The Structural Conception in Architecture in the Digital Era, Between Aesthetics and Ethics

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Abstract In the past the technological invention has often governed the creation of innovative forms (Roman concrete, steel, reinforced concrete, etc.), with the result of a substantial correspondence between conception and realisation. In the electronic and digital era, this role seems to be entrusted to the mathematical-numerical instrumentation offered by software. With the evolution of computational tools and numerical skills, the ability to design structural shapes has also become extremely refined, often in a direction that transcends the requirements of optimal mechanical performance, thanks to algorithms for generating purely geometric shapes. With the widespread of 'deconstructed', 'non-linear', 'virtual' architectures, the invention of new shapes seems to want to be free from the need to contemplate the various components of the design process, and in particular from the constructive one, often generating a dichotomy between represented and conformed architecture. In this context, it seems interesting to understand, with the help of some examples, how architecture can preserve a tectonic ethic (*firmitas*) in the digital age. Is it possible to exploit structural optimisation algorithms or artificial intelligence software for generating new forms in which the structural component maintains a significant role (with undoubted practical advantages)? Is it possible, albeit in a completely transformed formal context, to contribute to recovering a unitary conception of the design process, still conceived as a synthesis of all the Vitruvian components, which makes it possible to finalize the design towards effectively buildable forms, that do not fall, as paradoxically often happens, into automatisms of repetitive figurativeness?

Keywords Digital design · Structural optimisation · Artificial intelligence · Algorithms · Buildability

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1 Introduction. The Convergence of Technology and Aesthetics in Architecture, Seeking a Constructive Ethics in the Digital Era

In the ever-evolving realm of architecture, the interplay between technology and design has carved a transformative path, reshaping not only the physical structures we inhabit but also the very process by which these structures come into being. As we venture further into the digital era, the traditional paradigms of architectural conception and realisation are being redefined by the infusion of mathematical-numerical instrumentation and computational tools. This transformation prompts a profound exploration into the intricate relationship between aesthetics and ethics, as architecture navigates the terrain of innovation while preserving its foundational principles.

Historically, technological breakthroughs have often catalyzed architectural innovation, yielding iconic forms that reflect both the technical prowess of their time and an inherent harmony between concept and construction. From the resilience of Roman concrete to the soaring possibilities of steel and reinforced concrete, these materials have not only shaped architectural aesthetics but have also woven themselves intricately into the fabric of architectural realisation. However, the landscape has shifted with the advent of the electronic and digital age, as the torch of innovation is seemingly passed to algorithms and software, capable of generating complex geometric forms that often transcend mere mechanical functionality.

As these algorithms gain sophistication and computational abilities flourish, the boundaries of architectural imagination expand. 'Deconstructed', 'non-linear' and 'virtual' architectures [14] challenge the conventional notions of form and space, beckoning architects to relinquish conventional design paradigms. This departure from the conventional, although liberating, introduces a dichotomy between the represented shapes and the real forms, calling into question the equilibrium between the artistic vision and the practical constructability.

Amid this dynamic landscape, the exploration of a tectonic ethic emerges as a guiding compass. How can architecture navigate the digital currents while retaining the fundamental principles of stability and integrity (*firmitas*) that have been central since the days of Vitruvius [29]? Can the algorithms designed for structural optimisation coalesce with architectural intent to birth novel forms that harmonize with both aesthetic aspirations and real-world constraints?

In this inquiry, we delve into the heart of contemporary architectural discourse, dissecting examples of architectures that epitomize the intersection of mathematics, aesthetics, and technology. With an eye toward reconciling the seemingly disparate realms of form and function, this exploration seeks to ascertain whether architecture can bridge the gap between the ethereal and the tangible in an age where virtuality and materiality must converge.

2 Exploring Structural Conceptions in Architecture: Conciliating Vitruvian Influence and Digital Realities

Within the tapestry of architectural evolution, a crucial thread is the interplay between structural conceptions and the enduring principles of Vitruvian *firmitas*. This historical continuum unveils how innovative forms in construction have been underpinned by the quest for structural stability. By delving into the annals of architectural history, we endeavor to uncover the intuitive foundations that have fueled optimal design across eras.

Our inquiry then extends to the contemporary panorama, characterized by digital design and the proliferation of 'virtual' architectures. Amidst this landscape, the very essence of structural conception takes on new dimensions. A pivotal aspect of our investigation is the role assumed by technology and technique, with software emerging as a modern-day sentinel. We embark on a discerning exploration of the nexus between structural optimisation, parametric design, and the genesis of novel forms.

However, with this pursuit of innovation, a cautionary undercurrent emerges. The siren call of mathematical and numerical approaches, while alluring, raises concerns about the detachment from the tactile reality of constructed forms. The dichotomy between the virtual and the tangible beckons us to evaluate the equilibrium between computational prowess and the intrinsic tangibility that architecture embodies.

Starting from Torroja's seminal book, *Razón y Ser de los Tipos Estructurales* [24], his key concept of the "right cause" delves deeply into the quest for a comprehensive "philosophy of structures". This pursuit is oriented towards unraveling the inherent "Reason and Essence" that lies at the core of the collaborative efforts shared by both engineers and architects.

Torroja's approach deliberately attenuates the emphasis placed on quantitative elements within the realm of structural mechanics. This strategic diminution is motivated by the desire to avert a potential pitfall: that of allowing calculations to overshadow and monopolize the design process, potentially stifling the intuitive and creative aspects of conception. The dichotomy, often characterized as the 'design' culture versus 'verification' culture, occupies a central place in the practice of structural design and within this framework Torroja's approach aims to strike a balance between the analytical rigor of calculations and the imaginative spark of design, and prompts further exploration into the extent to which one can efficiently take into account both aspects.

In scrutinising this proposition, one might delve into instances where the quantitative facets of structural mechanics and the qualitative nuances of design intertwine in a symbiotic relationship. This could be evident in scenarios where the very act of calculation serves as a wellspring of inspiration, guiding the architect's creative vision. Conversely, instances might also arise where an intuitive design concept finds validation and refinement through meticulous calculations.

Moreover, the contemporary landscape of architecture and engineering, influenced by advancements in digital tools and computational methodologies, introduces a fresh layer of complexity to this discourse. The role of computation, while deeply rooted in quantitative analysis, is increasingly intertwined with design exploration. This integration challenges the clear demarcation between the design culture and verification culture, suggesting a potential synergy that could enhance both the aesthetic and ethical dimensions of architectural conception.

In essence, while Torroja's proposition poses a thought-provoking perspective on the interplay between aesthetics and ethics in architectural design, it beckons us to delve deeper into the intricacies of this relationship, it encourages a nuanced exploration of how the quantitative and qualitative elements of design and analysis coalesce, enriching and enlivening the very process of shaping our built environment.

The structural conception ranging from the tectonic meaning [9], referred to the Vitruvian *firmitas*, going through the mechanic-mathematic conception of rational mechanics, which implies the full awareness of models and methods of structural design, characteristic of the industrial and post-industrial era, after the developing of theory of elasticity in nineteenth century, veers toward a broader conceptual, philosophic, instrumental conception to be perceived as regulating principle related to the scientific thought tout court. Since the Renaissance the necessity of such a regulating principle was considered fundamental for the constructive process: "The way of carrying out a construction consists entirely in obtaining from different materials, arranged in a certain order, and artfully joined, a compact and—as far as possible—integral and unitary structure. A whole and unitary complex will be said to be that which does not contain parts split or separated from the others or out of their place, but in the whole extension of its lines it demonstrates consistency and necessity. It is therefore necessary to research, in the structure, what are the fundamental parts, what is their arrangement, what are the lines of which they are composed" [1]. This was also the inspiring principle of the masters of the Modern Movement [6], of the structuralist thinkers of the '70s [5] and of several architects who played a role in the development of contemporary architectural thought [12, 21].

In essence, the evolution of structural conception is a dynamic narrative that traverses artistic finesse, mathematical accuracy, and philosophical inquiry. This continuum underscores how architectural and engineering thought has evolved, adapting to the spirit of each era while continually pushing boundaries of creativity and knowledge. As we forge ahead, the interplay of these paradigms continues to enrich our built environment, weaving a tapestry of structures that mirror both human inventiveness and the profound exploration of existence itself.

In the contemporary electronic and visual communication era, where architectural design is influenced by concepts of deconstruction, non-linearity, and virtuality, the question arises: can architecture maintain a tectonic ethics while embracing these new paradigms, without sacrificing the communicative essence of the built work? Furthermore, how can the vast computational and technological resources available today be harnessed and managed to enhance architectural practice and contribute to improved quality of life for users?

Addressing these questions requires a multifaceted approach that integrates technological advancements while staying true to architectural values. To effectively navigate this landscape and leverage technology for positive outcomes, architects must strike a balance between innovation, functionality, and meaningful communication. In today's context, the role of technology extends beyond drafting and visualisation. It encompasses structural optimisation and parametric design, allowing architects to explore complex forms and systems that were previously unattainable. These tools enable architects to create efficient structures that are both visually compelling and structurally robust.

In summary, architecture's ability to uphold tectonic ethics, leverage technology, and prioritise human well-being in the design of new shapes hinges on a holistic and informed approach. By embracing advancements while maintaining a focus on foundational architectural principles, architects can navigate the complexities of the modern era and continue to create spaces that resonate on both aesthetic and functional levels.

2.1 Various Declinations of the Vitruvian Firmitas

Throughout the history of architecture, the ways in which the structure manifested itself were extremely various, both because of the technological evolution of building materials, and the consequent birth of a scientific dedicated knowledge, and for the continuous changes of the conceptual approach. The two aspects evolved in parallel, influencing each other in a continuous endless relay. The purpose is to investigate the different approaches represented in the history of buildings, not from a chronological point of view but from the one of design, by analyzing the different ways in which the structure was used to draw a building.

In this section, we briefly traverse the historical lineage of structural thought and journey through the contemporary realms, unraveling the intricate interplay between tradition and technology. Our investigation spotlights the transformative potentials as well as the pitfalls that beset a discipline at the crossroads of innovation and reverence for the pragmatic truths of the built environment. We want to highlight the risks that the imbalance between the three Vitruvian components entails, in particular, when the role of the structure within the design process is underestimated inevitably leading to a marked gap between idea and realisation.

In this regard we identified three gross categories—*Predominant Firmitas*, *Declared Firmitas*, *Integrated Firmitas*—in which a series of representative examples of how the structure has been interpreted to characterize an artifact are highlighted. There is also a fourth category, admittedly contradictory, the *Ignored or Negated Firmitas*, which we will discuss separately (Fig. 1).

Predominant firmitas in architectural terms, signifies a scenario in which the structural elements and principles take on a leading role in the design process, ultimately emerging as the defining characteristic of the building. In this context, the structural

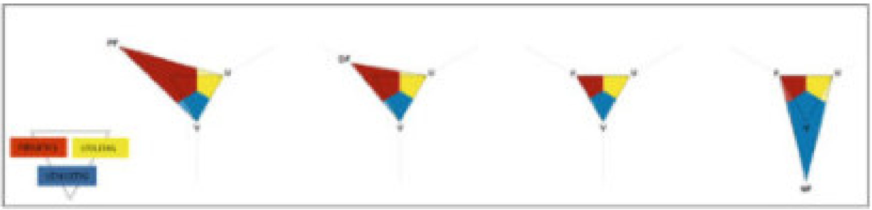

Fig. 1 Schematic of the various declination of Vitruvian *firmitas* PF—*predominant firmitas*, DF—*declared firmitas*, IF—*integrated firmitas,* NF—*ignored or negated firmitas* [25]

language assumes a central position, overshadowing other considerations such as distribution or form. The structural framework becomes not only the backbone of the construction but also a powerful representation of the building itself.

In historical contexts many architectural creations aligned with the concept of Predominant *firmitas*. In these instances, the structural aspects were not just functional components but played a pivotal role in shaping the overall design. The architecture of this era often exemplified the dominance of structural considerations, where the form and aesthetics of the building were influenced by and derived from the structural choices made.

In the architecture of the past until the Middle Ages the constructive technology, common heritage of people's experience, significantly affected the realized space. There was no dichotomy between design and construction, and we can speak of only one singular action concretized in the final building which shows an essential coherence of its structural conception (Fig. 2). On another level, Mechanics, considered as language of objects (lever, wedge, inclined plane), was developing in a very different frame. Nevertheless, the structural language, although only instinctively and experimentally understood, became predominant: maybe for the first time the structural conception was expressed with celebrative aim, although still in service of the functional demands [22, 26].

More recently the industrial revolution provoked a radical transformation of the consolidated building technologies, which called for the need of a new professional figure: the structural engineer, who bases his knowledge on the theoretic background of analytic mathematics and rational mechanics applied to the solution

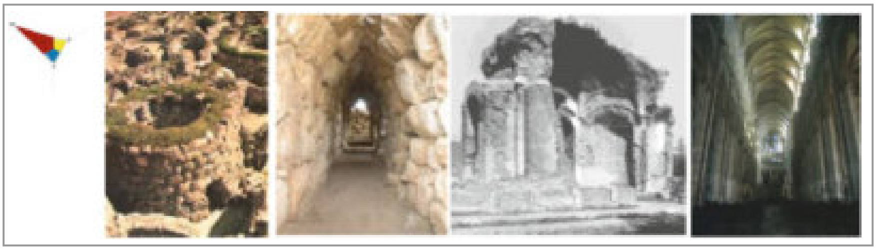

Fig. 2 Antiquity and middle ages—the material imposes the shape

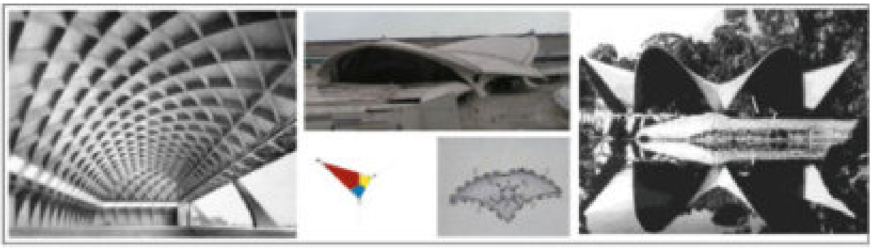

Fig. 3 Industrial and post-industrial era—the structural form

of structural problems. Mechanics and mathematics was growing together aiming at the rationalisation of the design process (Navier, Clapeyron, Maxwell, Mohr, Castigliano, Müller-Breslau, etc., e.g. [3]). The structural design became sensitive to formal arrangements: the art of construction released from the empiric dimension becoming science of the art of construction [19]. Consequently, the structural conception encompasses a comprehension not only of the methods but also the models of structural design, which plays a pivotal role in innovating new forms (Fig. 3). The process of rationalising structural design has spurred the proliferation of mathematical models, ingrained within Engineering curricula. However, the arduous nature of calculations has gradually eroded the holistic perspective of design, occasionally diminishing the richness of the creative process [17, 24].

Declared firmitas embodies an architectural approach where the structural elements, while clearly present, seamlessly blend with the overall design of the project. The primary supporting structure openly embraces its role within the composition, and this integration contributes to a balanced and rhythmic spatial progression. In this concept, the structural language harmonizes with other design components, ensuring both functionality and aesthetic coherence. Geometry plays a central role as paradigm of construction.

A strong correlation between geometry and structure is evident in architecture of the modern era (Fig. 4). Architectural design was intricately linked to the technological aspects that define or enhance the final outcome, a concept referred to as "operative geometry" by Bellini [2]. The mathematics/geometry adopted was traditionally linked to construction problems, that consisted in finding a way to realize a given geometric shape obtained with the exclusive use of a ruler, compass and set square that allow generating abstract forms. The vocation of constructors was mainly 'conformative' instead of 'representative' [10]; but they did not need the use of the language of the arising differential calculus. Even designers who were notable figures in the field of mathematics, such as Guarini and Wren, exclusively employed the language of classical geometry [26].

Geometry, acting as a fundamental construction paradigm, assumes a pivotal role also in numerous modern architectural creations where the structure is unveiled while harmoniously coexisting with the other components (Fig. 5).

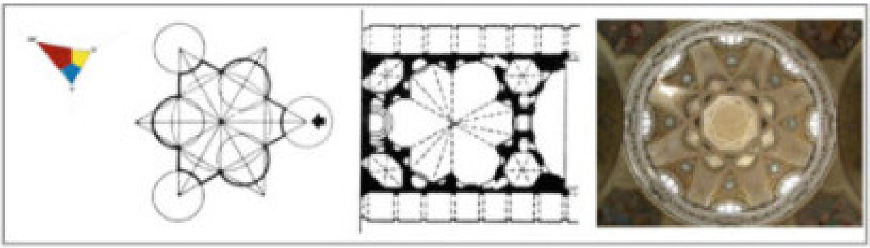

Fig. 4 Modern era—geometry as paradigm of construction

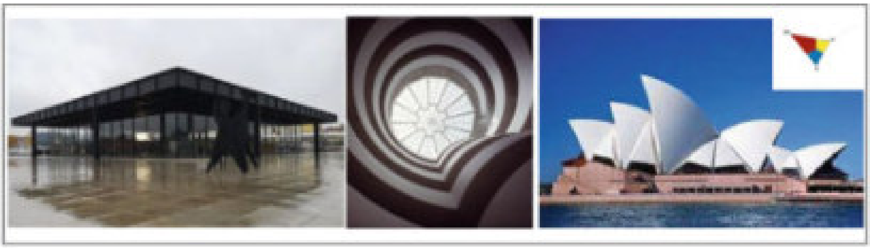

Fig. 5 Represented geometric shapes and configured forms

Integrated firmitas represents an architectural principle where a flawless equilibrium exists among three key components: structure, function, and form.

These elements unite harmoniously to form a singular entity, with each component fulfilling its purpose to serve the entirety of the design. The three Vitruvian components are in perfect balance. Structure, function and form come together in a single entity where each plays its role at the service of the whole and without any of the components prevailing over the others. The final result is the synthesis of this common work where the individual contributions are inextricable, masterfully combined into a unicum (Fig. 6).

Fig. 6 Structure, form and function

Ignored or negated firmitas. The focal point shifts towards the building's representative image, which assumes the paramount and primary role within the architectural framework.

The awareness of possessing the sufficient technological knowledge and the codification of the rules of good construction permeated the humanistic and renaissance culture. The tectonic aspect was subordinated to the geometric design: the world of the represented shapes started to contrast the world of the constructed forms: the geometrical design is indeed a paradigm of the construction that the construction itself is not capable of reaching, because the ideality in it is antonymic in comparison with the reality [20]. The architectural design specialized in the restrictive geometric approach (rules of the *divina proportione*) becoming a sort of conceptual exposition of the building itself. The consequence was selecting shapes independently from the structural needs, even providing wrong static interpretations depending on formal choices, as the consideration of the circle as the optimal shape for arches (Alberti). This led to the decoupling between form and structure formalized in the concept of ideal act of design: the geometrical design on which the concrete architectural operations are depending.

The dichotomy between design and realisation is accentuated in the contemporary era precisely due to the advancement of software, which allows for the generation of forms that can appear aesthetically satisfying, but may disregard other essential considerations, particularly those related to construction. The capabilities afforded by advanced numerical calculus now enhance the potential for designing novel structural forms, extending even into directions that surpass the demands of optimal structural performance (Fig. 7).

Fig. 7 Representative versus conformative dichotomy

3 Technology and Technique in Architectural Design

When delving into the realm of Vitruvian *firmitas* two distinguished approaches to structural conception can be essentially highlighted.

The first approach can be defined as the constructive conception (**technology-*techne***), which aims at credit the role played by the *firmitas* ('tectonics') in the realized architectures, focusing on the design of the realisation with a look at the needs of image communication with the intention to understand how the use of mathematical models (today essentially numerical procedures) conditioned or could condition the creation of 'new shapes', pointing out the risks arising when the so-called tectonic ethic is neglected (Fig. 8).

The second approach can be defined as the mechanical-mathematical conception (**technique-*calculus***), which properly use the language of mechanics and mathematics in the architectural design with also the aim of pointing out the, not always evident, links between architecture and scientific thought. Starting from the debate about the catenary, going through the shape resistant forms till to the recent procedure for optimal and parametric design (Fig. 9), the intention is to understand how the use of mathematical models (today essentially numerical procedures) conditioned or could condition the creation of new shapes, pointing out the risks arising when the so-called tectonic ethic is neglected.

Pierluigi Nervi's work serves as a paradigmatic embodiment of the former approach, which revolves around structural verification. In contrast, Sergio

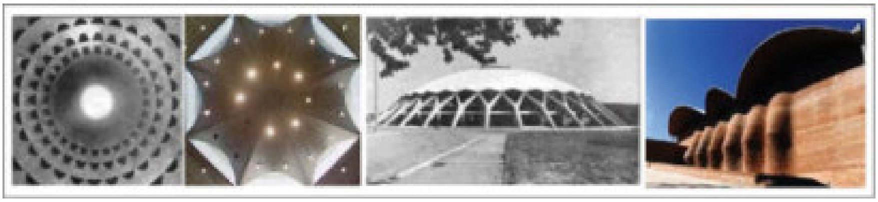

Fig. 8 The constructive dimension (technology)—influence of structural language on making architecture

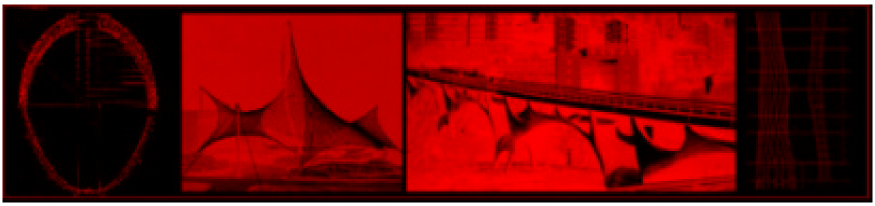

Fig. 9 The mathematical dimension (technique)—influence of mathematic/mechanic language on architectural design

Musmeci's work exemplifies the latter approach, focusing on structural design [16, 28].

Referring to the two outlined structural conceptions—technological and mathematical—it can be broadly asserted that in historical architecture, technological advancements, while being lately aided by the progress of structural mechanics, played a significant role in propelling and influencing the emergence of novel forms and constructed structures. The design concept harmoniously aligned with the eventual built outcome, as exemplified in Nervi's architectural achievements.

In contrast, the contemporary landscape sees the creation of innovative forms predominantly driven by digital design, occasionally with the bolstering support of optimal structural design. However, the design concept, contrary to the expectations and aspirations articulated by Musmeci himself, faces the potential of conflicting with the realized physical forms.

In the current electronic context and in the visual communication era, marked by 'deconstructed', 'non-linear' and 'virtual' architectures, a pertinent question arises: can architecture preserve a tectonic ethics while simultaneously retaining the communicative essence of the realized work? How can we effectively govern and steer the enduring legacy of computational technology to achieve mastery and maximize its utility in the service of the spirit? When Heidegger asked his contemporaries about modern technique, he wanted the people to reach the conditions that were necessary not only for dominating the technique, from the instrumental point of view ($t\varepsilon cn\eta$), but also for putting it in the "service of the spirit" ($\varepsilon pist\eta m\eta$). That, from Plato on, always directly defers to the essence of the technique: "there is nothing demonical in the technique, there is however the mystery of its essence" [13, 18]. How might we utilize this control to shape architectural endeavors that not only embrace innovation but also prioritize the achievement of Vitruvian standards, with the final aim that always should be contributing to improve the quality of life?

Addressing this inquiry necessitates a comprehensive examination of the prevailing structural conception. Particularly, it involves an exploration of the role played by technology and technique, concerning software tools, in today's architectural landscape. Central to this investigation is the evaluation of the functions of structural optimisation and parametric design. These elements play a pivotal role in the formation of new shapes and structures, ultimately contributing to the overarching goal of architectural improvement and heightened living standards.

4 Contemporary Technique: Software as Instrumentation in Architecture

In the present day, the term Technique finds its essence encapsulated within the realm of software. This encompasses a spectrum of numerical methods employed to generate intricate surfaces and volumes, such as NURBS (Non-Uniform Rational B-Splines). Additionally, software serves as a powerful tool for structural analysis and calculation, accommodating structures of diverse forms through Finite Element Analysis (FE), Structural Optimisation codes, and related methodologies. Finally, Integrating Artificial Intelligence (AI) into architecture can greatly enhance design processes, decision-making, and overall innovation, including generative design and/or parametric design, allowing exploration of creative solutions and enabling to adjust dynamically based design elements basing on predefined rules. By incorporating AI into architecture, you can streamline design processes, improve efficiency, and create innovative, sustainable, and functional spaces taking into account human needs, ergonomic principles, safety regulations, and aesthetic considerations to create environments that are both efficient and enjoyable to use.

However, it is important to approach software integration thoughtfully and ensure that human creativity and expertise remain central to the design process. The risks of the use of sophisticated software instruments in architecture as a mere mathematic-aesthetic exercise must be highlighted. The extensive application of advanced software creates a perception that the creation of new shapes is boundless and unconstrained, regardless of the building technology employed. The feeling of absence of (building) constraints fosters the pursuit of inventive new forms, accentuating qualities of diversity, originality, and uniqueness.

In the realm of digital architecture, the emphasis on technological advancements often overlooks the grotesque undertones inherent in the avant-garde movements of the '60s. Nevertheless, this culture transcends the confines of the avant-garde, transforming into a tangible and effective experience, that gives rise to architectural designs reminiscent of scenes from animated films (Fig. 10).

Some notable drawbacks arise:

Fig. 10 Form finding—beyond the avant-garde

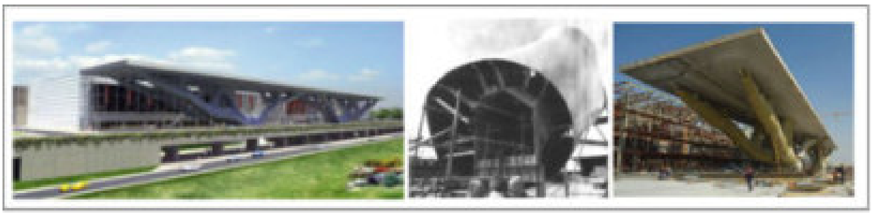

Fig. 11 Innovation in calculus versus tradition in building

Fig. 12 Detachment between virtual and built architectures

Fig. 13 Form finding—repetitive shapes through algorithms

(i) The progress in the 'innovative' designed shapes is not accompanied by a real progress in building technologies. In most cases traditional technologies are employed with very expensive working charge (Fig. 11).

(ii) This results in an escalating dichotomy between designed shape and final form, sometimes related to a feel of delusion when the effective reality imposes on the virtual one (Fig. 12).

(iii) Released the limitations of the analytical modelling that Torroja, Nervi and Musmeci complained, the architectural and structural shapes following mathematical-numerical rules may veer towards solutions of absolute geometric freedom and gratuitousness (screwed skyscrapers, dancing warped forms, etc.) and "the result is often casual [that means] subjectiveness, anecdote, dilettantism, libertinism, noise" [4]. As a plus, these outcomes, rather than truly groundbreaking, tend to exhibit a recurring figuration within a set of (similar) parameters, leading to a sense of déjà vu, easily reproducible by any software (Fig. 13).

5 Final Remarks

Today creativity imposes itself as diversity at any cost and the concept of "novelty as the foundation of the diffusion of the empire of consumption has taken over […]" ([12], p. 17), "The new becomes novelty and abandons any foundational claim to the establishment of differences (homologation). Everything is substantially still despite the incessant whirlwind of proposals, still in a time that pretends to be without history" ([11], p. 9). As a plus, the results, far from being really innovative, show, within the domain of (similar) parameters, repetitive figuration. Today creativity often prioritizes diversity without necessarily leading to true innovation. Instead, there's a focus on surface-level novelty, and even though there's a constant stream of new ideas, the underlying essence remains unchanged. The mention of the Manfredi-Nicoletti and Musmeci helicoidal skyscraper suggests that these architectural designs might exemplify this phenomenon. Despite their apparent novelty, they could be reproduced easily using numerical methods, suggesting that the apparent innovation might be more about style or surface aesthetics than genuine groundbreaking ideas (Fig. 13).

A solution to the perceived problem of superficial novelty and lack of true innovation in design could be related to the use of shape/topological optimisation approaches for creating new forms that are both innovative and practical for construction. This approach aims to ensure that the generated shapes are not just aesthetically novel but also structurally sound and buildable, aligning with the principles of the Vitruvian triad, which emphasizes the balance among utility, solidity, and beauty in design.

Shape optimisation involves using mathematical and computational methods to find the most optimal shape of a structure given certain constraints and objectives. Topological optimisation, on the other hand, focuses on determining the best distribution of material within a given design space to achieve specific performance objectives [7, 8, 23, 27]. By integrating these optimisation techniques into the design process, the designer aims to strike a balance between creativity, innovation, and practicality. This could lead to the creation of truly novel structures that not only push the boundaries of design but also adhere to real-world construction limitations and structural requirements. This approach would likely require collaboration between architects, engineers, and computational experts to ensure that the resulting designs are not only visually striking but also functional and feasible to construct. It's a way to bridge the gap between artistic creativity and engineering practicality, addressing the concerns raised above. "Creativity does not mean methodless, improvisation: in this way only confusion is created and young people are deluded into feeling they are free and independent artists. The series of operations of the design method is made up of objective values that become operational tools in the hands of creative designers" [15].

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