The Return of Nature as an Operative Model: Decoding of Material Properties as Generative Inputs to the Form-Making Process

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The abandonment of nature as an architectural model and the redefinition of the relationship between form and material were two of the main consequences of industrialization for modern architecture. While nature was replaced by the machine as a model for architecture, industrial production suppressed the craftsman’s knowledge of the material and the associated techniques once essential to the form-making process. Thus, the replacement of nature as a model implied that principles once related to natural processes started to be seen as industrial values, i.e., the economy of means stopped being recognized as a quality related to natural form-making processes and became a demand of industrial production. Nowadays, material properties and nature are being reintroduced into architecture with the help of digital technologies; that is, the return of nature though computation. As a result, nature has become an operational model as opposed to the visual or iconic one it used to be; its inner qualities and processes are being decoded in order to inform the form-making process and foster innovative digital ornamentation.
1. THE SHIFT FROM NATURAL TO INDUSTRIAL PRINCIPLES

1.1 The modernist denial of nature

The split between architects and engineers characterized nineteenth-century architectural history. While engineers were developing new constructive solutions and forms by applying scientific knowledge and industrialized technologies, most architects were employing industrial materials and techniques to reproduce traditional forms through historicisms. However, with the rise of modernism, a new architectural language emerged as architectural practice and theory were brought into line with industrial materials and productive processes. Consequently, the modern language implied the denial of history along with the issues that could evoke it, among them architectural ornamentation based on the representation of natural forms, that is, the imitation of visual appearances of nature. Ultimately, through the denial of traditional styles, modern architecture was refusing nature and all natural-based ornamentation. Following this break with the past and with tradition, architecture could become a discipline able to produce forms that have no model in nature [1].

Along with the denial of history and the exclusion of ornamentation, the refusal of nature by modern architects also implied a shift in the production system due to the fact that natural principles such as efficiency or optimization, essential to form-making processes in nature, started to be understood as industrial demands related to the costs of production. Thus, the idea of economy of means — maximum performance using minimal resources — was unlinked from natural form-making processes and started to be understood from the industrial perspective, in which matter was not influential on form-finding. If matter was previously a generator of form in the natural production system, in the industrial system it is regarded as a feature of form, but not its first cause [2]: matter ceased to inform the form-making process. Thus, architecture was influenced by the notion of “economy” that arose from industrial laws instead of those established in nature.

1.2 Architecture’s oblivion of material knowledge

The industrial revolution has been considered as the beginning of a new material era in architectural history [3], as the new material and productive conditions brought about by industrialization were reflected in the use of materials such as glass, iron and concrete. These materials embodied new constructive, structural and spatial possibilities, which were then exploited by the Modern Movement: while glass brought new spatial relations through the development of physical and conceptual transparency [4], steel and concrete made the frame structure possible and with it, the free plan.
Besides providing new materials, the industrialized production system led to a conceptual shift of *materiality*, as the uniformity and homogeneity of mechanized production was transposed to the products. The quest for the utmost efficiency aimed at maximizing and speeding up production, disparaged craftsmanship as the slowness and irregularity of its production methods were at odds with machines. The bonds that held the craftsman’s knowledge (*tecné*) and the materials were broken by mechanized production. While the quality of a craftsman’s work depended on his knowledge of the material and techniques [5], the industrial worker was valued for his capacity to produce more in less time [6]. Hence, before industrialization, craftsmen were aware of the complexity and heterogeneity of materials, and as they were continuously facing materials of different qualities, their task was to take advantage of the specific qualities of each material. In this sense, material qualities were integrated into the form-making process as the craftsman did not impose a form from the outside; on the contrary, the form was conditioned by the material properties [7].

As materials became homogenized through industrial production, their heterogeneous properties were forgotten and downgraded to a secondary role: the regularity of the machine processes required regular materials [8]. Material knowledge became detached from the design process and exclusively intellectual. Materials were assigned to simple and orthogonal forms in order to be produced economically. Therefore, from the industrial viewpoint, the significance of “nature” and “economy” changed radically: nature became just the place from which man takes his material, whereas a new artificial nature arose along with the industrial productive capacity. Economy was mainly related to the optimization of productive processes, so its relation to the form-making process relied exclusively on how to make architecture more economical in terms of the cost of production. Thus, the tectonic relation between the significance of “economy” and the architectural form diminished since the oblivion of the material knowledge and the denial of nature as an architectural model fostered a design process in which orthogonal and simple geometries became the new formal paradigm – among other reasons, because these shapes eased the industrialization of architecture. Consequently, ornamentation started to be seen as a *crime* because of the time and labour required to produce it [9], but above all, due to the fact that it was not an affordable option in a period in which architecture started to be determined by industrial means and purposes.

### 2. The Return of Nature Through Computation

#### 2.1 Revision of *means an purposes* in digital architecture

“Architecture is on the cusp of systemic change, driven by the dynamics of climate and economy, of new technologies and new means of production.”
This statement by Michael Weinstock contains and summarizes the fundamental means and purposes of contemporary digital architecture: the purposes, as the ideas that drive architecture, are defined by the economy and climate; the means, as the forces that support the architectural production, include technology along with knowledge, two forces that nowadays are perfectly merged in digital technologies.

The term economy was already in use in the nineteenth century; J. N. L. Durand contended that buildings had to be convenient and economical [11]. In his book *Architecture and the Crisis of Modern Science*, Alberto Pérez-Goméz reminds us that according to Durand, buildings should be designed with simple and symmetrical geometrical forms in order to construct the most convenient building with a given amount of money [12]. Therefore, for Durand, economy was synonymous with efficiency due to the fact that both words meant the achievement of the maximum result with the minimum effort, that is, with maximum economy. Then, what was not strictly necessary had to be avoided. Furthermore, Pérez-Goméz argues that for Durand necessary was synonymous with convenient, since convenience was achieved in architecture by the satisfaction of its fundamental purpose: to sustain human life. Consequently, for Durand:

“Architecture should merely be assured of its usefulness in a material world ruled by pragmatic values [so] no architectural decoration would be pleasant [...] unless it sprang from the most convenient and economical disposition.” [12]

This standpoint paved the way to twentieth-century functionalism and the denial of ornamentation in modern architecture: after functionalism, the symbolic values of architecture were downgraded to a secondary role. Since then, architecture has mostly been concerned with physical–quantitative production, so its transcendental horizon – once embedded in nature-based ornamentation – was transposed to production techniques [13].

Nowadays, digital technologies are changing the conception of economy that emerged under the industrial influence; as Weinstock argues, the new technologies are also driving architecture to a systemic change. A new significance of “economy” is coming to the fore as productive processes aided by digital technologies are not constrained by the simplicity, orthogonality, regularity and homogeneity that characterized the early industrialized productions. As CAM technologies enable the production of non-standardized objects at reasonable costs – which means that the production time does not dramatically differ between homogeneous and heterogeneous goods – the meaning of “economy” is also changing: beyond the industrial conception, which sees “economy” as related to an efficient productive process, the digital conception also looks back to natural form-making processes, in which economy is not only related to the generative phase, but also encompasses the future performance of the design through the optimization of the object’s form.
Although digital technologies are changing architecture’s means, its purposes are close to the architectural necessities stated by Durand: in both cases, it seems that the main purpose is to sustain human life. If this is true, the difference between digital architects’ and Durand’s notions of architectural necessities relies on the view of nature that arose in the late 1960s: the Earth started to be viewed as a finite world with limited natural resources that may be depleted. From this viewpoint, Durand’s definition of convenience would match today’s sustainability due to the fact that, in both cases, the goal is to improve human well-being, but while nature was seen during the Industrial Revolution as an infinite source of resources available for industrial exploitation [6], nowadays, the sustainable approach to human well-being relies on the conservation of these resources. Accordingly, sustainability can be seen as the necessity that drives architecture, or in Mark Jarzombek’s words:

“In recent years there has been a growing interest in the project of Sustainability as a site where ethical commitment, architectural practice, capitalism and good design could come together.” [14]

Therefore, architecture understood as an institution [15] [16] is determined by communities, governments and industrial developers, which are adopting an approach to sustainable community and economic development all over the world [17]. Thus, sustainable development inserts architecture into a global policy, defined by Al Gore during the 1992 Rio Conference on Environment and Development as economic progress without environmental destruction [18]. Above all, however, it is important to remark that sustainability was vital for the reacceptance of nature in architecture, not only as the supplier of natural resources, but also as a source of information.

2.2 The return of nature as an operative model

Even though the comparison between craft and industrial production mirrors the break between the form-making process and nature, its origins need to be sought in the Scientific Revolution rather than the Industrial Revolution. Since the Galilean distinction between primary and secondary qualities, and the following Cartesian separation between mind and body (res cogitans, res extensa), the understanding of nature in scientific thinking has been exclusively based on what appeared tangible in the world; that is, the quantitative, objective, measurable and ultimately controllable physical properties of nature [19]. Everything that could not be expressed in mathematical terms was deemed to be irrelevant, so not only material properties, but all the properties of living organisms that could not be observed using scientific methods were neglected. Thus, science paved the way toward a mechanistic model of the world in which the role of nature was taken over by the machine. The understanding of the universe as a machine [20] and the representation of reality in mathematical terms
effectively prompted the decline of nature as a model for arts and architecture, while the new model was perfectly suited to the rationality of scientific thinking and the industrial standardized production as pillars of modernism.

However, nature has been revaluated in architecture since the mid-twentieth century as Cartesian reductionist analysis was questioned by the fact that knowledge was fragmented and isolated, diminishing the human capability to relate the separated parts, along with the facility to recognize the underlying structure behind the whole. Richard Buckminster Fuller, aware of this conceptual abruption, saw that specialization prevented a holistic perspective by which the process of understanding focuses on how things influence one another within a whole, instead of looking at them in isolation [21], i.e., system thinking. The City Tower Project by Louis Kahn helped to introduce operational principles of system thinking that were further developed by the Metabolist and Team 10 proposals in the 1960s, but most of these projects, beyond geometric configuration based on the flexible growth patterns of nature [22], were closer to the mimesis of artificial systems (Figure 1). However, Gordon Pask, in his article of the late 1960s titled “The Architectural Relevance of Cybernetics”, highlights the idea that architecture and cybernetics share a common philosophy, i.e., the philosophy of operational research. Then, architects would be the first and foremost system designers [23]. For Pask, buildings were part of an ecosystem in which they interact with its inhabitants while determining their behaviour. The conception of buildings as interactive objects and the built environment as an interactive space was encouraged.

Besides the operational approach, the geometrical representation of the DNA structure was a crucial fact for today's understanding of nature, and consequently, for its return to architecture:

“... the two-meter-high model, photographed for Time magazine in the spring of 1953, became a new emblem of nature” [24].

Once again, the technological progress added to a scientific model of reality opened up the possibility to act on nature in different ways by describing its enigmatic configuration in a scientific language. Nature, and with it materiality, was now accessible as never before: a fact that enabled
the reintroduction not only of material properties into the form-making process, but also of natural properties of living organisms that did not conform to the previous mechanical model. Therefore, with DNA’s geometrical representation and computers’ development, nature’s inner structures and processes could be decoded in order to reproduce them artificially through digital design, either for representational, generative, evaluative or performative purposes [25]. After its denial by modernism, nature could be reintroduced into architecture, but in an unprecedented way: after industrialism, nature, as a model, was replaced by the machine; after informationalism [26], nature was reintroduced through the machine, i.e., through computers (Figure 2).

Thus, nature was no longer an iconic model to be reproduced visually or formally. As its inner structures and processes gained importance, its apparent qualities became irrelevant. Nature’s relevance shifted from its extrinsic to its intrinsic qualities [27], since digital environments, computational processes or mechanisms have expanded the scope of the designer [25]; in other words, its understanding changed from a visual to an operational approach, making the process more important than the product, the system more important than the form and the performance more important than the object [24] – a fact that is closely related to the programmatic capacity of computers to manage tasks, contrary to previous mechanisms that were merely used to execute tasks. After being seduced by digital imagery during the 1990s [25, 28], architects began to recognize that computers enabled them to rethink materiality and consequently its capability to inform the form-making process, thanks to their capacity to work with thoroughness that was not possible before the advent of such tools [29].

After the discovery of the DNA structure, information started to be seen as a source of life, a view that encouraged an evolutionary approach in which architectural design is comprehended as a generative instead of a representational process. A generative process is based on the decoding of information, which is subsequently used to inform the form-making process. Therefore, in order to outline this evolutionary model, as John Frazer named...
it, it is necessary to define a genetic code script, rules for the development of the code, mapping of the code to a virtual model, the nature of the environment for the development of the code and, most importantly, the criteria for selection [30]. From this perspective, the design process is driven by form-generating rules that consist of processes rather than components: in other words, a process-driven architecture that comes to the fore as a property of the process of organizing matter, rather than the matter thus organized [30].

3. DESIGN PROCESSES INFORMED BY THE NATURE

3.1 Physics-based design and the aesthetics of economy

Deriving architectural forms from intrinsic material properties is not new in architecture; for example, in the mid-twentieth century, a group of architects and engineers started to study the material properties of concrete. Among these architects and engineers were Félix Candela, Eduardo Torroja, Eladio Dieste, Pier Luigi Nervi and Ricardo Morandi, all of whom had in common the idea of exploiting concrete’s potentiality to generate new architectural expressions inherent in its material properties: in other words, structural forms based on material qualities. Thus, technical and aesthetic research was fostered on the idea of structural efficiency, that is to say, to make a virtue out of economy [31]. Consequently, these designers drew together form, force and structure as the generative forces of their projects, an approach that comes to light through Nervi’s conception of building correctly, which implies the simultaneous satisfaction of functional, economic and aesthetic requirements [31]. In this sense, a new conception of “economy” arose from the one that had prevailed since industrialized processes comprised architectural production. Before the mid-twentieth century, the meaning of “economy” in architecture was primarily related to the costs of production, that is to say, an efficient constructive process achieved by optimizing time and costs through simple geometric forms; after the mid-twentieth century, “economy” was also related to the architectural form, starting to be understood as the optimization of the form according to its structural performance.

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Figure 3: Aesthetics of economy.
The architectural conception of “economy of means” was enhanced since its productive–industrial meaning was pushed forward, by introducing a tectonic viewpoint that relates the significance of economy to form, function, aesthetics and matter. Since then, terms like “efficiency” and “optimization” have not only pointed to a technical process, but also to architectonic issues such as structure and matter, enabling an aesthetics of economy defined by geometry, matter and physics (Figure 3). Ultimately, the structural expression of efficiency opened up the possibility to bring together again the intellectual–rationalistic and the sensitive–symbolic realms, which were split by the schism between art and science during the nineteenth century.

3.2 The computational approach

The form-finding process prefigured by the works based on the aesthetics of economy is closely related to “digital form-finding” [32], as, in both cases, material properties are a determinant issue in the manipulation and control of formal elements during the design process. In this sense, the conceptual and methodological approach of the design processes that fostered the aesthetics of economy set the basis for a physical-based design in which material properties and structural behaviour become the main input to the form-finding process. One of the main differences between the architects–engineers of the mid-twentieth century and the digital approach to form-making can be found in the evolutionary model indicated by Frazer, a model that was implemented thanks to the capacity of ICTs to decode material information, in order to inform the design process, and then encode it back into the form. In this sense, the advancement of genetic engineering gave architects a better understanding of the importance of the physical processes of self-material organization and structuring in morphogenetics [33].

This understanding lies at the core of computational design, a design methodology that brings architecture into line with the digital era, since information is applied in order to generate new information that can be useful for creating or improving products and/or processes [26]. This represents the main difference between computer-aided design (CAD) and computational design: in the first case, information provided by computers is useful for the representation and construction of an existing design so this information is not influential in its form-making process; in the second, the information provided by computers surpasses the initial information, so the new data generated are applied during the design and the constructive process [25]. Therefore, in computational design, “computation” refers to the processing of information used to inform the form-making process and its subsequent materialization, by embedding the intrinsic behaviour and characteristics of matter as generative drivers of design and the constructive process [33]. Thus, materiality arises as the generative driver of
a form-making process defined by the feedback loops of information related
to matter, form, performance and production.

The design process of the ICD/ITKE’s Research Pavilion 2010 can be
considered as a \textit{form generative process} in which the form emerges from the
inner properties and behavioural constraints of the material, in this case,
plywood strips. As stated by Fleischmann, Lienhard and Menges:

“The result is a novel bending-active structure, an intricate network of
joint points and related force vectors spatially mediated by the elasticity of
thin plywood lamellas.” [34]

As stated by the project authors, the main input in the form-making
process was the information, obtained from physical form-finding
experiments, on the structural and material properties of wood: more
precisely, its elastic bending characteristics. This \textit{material information} was
introduced into an informational model in order to generate a design model
in which geometric and morphological requirements were defined through
computational algorithms. The fabrication of these plywood sheets was
assisted by CAM technologies, but a crucial fact for their manufacture was
that the fabrication and construction processes were inherent in wood’s
material properties and behavioural constraints; in other words, the
fabrication restrictions were integrated into the design process [34].

Experimental construction projects like La Voûte de LeFevre, the AA/ET
Pavilion and the Textile Module are in line with the ICD/ITKE’s Research
Pavilion (Figure 4): they mirror the way in which nature is informing
architecture through digital technologies, as these tools traduce natural
material’s “coded” information into architectural form-making inputs.
Therefore, material behaviour and manufacturing restrictions are not
understood as constituting constraints that merely need to be
accommodated [35]. On the contrary, the unfolding of the intrinsic material
capacity and behaviour enables a form-making process defined by an integral
articulation – across different scales of magnitude – between the
formal–structural performance and the material behaviour constraints [33,
35]. Consequently, the computational approach restores the \textit{natural meaning}
of “economy”, since it was diminished by the industrial–mechanistic ideology, as it is related to both efficient manufacturing along with straightforward assembly and the optimization of the structural and geometrical performance through the integration of material properties into the form-finding process.

Despite the new relationship between architecture and nature, architectural practice in industrialized societies continues to be particularly influenced and assessed by the preponderance of economic rationalization, i.e. the material needs over the symbolic ones and the intellectual judgement over the empirical one. This is, to a large extent, the result of the return of nature through the machine, since the rational values embedded in industrial machines — efficiency, productivity, optimization, etc. — are the same as those that drive production with digital machines. Therefore, the understanding of nature continues to be framed by several industrial principles, among which is the logic in which reality is not even what is seen, but what can be quantified [36]. Consequently, architectural practice in the digital age continues to be implicitly guided by the production values prevailing since the rise of industrialism.

4. DIGITAL ORNAMENTATION: THE INVERSE RELATIONSHIP BETWEEN INFORMATION AND FORM

The rejection of nature as an architectural and ornamental model during modernism not only responded to the denial of history and the influence of scientific thinking in the perception of nature, but was also linked to the rise of industrial materiality. With regard to ornamentation, the development of the continuous flat surface, which characterizes modern architecture, mirrored the development of a new architectural language based on the development of industrial cladding materials. Therefore, through the influence of plastering, architectonic ornamentation ceased to be figurative and sculptural and became abstract and geometric due to the homogeneity of the material. Consequently, ornamentation started to be seen as superfluous by modern architects, who overlooked the fact that the function of ornamentation is to communicate a message: to transmit information through form. In the classical period, the ornamental message was mystical; after the Renaissance, it became social and political; with industrialization, it turned out to be economic. Thus, with the rise of industrialized materiality, the material became the medium to transmit the message of a new morality [3], which saw in industrial materials an aesthetic resource by applying them with sincerity, simplicity and honesty.

Even though the meaning of ornamentation has changed throughout history, a common factor has remained: its material configuration is informed by the message. In other words, the form is conditioned by the information to be communicated. In this sense, the ornamental relationship between
message and form remained during the first decade of the twenty-first century, a fact reflected by projects such as the 2002 Serpentine Gallery, the Watercube in Beijing or Beijing's National Stadium. Although these projects maintain the same relation between information and form, the ornamental qualities of their envelopes not only enable the link between architecture and culture, but, above all, represent the invisible forces of society [37].

If we adopt the standpoint of historical materialism, as the mode of production of material life conditions the general process of social, political and intellectual life [38], then we can argue that while Le Corbusier’s Domino project or Mies’s Seagram Building expresses the linearity, homogeneity and simplicity of industrialized production, the projects mentioned earlier exemplify the plurality, heterogeneity and complexity of today’s globalization and informationalism. These network structures not only exhibit the overcoming of standardization through their non-linear and hybrid organization; above all, they mirror the structure of the global production, economy and culture as systems grounded on the information flows supported by information networks (Figure 5).

These digital surfaces blur the differentiation between structural and ornamental elements, as the tectonic–functional and communicative–decorative qualities of these envelopes merge in singular networked surfaces. Despite this feature, the previous relationship between message and form has remained due to the fact that material properties were not decisive in the form-making process. In other words, the approach towards nature was representational, so the form generation relied on a visual understanding rather than the decoding of intrinsic information. However, with today’s digital technologies, the form can be determined by the information decoded from matter: if the architects and engineers of the mid-twentieth century developed an aesthetics of economy based on an understanding of the material properties and behaviour, that is to say, matter as information, today, information is our matter since the form-making process is determined by the material information modelled and processed with the aid of computer technology.

Hence, through computational design, the ornamental relationship

![Figure 5: Industrial simplicity vs. informational complexity.](image_url)
between information and form has changed since material properties operate as a generator of form. In other words, concepts do not determine form — understood as material configuration; on the contrary, the decoding of material data and its processing through digital technologies emerge as the main driver of form. If the ornamental form was previously driven by ideas — mystical, political, social or economic — nowadays, digital ornamentation is also driven by matter — material intrinsic properties and qualities. Material-based architecture is coming to light as the design process relies on both the intellectual approach that has prevailed since the Renaissance and the holistic comprehension and instrumentation of the natural properties of matter. Finally, the conceptual and methodological approach to the development of digital ornamentation had already arisen; now, it mainly depends on the capacity — of architecture and the building industry — to produce it affordably on a large scale.

5. CONCLUSIONS

This work exposes that the architectural rejection and reacceptance of nature, during the last century, was not exclusively an ideological issue. From this standpoint, the modernist rejection of nature is considered as a consequence of the machine’s influence over the productive system and the rationalist thinking that evolved next to it in industrialized societies, an ideological influence that led to the architectural rejection of the ornament as it was related to nature and, therefore, opposed to industry. With modernist abstraction of the ornament — based on the pureness of forms and materials — it turned out to be exclusively intellectual, tantamount to the Renaissance abstraction of the design process in which it was seen exclusively as an intellectual process. On the contrary, digital technologies are prompting a new ornamental discourse after modernism’s abstraction muted it; therefore, the new instrumentation of matter and the return of nature as an architectonic model are seen as a consequence of integrating ICTs into architectural design and construction processes.

The recent understanding of nature through digital technologies is fostering innovative design processes based on an operational approach, i.e., decoding the intrinsic properties of matter in order to inform the design process. From this viewpoint, a new ornamental discourse may come to the fore through the revaluation of the forces that drive architecture, the same forces as those that are communicated through the ornamental message. Since the industrial revolution, economy has prevailed as one of the main principles that drive architectural thinking and practice, but the term has been mainly related to the optimization of industrialized productive processes. Nowadays, the significance of economy comes from the understanding of natural form-making processes along with industrialized ones. In other words, the economy of means is determined by the performative relations between form, matter, structural forces and
materialization. This new significance of economy, which is driving digital architecture, is bringing ornamentation back: ornamentation that is “economic” in Durand’s terms, since it is the most convenient and economical disposition of matter.

However, the return of ornamentation and nature to architecture is currently influenced by machines and computers. Therefore, it is oriented by several mechanic–production values that have prevailed since industrialization: values driven by a rationalist logic determined by economic decision models that expel all kinds of mystical ideas [39]. Thus, the predominance of intellectual judgement over mystical and empirical experience remains, since the “technical order” established by mechanized production prevails over the preceding “natural order”. In this way, the symbolic horizon of digital architecture still has to be questioned, but taking into consideration that the computational return of nature and the digital ornamentation offer the possibility to complement the rationalist logic that predominates in architectural production. This is a possibility encouraged by digital technologies, since they have expanded our notion of nature by enabling the quantification and control of physical and non-physical phenomena ranging from micro to macro scales. In this scope, a digital–empirical approach is coming to light as digital tools are enhancing a sensorial attitude – along with the intellectual one – based on the interaction between buildings, humans and the environment. Projects like the Arab World Institute (Nouvel), the Media-TIC (Ruiz-Geli) or Responsive Surface Structures (Reichert & Menges) raise the possibility of a phenomenal-based ornament focused on the empirical and sensitive spheres of architecture, as these projects explore the responsiveness and adaptability of the building by interacting with the environment through their envelopes. Therefore, the “digital” interactions between nature, humans and machines are providing the possibility to recover the non-rational horizon that was diminished by the industrialized notion of “economy” that prevailed during the twentieth century.

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