ABSTRACT

Introducing design innovation within structural systems normally requires the development of novel design strategies for exploring different solutions in which optimized shapes can be derived from material behaviors and force principles. This condition is particularly important for bending- and form-active structures where intricate geometrical arrangements can be produced by combining simple discrete components. The use of real-time physics-based simulations as design tools has rapidly become popular for addressing these problems. However, all numerical methods tend to lack the interactive and playful characteristics that are intrinsic in traditional analogue methods. Because of this, the intuitive and creative characteristics of digital design processes are limited, and therefore a gap between analogue and digital design practices is progressively created.

In this paper, we present a design approach we call "digital vernacular," which involves the combination of interactive and playful characteristics of empirical and experimental methods within numerical models. This approach originates from the technical framework of topology-driven form-finding, which addresses the activation of topologic spaces during real-time physics-based simulations. The presented study is placed within a larger body of research regarding simulation-based design and aims to bridge the gap between analogue and digital design practices. Two computational frameworks based on particle-based methods and a set of research projects are presented to illustrate our design approach.
ANALOGUE AND DIGITAL REALITIES
The inherent relation between aesthetic qualities and structural efficiency rising from form-finding processes is often associated with a vast range of design opportunities for generating innovative architectural solutions. This is particularly important for structural systems where complex geometric arrangements can be produced from the combination of rather simple components, as in the case of bending- and form-active structures. However, exploring those opportunities is a non-trivial task, demanding us to expand outside current modeling paradigms and to integrate material behaviors and force principles in the entire design process. For a long time, this was addressed through empirical or experimental methods to strengthen the intuitive characteristics held by analogue models to carry out fast physical calculations while dynamically altering the design. The aim hasn’t only been to create original architectural solutions, but also to introduce an insightful and methodological design practice.

In recent years, the use of real-time physics-based simulations as design tools has become an important research trend within this field. Here, simulations demand extended levels of flexibility, not common in numerical models, to facilitate design iterations and extend modeling freedom. The common assumption has been to improve the convergence rate of models without affecting its internal organization originally designed for running analysis tasks. From an initial and static topologic input, an optimized geometric model is returned, which means that the topologic problem is out of the scope of the numerical process. This clear separation is advantageous for supporting higher degrees of complexity within the numerical model, but only at the cost of losing the user-model interactivity that is distinctive in analogue methods.

This separation is even more evident when looking at the design approaches used to categorize bending-active structures (Lienhard et al. 2013). Lienhard established such a categorization according to the use of analogue and numerical methods in the design process. This categorization defines behavior-based design approaches as those that are built from empirical tests and geometry-based approaches as those that are principally driven by the experimental usage of analogue models. In contrast, the use of numerical models is fully enclosed within the integral approach, which allows users to extend the geometric control of the structure but limits their capability to alter the design at will. An example of the latter is the ICD/ITKE M1 La Tour, where the topological arrangement of GRP rods was solved through studies on analogue models. As a result, a gap has been gradually opened between analogue and digital design practices.

BACKGROUND
From Empirical to Numerical Design Practices
The concept of deriving the geometrical shape from material behaviors is not completely new in architecture. In fact, several examples of vernacular architectures in various cultures have made an extensive use of this principle. A detailed review of these structures can be found in Lienhard et al. (2013). So far, the high-tech industry of expedition tents has established design workflows that are based on the empirical analysis of full-scale prototypes (Hillberg 2018). In a more experimental context, Gaudí addressed the generation of optimized funicular geometries from the very beginning of the design process by adapting the 17th century principle of analyzing the static equilibrium of arches through an analogy with hanging cables (Huerta 2006). Such a valuable contribution was later reinforced by the renowned work of Heinz Isler, whose innovative experimental solutions addressed the design of thin shell structures (Chilton 2000). The most comprehensive study to date regarding the use of experimental methods was conducted by Frei Otto and his multidisciplinary team at the University of Stuttgart (Gass, Otto, and Weidlich 1990). Those methods permitted the identification of important design parameters for controlling the fundamental relationships between the form of a structure and the forces acting on it (Gaß 2016). All these efforts demonstrate the relevance of analogue practices and their intrinsic characteristics for conducting highly intuitive and interactive design processes.

Under these conditions, designing with numerical models necessarily demands similar levels of playfulness and interactivity within digital workflows. However, this concept contradicts classic approaches where the flexibility of the simulation is radically reduced in the service of mechanical accuracy. Particle-based methods (PBM) have become important for addressing these problems due to their relative ease of implementation, versatility, and convergence speed. The most common implementation of PBM for these purposes has been in particle-spring systems (Kilian and Ochsendorf 2005), which are force-based schemas sharing close similarities with explicit methods like dynamic relaxation (Day 1985). Since then the fastest growing efforts have been conducted to facilitate PBM’s usage within different modeling environments. In this context, an important contribution was the integration of more mechanically accurate formulations within position-based schemas, given the capacities of these schemes to improve numerical stability and convergence rates (Bouaziz et al. 2012; Bouaziz et al. 2014). Nevertheless, all these efforts
maintain the standard linear organization of the numerical workflow, which requires users to break the simulation into several steps before achieving a mature and more desirable solution.

**Network Models and Numerical Control**

The underlying principle among all numerical methods is the necessity to run calculations on top of a discretized model. Fenves and Branin (1963) are among the first to propose the use of network models based on graph theory and branch-node matrices for structural analysis. Linkwitz and Schek (1999) then used these models to address form-finding problems of tensile structures by computing force–length ratios. The dynamic relaxation method (Day 1965) and the entire family of PBM (Nealen et al. 2006) were also designed to make an extensive use of network models. The great benefit of these models is that initial conditions required for starting the numerical process can be treated independently in relation to quantifiable values and topologic properties. From a classic perspective, network models are designed to exhibit a simple and static behavior: to provide fast access to specific databases without any further specification for data modification. Our hypothesis is that such a rigid constraint produces the limited levels of interactivity reported in numerical models, and is therefore the origin of the above-mentioned gap between analogue and digital design practices.

**A Shrinking Gap Between Analogue and Digital Models**

To our knowledge, efforts for bridging this gape has not been entirely addressed in form-finding and structural analysis. Important references addressing a comparable problem, but within a completely different context, are found in the field of surgical simulators. Because these types of models are utilized to effectively train surgeons, complex simulations of soft tissues need to be combined with extended levels of user-model interactivities. For instance, training solutions for minimal invasive surgery were initially addressed through analogue models named box-trainers before progressively being switched to computer-based simulations (Constantinos 2016). In this case, numerical models can support real-time deformations in combination with dynamic topologic alterations associated with basic surgical procedures like cutting and suturing. With fast developments, efforts were naturally directed towards more immersive spaces for improving the efficacy of surgical training. In any case, new surgical routines have forced the rethinking of classic solutions to train surgeons, and in a similar way today's innovative criteria for novel architectural solutions are forcing the rethinking of the entire design process.

**DIGITAL VERNACULAR DESIGN APPROACH**

This research is then constructed under the general assumption that the activation of topology modeling within real-time physics-based simulations can bridge the gap between analogue and digital design practices, and therefore stimulates the development of novel structural typologies. Following Lienhard's categorization logic, we propose to categorize these emergent typologies within a new approach we call "digital vernacular." The digital vernacular approach addresses the design of structural systems through hybrid computational models that combine the playfulness of analogue models and the geometric complexity of numerical ones (Figure 2). This field of study is then part of a larger research group investigating simulation-based design.

The implications of activating topology spaces within real-time simulations are addressed within the conceptual framework of topology-driven form-finding. This concept suggests a more flexible numerical form-finding process wherein geometries can be variegated through dynamic calibrations of quantifiable parameters, but most importantly, can be differentiated by altering network models on the fly (Suzuki et al. 2017; Suzuki and Knippers 2018). Topologic operations that are implicitly found in analogue modeling, like adding, subtracting, cutting, joining, separating, or sliding pieces of materials, need to be integrated within the simulation-based design workflow. On this basis, designers can fully explore modeling spaces and change designs at will while perceiving their structural performance and material behavior. The most important aspect here is the necessity to constantly update the connectivity of the model without producing a mismatch in the numerical process.

This problem can be faced through continuous reconstructions of the entire database of numerical solvers. Ahlquist et al. (2015) addressed the topological alteration of spring models.
meshes by making use of an open source physics library developed by Greenwold (2018). A different study proposed the use of a computational pipeline based on Kangaroo2 (Piker 2018) and NetworkX (Hagberg et al. 2018) to support dynamic topological changes during form-finding (Deleuran et al. 2016). In both cases, physics libraries were originally designed to support static or quasi-static topological models. This means that the entire database of the numerical solver needs to sort and reallocate the required data with each transformation. For that reason, we consider this method as highly difficult to maintain due to the risk of error-prone operations.

To avoid this problem, we proposed the usage of a rule-based evolving network model for driving the numerical process (Suzuki and Knippers 2017). This model is designed with a flexible data structure that supports multiple and mutable connections between sets of particles. The model can dynamically evolve without the necessity to reconstruct the entire database of the numerical solver. However, this doesn’t necessarily secure numerical stability and convergence. Therefore, we proposed to extend additional information within the entire network model to describe current states. All sorts of topologic transformation introduced by the designer are then controlled through codified rules that are triggered by these states. We have found that this method is highly convenient for changing the connectivity of the model on the fly without producing numerical errors. As a result, all the developments presented in the following make extensive and differentiated use of this method.

MERGING FORM-FINDING REALITIES

ElasticSpace

ElasticSpace is a custom-built Java application for the design of bending- and tensile form-active structures and hybrid byproducts. The software implements a numerical model that makes use of a force-based schema with
support to continuous topologic operations on the fly. The model incorporates mechanisms to simulate linear and surface tensile elements, and beams with 3DOF per node (Barnes 1999; Adriaenssens and Barnes 2001). The connectivity of the model is stored within a pointer-based half-edge (PHE) data structure, where the required local connectivity of each mechanism is defined and tracked during the simulation. By approximating the playfulness of analogue methods, ElasticSpace allows for the design of complex geometric arrangements from the progressive addition, deletion, and modification of smaller components. The software was initially released and tested for the final installation of the Architectural Association Visiting School in Madrid 2016 by Manuel Jimenez Garcia, Seiichi Suzuki, Christina Dahdaleh, and Nagami. Design, which was designed to be used as the check-in counter at the Madrid Architects’ Association (COAM). This structure consists of a complex arrangement of robotically bent aluminium bars shaping the desk of the counter, which in turn hangs from a non-standard load-bearing network of GFRP rods that gains structural integrity through local deformations induced by bundling characteristics (Figure 3a). The elastic network is hierarchically organized according to cross-section diameters of pultruded GFRP rods ranging from 5 to 20 mm. To study methods for introducing stiffness in the structure, a computational model in ElasticSpace was used to evaluate the strategic aggregation of rods according to a specific assembly sequence logic (Figure 3b).

Another example showcasing the use of this software is the bending-active tensile hybrid (BAT01) pavilion designed by Evy Slabbinck and Seiichi Suzuki, and proposed in the context of the announcement of Pafos as the 2017 European Capital of Culture (Figure 4a). The structure is shaped from the combination of a column-like element constructed from four drop-shaped elastic rods that form a steady base, a membrane that is partially connected to the column-like element, and a floating elastic ring that tensions the membrane. With this arrangement, the hybrid structure solves all forces internally without projecting reactive forces towards the ground. The geometry of all components is varied and optimized to its specific structural behaviour. One important aspect of this study was that all topologic operations were tracked and recorded to later retrieve a chronologic inventory of transformations guiding the assembly sequence of the pavilion (Figure 4b).

More exploration of novel form-finding strategies using ElasticSpace was conducted during the Form and Structure seminar of the ITECH master program at the University of Stuttgart. As a general remark, the development of this software has shown how intuition and creativity can be fully integrated within a simulation-based design process. Yet it has also proven the necessity to address different implications relating to data-structure design, discretisation, interactivity, and decision making, which need to be entirely controlled within this design approach.

**Iguana Framework**

From previous results, efforts were focused towards the development of Iguana, which is a robust computational framework for creating custom and highly flexible form-finding implementations in different design environments. Iguana is described as a comprehensive physics library developed as a Java and C# API that makes use of concurrent and GPU-accelerated computing for numerical integration (Suzuki et al. 2018). The user can implement different numerical models that can be built with a conditional stable force-based scheme, an unconditionally stable position-based scheme, or a combination of both. An Iguana numerical model is hierarchically organized within three levels to facilitate the evaluation and modification of different parts of the simulation. We considered the macro-level as the total domain of the numerical model where it can be perceived as a single and coherent construct. The meso-level outlines specific subdomains of the model that represent collections of similar mechanisms holding a close relation to each other. This could be, for example, a
collection of cable mechanisms shaping a cable-net component that is part of a larger numerical model. Furthermore, fundamental building blocks like particles and mechanisms can be identified and analyzed at the micro-level. An extended catalogue of mechanisms, which includes shell elements (Tachi 2013; Batoz 1982), beams (Adriaenssens and Barnes 2001; Li 2017), and tensile elements (Barnes 1999), is implemented. The key feature of Iguana is the support of topology modeling during real-time simulations and an active control of interactivity through a selective activation of mechanisms. To facilitate the use of multiple types of mechanisms while keeping track of topologic changes, the connectivity of the model is stored within an array-based half-facet (AHF) data structure supporting multi-dimensional networks and non-manifold topologies. The framework is currently being used for the development of ElasticSpace2.0, built with JavaFX and IguanaGH, a Grasshopper plugin for Rhinoceros 6. The new generation of ElasticSpace, with extended support to topologic operations, was tested in designing the proposal of the Latin American Network of Fab labs (FABLAT) pavilion at the occasion of the Fab14+ Conference in Paris (Figure 5a). The model was progressively built through the interactive creation and connection of elastic rods and the generation of membrane meshes connected together to shape an intricate geometry. At this point, it was important to test how the selective activation of simplified or mechanically derived mechanisms in relation to modeling necessities

![Diagram](https://example.com/diagram.png)

**Figure 5a:**
- **a)** FABLAT Pavilion
- **b)** Selective activation of mechanism within ElasticSpace2.0.
can increase the interactivity of the design process without breaking the numerical process (Figure 5b). The basic building blocks of the model are beams with 3DOF and 6DOF per node, cables, and tensile surface mechanisms.

In addition to this, Iguana is being utilized for the ITECH master’s thesis, “Self-choreographic networks,” by Mathias Maiehofer and Valentina Soana. This research investigates the development of a dynamic structural system with multiple states of equilibrium based on the combined use of linear elastic components, robotic actuators, and computational engines. This study addresses a novel integration of numerical models and physical data to represent in real time the current equilibrium state of such a flexible structure, and to predict untested states under quite realistic conditions for assessing further transformations (Figure 6). For this specific project, a sliding joint controlled by a user-defined input was required. The problem of simulating this sliding behavior within a discretized model is that the transition from one known discrete position to another is far from smooth. This condition implies a less explicit topological change, requiring the creation of a temporary particle when the join is located within this transition and its deletion when it arrives into a known discrete position. We have realized that these types of topological transformations are particularly useful for modeling different equilibrium stages of adaptive structures. As a result, all these efforts are showing how more flexible numerical models are rapidly promoting design innovation and creating novel modes of interaction among users, designers, and structures.

**Immersive Spaces**

Given the complete design freedom reported earlier, we started to address the logical extension of these form-finding procedures into immersive spaces for enhancing the design experience. The use of virtual reality (VR) technology is continuously growing within architectural practices. At the moment, it’s mainly oriented towards the visual representation of a digital model for enhancing the perception and evaluation of architectural spaces. However, in the context of this research, VR is considered as a medium to improve the playfulness of the design process and therefore create new experiences when modeling with real-time physics. This condition is eventually deriving into the gamification of form-finding processes for mastering the design of equilibrium shapes. For conducting those routines in VR, a custom Android application for Daydream and Cardboard platforms was developed in Unity3D based on the Iguana API. For this first study, these platforms were selected because of their affordability and compatibility. In fact, Cardboard is to date the most accessible and affordable VR platform. Therefore, we decided to work only with simplified beam and cable mechanisms for addressing the design of a simple bending-active tensile hybrid structure. The perception of the three-dimensional space radically changes within the VR application, and form-finding routines need to be adapted accordingly. The user’s head orientation is controlled through gyroscope sensors in combination with a standard wireless remote controller to set the position in space and manage the dynamic creation of new elements within the numerical model. By being fully immersed into the digital space, the designer can progressively build a system while perceiving deformations and spatial qualities in a process comparable to the design of vernacular structures (Figure 7). As a result, immersive form-finding practices radically change the design experience and drive the designer into a space where analogue and numerical characteristics are merged.

**CONCLUSION**

The activation of topologic spaces during form-finding results in a powerful modeling strategy for shrinking the gap between analogue and digital practices. This condition allows for the exploration of novel structural typologies through a design process that combines the playfulness of empirical and experimental methods with the complexity of numerical models. We proposed to categorize such a design approach as digital vernacular. In doing so, efforts were required to reorganize standard numerical models based on PBM to support those required levels of flexibility and interactivity. This was addressed through the conceptual framework provided by topology-driven form-finding. Within this framework, we realized that the conceptualization of an evolving network model and the appropriate design of its data structure are particularly important for extending modeling capabilities during numerical form-finding. Such network models were primarily used for the
development of ElasticSpace and Iguana. From these developments, we presented different examples for showcasing the design of structural systems through the combination of real-time physics with geometric and topologic modifications on the fly.

We consider that the digital vernacular design approach can stimulate design innovation by entirely activating the creative and intuitive characteristics of digital design processes. In fact, this is well suited for the study of design concepts like structural adaptivity or system reconfiguration. What is more, this approach can open new questions regarding novel design to fabrication models where geometries need to be regularly recalculated for adjusting to unpredictable fabrication events.

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**IMAGE CREDITS**

Figure 6: Mathias Maierhofer and Valentina Soana, 2018

All other drawings and images by the authors.
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