic stage the microalgae are dead, hence they cannot perform photosynthesis and capture CO_2. However, in other research fields, such as bioengineering, researchers are developing microalgae bio-printing technology in order to fabricate a biological tissue through the layering of living cells (Karoly et al. 2013).

9.4 Conclusion

Microalgae is outstanding among all the types of biomass sources in its ability to respond to the challenges of the future in terms of availability, high growth and production rates, yield per unit area, not competing for arable land, being most suitable optimal sources for both liquid and gaseous biofuels and valuable co-products within biorefineries. The high production cost of microalgae makes them currently an uncompetitive feed option, but the situation may change in the near future (Lamminen et al. 2019). Looking at all of these examples and considering the need of lowering the expenses without jeopardizing the efficiency, both cost and production could be optimize in a logic of mass production of microalgae cultivation systems at an urban scale (Bogias 2014).

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Chapter 10
Towards an Advanced Acoustic Ecology

Andrea Giglio

Abstract In the seventies, M.J. Schafer identified the first industrial revolution as a watershed that altered not only the soundscape (from lo-fi soundscape to hi-fi soundscape) but also the way it is perceived. The outcomes of this above-mentioned first industrial revolution created new sound conditions characterized by a continuous overlap that have affected the human being's perception with negative effects on it, overturning what William Gaver defined "everyday sounds" (Schafer 1977). Forty-two years later we are experiencing the fourth industrial revolution that is affecting also the construction world (Schwab 2017). Robotics, artificial intelligence, nanotechnology, biotechnology, IoT, bespoke materials etc. are increasingly embedded within the new design approaches for the construction of sustainable architectures. Scientific speculation on this topic is such that we no longer speak of digital but of post-digital architecture. A phase in which the direct link between the digital and material (from bits to atoms) has shifted to the new relationship to neural system of the human being (from bits to neurons) (Carpo 2018). This new paradigm affects the way "objects" are designed and their way to influence modern soundscape. Base on this cultural background, the chapter intends to point out the framework of the research line "Advanced Acoustic ecology" developed on the base of a new approach of acoustic design: sound driven design.

Keywords Soundscape ecology · Architectural acoustics · Computational design · 4th Industrial revolution

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10.1 Introduction

Humans' activities are leading to some intense techno-scientific transformations that have endangered the balance of the earth. If no remedy is found, the ecological disequilibrium this has been generated will ultimately threaten the continuation of life on Earth.

Only in the last decades, the solutions to the most known dangers that threaten the natural environment of our societies have been based on an ethic-political articulation. This, that Felix Guattari defines *ecosophy* (philosophy of ecology), tackles these issues from a purely technocratic perspective taking in account "three ecological registers: the environment, social relations and human subjectivity" (Guattari 2008).

The environment has a key role in the definition of social relations and in the way human can modify its subjective perception. Therefore, as architects, we have the responsibility to provide environmental and spatial conditions able to guarantee micro-climatic comfort and functionality.

Temperature, pressure and humidity become "bricks" for a new architectural discipline that influence the use of "traditional" building elements in order to design spaces as atmospheres (Fig. 10.1), as "voids where we live, hollows in which our body will be able to work and love". As Rham 2018 pointed out in his works.

Among these elements, sound also plays a fundamental role. Research studies have shown that in the long run, bad acoustic conditions can have negative effects on the users, causing physical diseases (Stewart et al. 2011). Moreover, these physical diseases will also influence the perception of the space, determining an alteration of the judgment of its aesthetic qualities. Architectural acoustics allows us to make a series of choices to control these soundscape conditions considering the sound sources and the "objects" placed in the space.

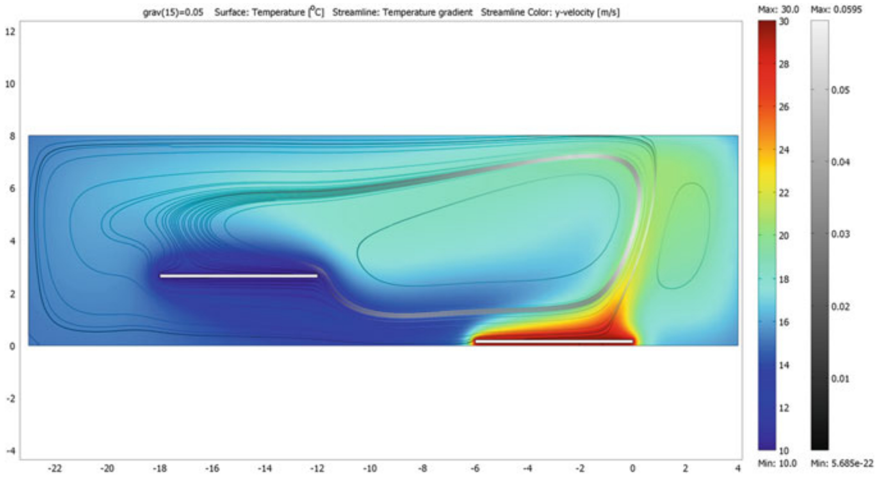


Fig. 10.1 2008_Digestible gulf stream, 11. Biennale di Architettura. Philippe Rham architectes

Nowadays the potentialities of computational thinking and the innovations in materials and technologies are leading towards more performance driven design processes aiming at improving and adapting the environmental comfort of spaces according to the users' needs. How are these processes affecting the architectural acoustic?

The aim of this chapter is to define a framework, which is based on the theoretical background of the research line on architectural acoustics developed at Department Architecture, Built Environment and Construction Engineering of Polytechnic of Milan. The above-mentioned research line intends to focus on how emergent groundbreaking design processes can affect acoustics.

10.2 Acoustic Ecology

The acoustic ecology, also known as soundscape ecology, is a discipline studying the relationship, mediated through sound, between human beings and the environment (Wrightson 2014).

The philosophy underpinning acoustic ecology is profound: its author R. Murray Schafer, a musician, composer and former professor of Communication Studies at Simon Fraser University (SFU) in Burnaby, Canada, identifies the acoustic environment as "macrocosmic musical composition" and furthermore, he states that we bear responsibility for its composition (Schafer 1977).

This idea was so revolutionary that influenced also the music production: John Cage's music compositions was made from everyday world sounds in order to evoke an experience of musical listening to nonmusical sounds (Cage 1961).

What are the "notes" of this composition?

10.2.1 The Balance of Soundscape Before the Industrial Revolution

The sonic and acoustic environment is the sound coming from all sources that we are able to hear in that environment. They can characterize a space and include:

- biophonic sounds produced from animals;
- geophonic sounds of physical environment such as wind;
- anthropogenic sounds such as speech, motorised traffic, machines or music.

In combination, sound pressure, frequency, time and context, all define the so-called soundscapes, which can be understood as mixes of biophonies, geophones and anthrophonies. As context, the soundscape is also defined from the "objects" placed in that space that can become indirect sound sources thanks to the phenomena of reflection, diffusion or diffraction. The direct and indirect sound sources compose the everyday sound.

An ecological approach allows to define a framework to analyse and categorize the everyday sound (Gaver 1993). This framework encompasses the perceptual attributes and dimensions that characterize the auditory perception of the event listening rather than simply considering the perception of sounds. It means that we analyse the sound phenomena creating a relationship between sound hearing and the environment (different from music listening in which the perceptual dimension is related only to the sound itself). This approach leaded to the creation of three levels-map based on sound-producing events (Fig. 10.2). The first level refers to classes of materials and those interactions that can make them sound. The second level divides the sound-producing events in three categories: those ones involving vibrating solids, aerodynamics and liquids. The third and basic level of sound-producing events defines the simple interactions that can bring solids, gasses and liquids to sound.

R. Murray Schafer's research went in the direction of representing the sound conditions as well. He created a basic 'level of sound versus time' diagram charting the more prominent sonic features of the soundscape over a twelve-month period (Fig. 10.3). Thanks to this chart he was able to identify the contrast between pre-industrial and post-industrial acoustic environments (first industrial revolution). Moreover, he was able to note the level of natural environmental sounds—such as weather and animals—varied in repeating cycles.

Both methods revealed so many limitations in terms of reproduction of reality that Gaver himself admits that this approach is far to be complete, even if he created a hybrid event to study the combination of the previous levels. One of the reasons is that this map does not enable the description of more complex events.

From those experiences to our ages, several researches have tried to bridge this gap thanks the opportunities offered by the advancement of science and technology.

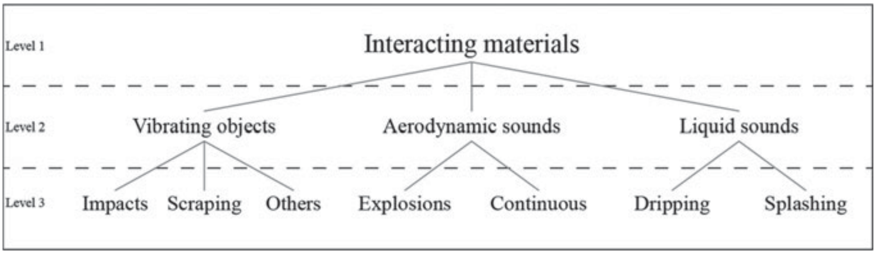


Fig. 10.2 A hierarchical description of simple sonic events (Gaver 1993)

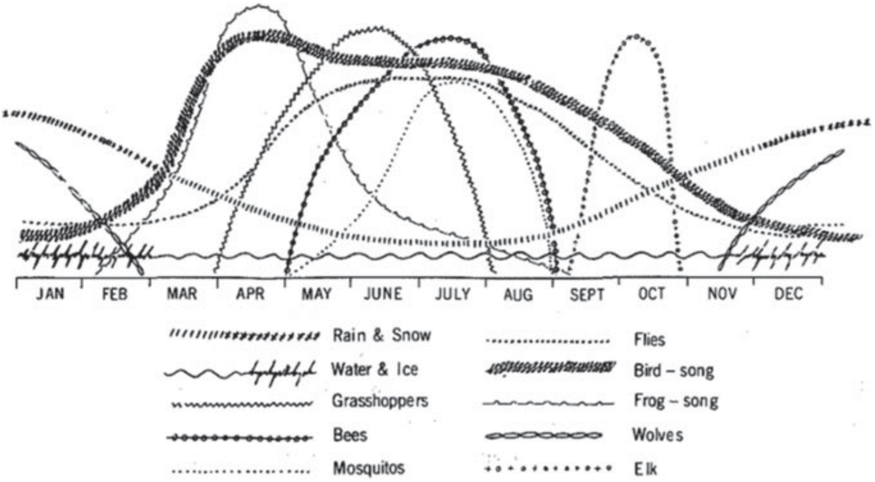


Fig. 10.3 Annual cycles of the natural soundscape of the west coast of British Columbia by relative volume of sound (no scale). (R. Murray 1978)

10.2.2 Seeing the Unseen

Today thanks to computational knowledge, we have the tools to handle this complexity and Gaver's ecological approach can find an updated continuity in the research of prof. Alma Farina. He demonstrates how advanced technologies, such as passive recording, facilitate the accumulation of huge amounts of acoustical data (Farina and Gage 2017). Moreover, he developed a software:

- To assess the biodiversity based on sounds emanating from a variety of environments.
- To investigate environmental sounds implications impact on climate change and urban systems.
- To assess the relationship between landscape ecology and Ecoacoustics.

In addition to the rhythmic balance in sound level that Schafer identified in natural habitats, Krause suggested an equilibrium is also apparent across the audio spectrum (Krause 1993). Both of them observed that while the hi-fi soundscape is balanced in terms of level, spectra and rhythm, the lo-fi soundscape features an almost constant level.

Acoustical spectrographic maps transcribed from 2500 h of recordings confirmed his suspicions: animal and insect vocalisations tended to occupy small bands of frequencies leaving "spectral" (bands of little or no energy) into which the vocalisations of other animals, birds or insects can fit. After the several industrial revolutions, this equilibrium is still broken. The spectrogram developed for the exhibition "The animal orchestra" by Bernie Krause at the XXI Triennale well represents this concept through a spectrogram (the spectrum of frequencies of a signal as it varies with time).

Fig. 10.4 The Great Animal Orchestra, Bernie Krause and United visual artist. 2016

Beginning by recording the sound of wheat growing in a Kansas field, Bernie Krause has spent the last 40 years recording ecological soundscapes and the sounds of over 15,000 species. Due to human actions, half of the wild soundscapes he has on tape no longer exist (Krause 2012).

The Great Animal Orchestra is a three-dimensional installation that allows listening to sound and visualizing soundscapes simultaneously (Fig. 10.4). The movie sequence explains how biodiversity has dramatically deteriorated the equilibrium and the conditions that characterized the pre-industrial revolution condition.

His meditative work explains the necessity of preserving the beauty of the animal world from the sound conditions caused by humans' activities.

10.3 The Acoustic Ecology in 4th Industrial Revolution

The coming of Walkman invention of 1979 can be considered as a revolution of the paradigm of soundscape environment's perception. The idea to be part of a collective soundscape that builds a "community sense" in which each of us is not just a passive listener of the sonic condition but someone that can become a sound source is broken. Each person creates its own sound "bubble" isolating itself from what happens around. Mainly we can say that each person can choose the specific sound condition (often music) to experience the daily life.

The Walkman is the outcome of a technologic culture, daughter of the innovations of the industrial revolutions that allowed to decrease the dimensions of the old stereo in a light, transportable device and to listen to music wherever.

Scaling down the matter, it is an example of the effect of technology on the development of an advanced soundscape ecology.

The industrial revolution has affected the conception of products design processes and manufacturing. Today computational thinking and advanced digital fabrication assume an important role in the definition of performative architecture that push the concept of sustainability and integration in the natural environment.

However, the outcome of these processes is not always considered safe for the living systems on the hearth. The idea to optimize time and cost leads the designer to forget to bear in mind the relationship between the product and the environment. This is the weight of architecture. Each object placed in a space will affect that specific soundscape and, in this way, the perception of it. In the last years, it has become relevant to control this parameter in order to improve the micro-climatic conditions for humans; several researches demonstrated that we should take care also to the consequences on other living systems as we show in the following paragraph.

10.3.1 The Effect of the Sound Produced by Humans' Activities

In 2012, Jesse Barber, a professor at Boise State University found a method to measure traffic noise effect on creatures other than humans.

Together with a group of researchers, he mounted fifteen pairs of bullhorn-like loudspeakers on the trunks of Douglas-fir trees in a wilderness area where no real road had ever existed. During the autumn bird migration, they played the traffic recordings that they had previously collected on Going-to-the-Sun Road, in Glacier National Park.

The recorded sound wasn't deafening by any measure, but its effect on migrating birds was immediate. During periods when the speakers were switched on, the number of birds declined, on average, by twenty-eight per cent, and several species fled from the area entirely. Notwithstanding this, some of the biggest impacts were on the species that stayed. For instance, the sound conditions did not affect the number of warblers but their weight. In fact, when the researchers weighed them, they found that they were no longer getting fatter as they should have been, since fat fuels their migration (McClure et al. 2013).

A dozen years before the phantom-road experiment, a group of American researchers performed a similar study underwater.

Peter Tyack, an American behavioural ecologist of the Bay of Fundy, researcher at the Woods Hole Oceanographic Institution, in Cape Cod, explained that sound can harm marine creatures both directly, by physically injuring them, and indirectly, by interfering with their feeding, their mating, and their communication. He measured concentrations of stress-related hormone metabolites in the faeces of whales in the Bay of Fundy. In mid-September 2001, the metabolite concentrations fell; while in the following season, they had gone back up. The scientists had been using hydrophones to monitor underwater sound levels in the bay, and they realized that the drop-in stress had coincided exactly with an equally sudden decline in human-generated underwater noise. The cause was the temporary pause in the ocean shipping which followed 9/11.

His researches demonstrate that the human's vision-based knowledge of reality is not the same for the other living creatures. Underwater, the seismic air guns, used to search for undersea deposits of oil and natural gas, are the loudest human sounds in the oceans. This noise pollution can also interfere with mating calls, thereby reducing the reproductive success of many species, including ones that have already been hunted virtually to nonexistence (Southall et al. 2019).

Sound conditions, with others environmental stimuli, such as temperature, light, wind can have negative or positive effects on plant growth.

Chowdhury et al. (2014) demonstrates that sound waves with specific frequencies and intensities have significant effects on a variety of biological, biochemical, and physiological activities including gene expression in plants. However, sound waves with high frequency and intensity can be harmful to the proper growth and development of plants.

Moreover, of course, they can be harmful for humans too.

Arline Bronzaft, professor of environmental psychology at City University of New York, demonstrated the effect of noise conditions of humans' activities and on public health. For example, she investigated the effect of passing trains on the classrooms of a school in Inwood, near to the northern tip of Manhattan.

On those classrooms in the side of the building, facing the tracks, decibel readings raised up to rock-concert levels for roughly thirty seconds every four and a half minutes. During those periods, teachers had to either stop teaching or shout; then, once a train had passed, they had to regain their students' attention. Bronzaft obtained three years' worth of reading-test scores from the school's principal. The results lead her to the conclusion that the sixth graders on the trackside of the building had fallen about eleven months behind those on the quieter side.

She was able to show that those measures had been effective and that the gap in test scores between students on the exposed and less exposed sides of the building had disappeared thanks the using of resilient rubber pads (Bronzaft 1981).

Moreover, this last research underlines how the elements placed in a specific space can play an significant role in the controlling of the sound conditions.

10.3.2 From Sound to Form

At the Defcon security conference in Las Vegas, Matt Wixey, cybersecurity research lead at the technology consulting firm PWC UK, stated that it's surprisingly easy to write custom malware that can induce all sorts of embedded speakers (laptop, a smartphone, a Bluetooth speaker, a small speaker, a pair of over-ear headphones etc.) to emit inaudible frequencies at high intensity, or blast out audible sounds at high volume.

Those aural barrages can potentially harm human hearing, cause tinnitus, or even have possible psychological effects. The situation is so undesirable that the acoustic academic research community has increasingly been warning about the issue (Leighton 2018).

This experience confirms the key role of sources in the definition of a new soundscape ecology, which deals with the geometrical and material conditions as well.

This is clearer in performative field. The new electronic technologies push towards the birth of innovative artistic languages that include sound manipulation. From silence to noise, from phoneme to instruments, to the infinite possibilities of technical reproduction, over the years, artistic speculation had played with sound, contaminating cinema, art, choreography, literature, publishing and mass media (De Sanctis Mangelli and Pedace 2019).

The sound sources differ from the traditional physical representation such as common speakers, rather becoming the effect of combination of several elements like cables or inter spaces: 3 dimensional spaces turn into sound sources of a new immersive sonic experience.

In this direction, the work of Bernhard Leitner is interesting to analyse. In his work, technology is controlled so much in detail that the sounds are conceived as constructive material, as architectural elements that allow a space to emerge. Sounds move with various speeds through a space, they rise and fall, resonate back and forth, and bridge dynamic, constantly changing spatial bodies within the static limits of the architectural framework. The idiosyncratic spaces that emerge cannot visually be fixed and are impossible to survey from the outside, audible spaces that can be felt with the entire body.

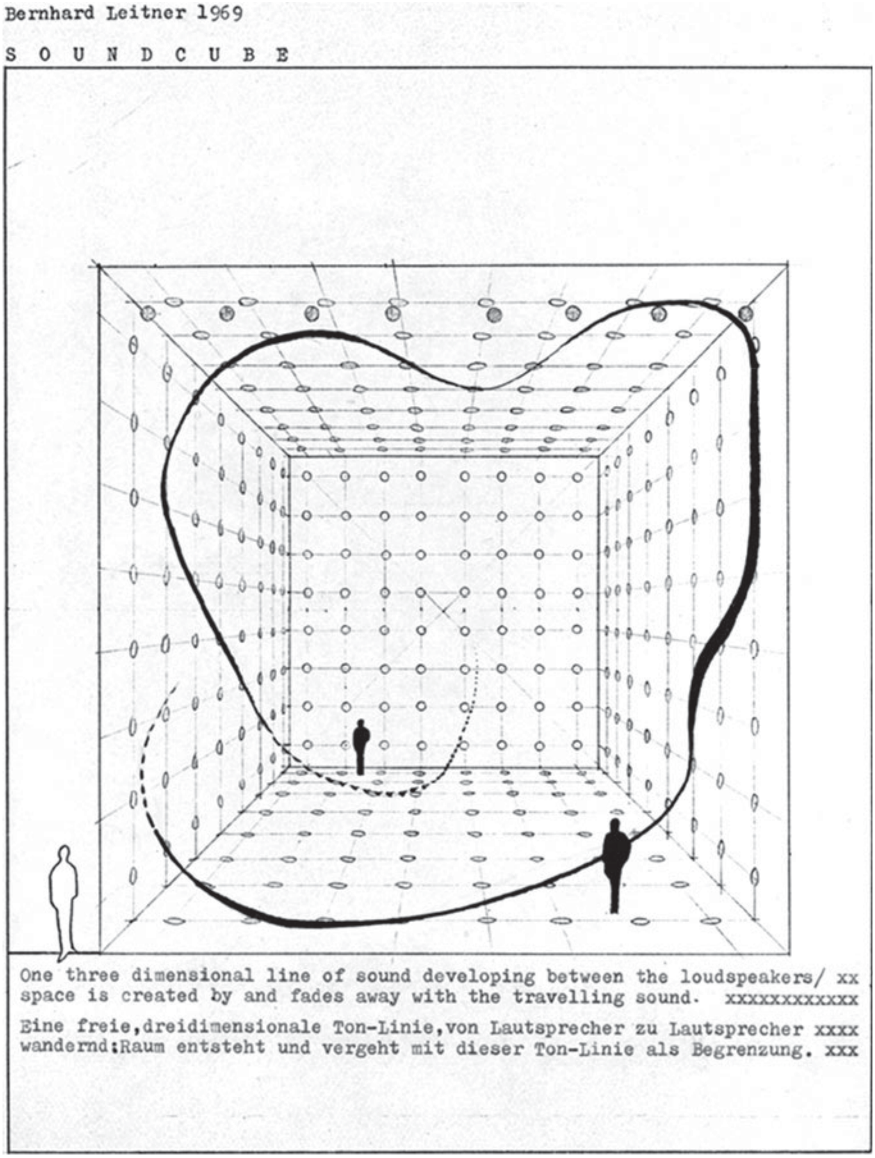
Leitner's works are an example of how the combination of controlled sound sources and architectural settings enables designers to achieve very specific sound conditions (Fig. 10.5).

10.4 Advanced Acoustic Ecology and Sound Driven Design

Nowadays the progresses in computational advanced tools can provide architects and designers the instruments needed in order to increase their awareness regarding the choices of their design and to improve their control of the consequences in a real environmental context.

As we have seen in this chapter, the soundscape can be controlled in several ways, starting from sound sources to the "objects" placed in the space. The relationship between human and acoustic conditions is a consequence of controlled and more aware design processes and not just a random addition of elements. To get to this, a shift in the design approach is required. An approach that recognizes the sound as a fundamental parameter to provide high micro—climatic conditions (with light, temperature, wind, humidity) not just for human beings, but also for the other living systems, like flora and fauna. An approach that we can call *sound driven design* .

This approach can affect several aspects of the design process:



One three dimensional line of sound developing between the loudspeakers/ xx space is created by and fades away with the travelling sound. xxxxxxxxxxxx

Eine freie,dreidimensionale Ton-Linie,von Lautsprecher zu Lautsprecher xxxx wandernd:Raum entsteht und vergeht mit dieser Ton-Linie als Begrenzung. xxx

Fig. 10.5 Soundcube. Bernhard Leitner. 1969

- **Advanced simulation tools**: Currently, in acoustic design as well, a huge amount of information has to be handled in order to achieve more performative outcomes to satisfy comfort needs. This process requires a methodological instrument to structure the design problem and to develop a heuristic mechanism for the acquisition of broad rules to handle the specific solution needed.

Today, digital tools handle large complex problems evolving from generative into intuitive tools such as Artificial Intelligence (AI). AI, through deep learning, discovers intricate structure in large data sets, by using the back propagation algorithm, to indicate machine's way to change its internal parameters thus helping to develop unpredictable innovative solutions (Giglio and Paoletti 2019).

- **Knowledge in sustainable material system**: According to the definition of sustainability of the Brundtland Report (UN. General Assembly (42nd sess. : 1987–1988) 1988), "Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs". A material can therefore be considered sustainable if its production enables the resources from which it was made to continue to be available for future generations, has the lowest possible impact on human health and on the environment and reducing energy consumption. Many currently used acoustic materials go in the opposite direction in terms of energy consumption and greenhouse gases emissions. Some of these materials can be harmful for human health (like mineral wools, polyurethane foams etc.). Therefore, a great attention has been given to "green" materials, especially in the building sector. Many research centres have developed new sustainable materials, in many cases with interesting thermal and acoustical properties (Asdrubali et al. 2012). Most sustainable materials for noise control can be divided into three main categories: natural materials (coconut, kenaf, hemp, mineralized wood fibres), recycled materials (waste rubber, metal shavings, plastic, textile) and mixed and composite materials.
- **Digital fabrication processes**: advanced manufacturing machines allow to treat materials in order to improve their acoustic performance. Subtractive and additive manufacturing are emergent technologies coming from other fields that can open research paths that go in the direction of:
  - Reducing the amount of waste material.
  - Achieving complex geometry to cope with complex problems.
  - Reducing the work time.
- **Holistic methodology**: Holistic methods for acoustic design project have been increasingly developed, combining the knowledge gained from physical acoustic researches, early stage noise mapping, architectural parameters and psychoacoustic. The aim of these methods is to combine subjective and objective parameters.
- **Embeded nature as active or passive element in spatial context**: nature has to be considered as part of the eco system in which we are working on. For this

reason, we have to embed it in design process, as well as the insights about the effect of our choices on the natural context.

The previous points can be considered as the boundaries of a new area of acoustics aiming at building an Advanced Acoustic Ecology.

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