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Evolution and Projection of Computational Design Theories: Generation, Analysis, Selection and Fabrication

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Abstract

We can identify a milestone in computational design theories in the intersection between paradigms derived from theories of complexity and technological developments in the early 90's. These theories provided the I foundation to build interpretation of the potential of the technology by adopting a language based on complexity to frame processes of generation, analysis, selection and manufacturing. To better understand the roots and direction of computational design theories, this study makes an in-depth literature review of four vectors involved in the formation of current dominant theoretical and technical approaches: theories of complexity, technological developments, professional practice and academia. The information collected is organized in chronological order in parallel timelines to facilitate readings exposing the intersections and synergies. The results show the emergence of theoretical approaches based on the convergence of theories and technologies, proof of concept in professional practice and consolidation in academia.

Keywords: Generative Design, Performance Analysis, Data Analysis, Decision Making & Fabrication.

INTRODUCTION

The goal of this research is building an interpretation of the origin, current state and projection of computational design theories in architecture. Although the technological developments in Computer-Aided Design (CAD) date from the 60's and 70's (Eastman, 1999), and even before the iconic Sutherland's "Sketchpad" project from 1963, it is in the early 90's when a qualitative change occurs in the way architecture conceives CAD. This change is due to the adoption of frameworks imported from theories of complexity that facilitated the process of building interpretation of the potential contribution of technology in creative processes. This intersection promoted the adoption and adaption of a pseudo philosophical language to describe both processes and results. Design theories made their own expressions from theory of complexity by extending concepts such as variation, evolution, differentiation, self-organization, or emergence (Deleuze & Guattari, 1988) to build interpretation of the potential application of existing design and analysis software (Lynn, 1998), process that is still ongoing nowadays. Nevertheless, we can also notice that more recently computational design theoretical approaches are arising purely from the capabilities of the technology itself.

The role of the architect is not only to design the building, but also the process. Today, it is inconceivable the design practice without the assistance of computational technology along each of the stages (Iwamoto, 2006). The historical pattern of importing computational methods from other disciplines such as information technology, CAD systems, analysis software, or manufacturing machinery, has allowed an exponential evolution of theoretical and methodological approaches to design.

This study explores the emergence of design theories and related methods from the interaction over time of four vectors: the theories of complexity and their impact on the generation of discourse, the technological developments that trigger the implementation of new design methodologies, experimental works by the professional practice and the evolution of the academic discourse through the CAD conferences. Specifically, we trace the evolution of four trends of development of computational design theories: generation, analysis, selection and Fabrication.

Generation - From Parametric to a Topological Modeling - Parametric modeling proposes an epistemological change by producing typologically correlated design alternatives (Oxman, 2017), however, in a limited single topological field (Bernal, 2016). Nevertheless, current research explores the emergence (Hemmerling & Nether, 2014), mutation (Harding & Shepherd, 2017) and manipulation of the topological structure, expanding the range of geometric variations (Aish, et al., 2018).

Analysis - From Simulation to Prediction. – Performance-based design evaluates form versus function (Kalay, 1999) providing feedback along the design process. Parametric analysis combines performance-based design methods with parametric modeling to facilitate the analysis of vast populations of alternatives. Current trends explore the adoption of machine learning algorithms (Belém C, et al, 2019) to find patterns that allow predicting performance of non-evaluated alternatives (Khean, 2018).

Selection - From Heuristic to Data Driven Decision Making - Expert designers typically base their decisions on experience or heuristics (Lawson & Dorst, 2009). However, this approach has limitations to discriminate within the vast design spaces of alternatives generated by either contemporary parametric analysis or machine learning enabled processes. To address these limitations, sampling techniques, in combination with sensitivity analysis (Maltais & Gosselin, 2017), are allowing to quickly quantify the influence of each parameter on the outcome and providing objective data to support the subjective process of decision-making.

Fabrication - From Cutting to Printing - Digital fabrication brought the architect closer to production (Ortega, 2013) achieving an accurate representation of complex geometries, which were previously built through laborious processes of cutting and assembling (Torreblanca, 2016). The exponential evolution of 3D printing techniques from the printer to the use of robotic arms has allowed experimentation with different materials and methods (Gramazio & Kohler, 2017). Today the focus is not only on taking these productions to real scale, but also responding to environmental conditions through simulation of multiple aspects (Sanguinetti, 2019).

This chronological study of the proposed four trends of evolution and their correlations visualizes the connections across theoretical frameworks, technological developments, relevant experimental works, and research in academia to understand the theoretical roots of contemporary computational design theories. It also traces how and when architecture adopted methods from other disciplines to model complex, evolutionary, continuous, and singular forms, highly informed and far from classical symmetry (Oxman, 2017), through the exploration and analysis of design alternatives.

METHODOLOGY: TIMELINES OF DRIVING VECTORS

Parallel timelines visualize the four vectors shaping computational design theories to identify the main milestones of each vector, facilitate readings across time and quantify the gaps between emergence and adoption of technologies. Mapping the turning points in the brief computational design history builds the narrative of the rise of theoretical and methodological developments and provides a framework to project further trends of evolution.

The timeline of theories of complexity brings together the frameworks supporting the interpretation of the potential impact of CAD technologies on professional practice and academia. The technological developments expose the early manifestations of technologies and their consolidation in the implementation of all kinds of tools. The vector of the practice brings together a catalog of experimental architectural projects emphasizing the relationships between the use of technology and the formal language. The depiction of calls and tracks of the main CAD conferences organized in thirty eight different categories, visualizes the fluctuation of the topics of interest in academia. The range of years studied is subject to the information available on the web for each conference, which is detailed below:

- Association for Computer Aided Design, ACADIA: 2011 – 2020.
- Education and Research in Computer Aided Architectural Design in Europe, eCAADe: 2001 – 2020 (2008 no information available).
- Association for Computer-Aided Architectural Design Research in Asia, CAADRIA: 2014 – 2018 (2015-2017 no information available)
- Iberoamerican Society of Digital Graphics, SIGraDi: 2010 – 2020. (2011 no information available).
- Arab Society for Computer Aided Architectural Design, ASCAAD: 2005 – 2018 (From 2007 non-periodic events).
- CAAD Futures: 2009 – 2017 (Held every other year).
- Digital Futures: 2020 (Singular global event).

The specific study of the conference topics focuses on the cross-relationship between two categories: technology and design theories. They are plotted in separated timelines showing the temporal gaps by conference, years of consolidation in academia, dominant theoretical approaches, design methodologies, evolution of topics, emerging hybrids theories, and the entry of new themes. To better understand the roots and process of formation of computational design theories, a timeline for each trend exposes the dependencies between different computational theories and the fundamental technologies they are based on.

RESULTS: FOUR TRENDS OF DEVELOPMENT

The timelines identify the main milestones of the four relevant vectors that contribute to the formation of computational design theories. Cross-readings show time lag between creating a technology, adopting it in professional practice, and consolidation in academia. For example, parametric modeling was developed in the 70's, 1985 the first software was launched, twelve years later in 1997 the first significant use in architecture was recorded, and in 2006 it was consolidated in the academia as a recurring topic. Similarly, digital fabrication, widely adopted in other disciplines such as mechanical engineering or aerospace in the 80's, and based on numerical control machines and languages initially developed in the late 40's, is a regular topic in CAD conferences only since the mid-2000s.

In academia we observe trends and new entries. The topics largest presence over time are simulation and analysis in the technology category, and digital fabrication within design theories. Regarding the most recent entries in technologies we can find the internet of things in 2016, machine learning in 2018, robotic automation in 2019 and more recently mixed reality in 2020. Chronological gaps also occur between conferences and two behaviors are recognized: the precursor conferences that include a theory or technology early on, and the conferences that include the topics late in the adoption process defining the time lags. eCAADe shows a tendency to adopt the topics early on while SIGraDi shows higher delays in new entries in the list of tracks.

3.1. GENERATION - FROM PARAMETRIC TO A TOPOLOGICAL MODELING

Computational design evolved in response to a complex set of influences that have been transforming the conception of form generation (Oxman, 2017). Today, programming languages embedding design rules make, in many cases, designer depending on these rules (Herrera, 2007). The generation process has branched out into different approaches, exploring different methodologies according to technological possibilities influenced by mathematics, biology, or theories of evolution, just to name a few (Figure1).

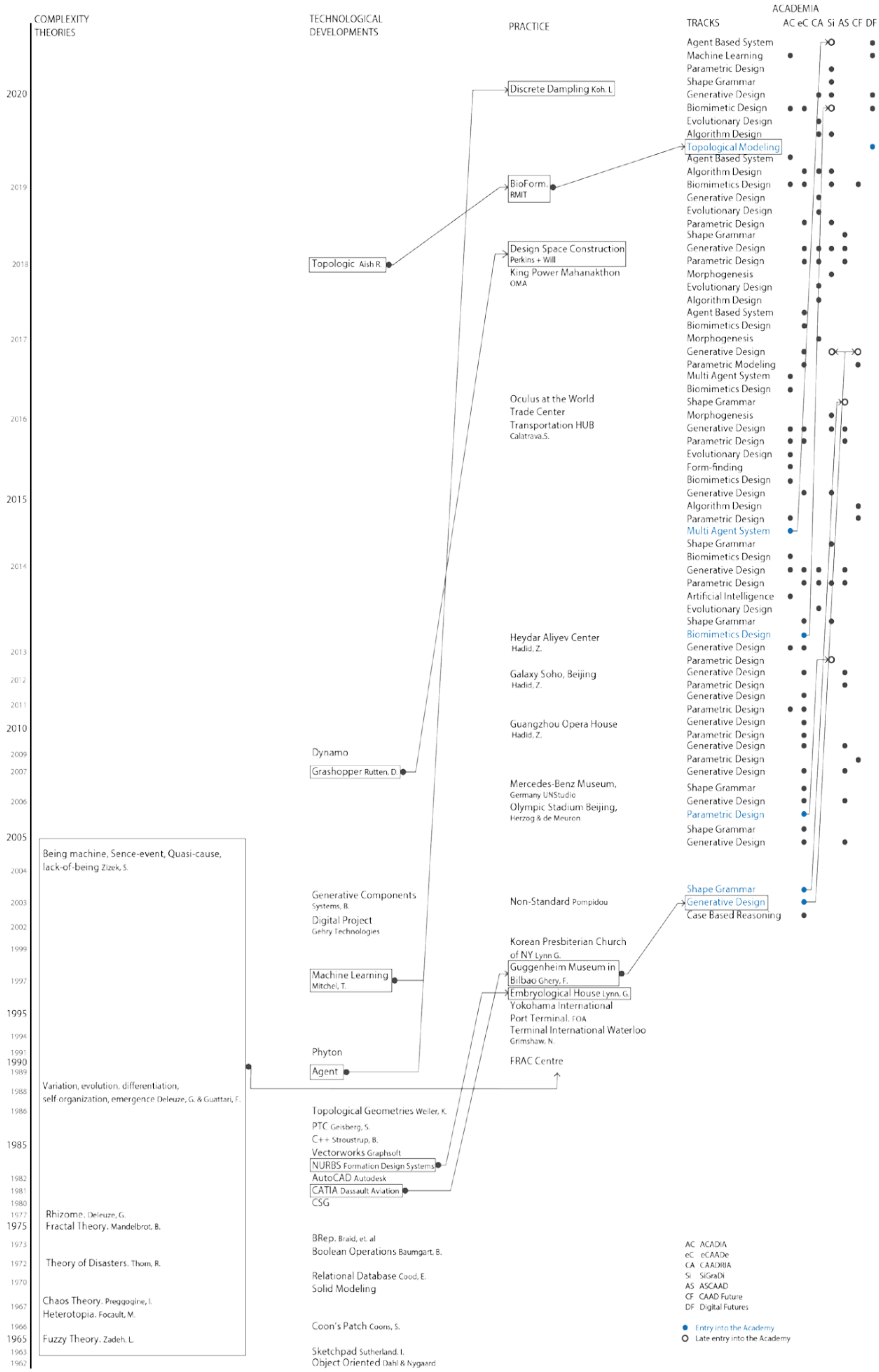

Figure 1: Generation Timeline.

Parametric design is currently one of the dominant approaches with a presence on the tracks of most CAD conferences since the mid-2000s. This is based on parametric modeling, a technology developed since the 1970s, which had its first impulse in 1985 with Samuel Geisberg's Parametric Technology Corporation (Teresko, 1993). Its adoption from engineering to architecture in 1997 marked a change where the production of design alternatives derived from the same topology has allowed and enhanced the exploration of formal complexity. This technology interpreted under Deleuzian notions of iteration, variation and evolution is the base of what is now known as parametric design. It allows instantiating complex geometries through the formalization of rules, restrictions and protocols, opening a field of exploration called design space derived from all possible combinations of input parameters. OMA's 2018 'King Power Mahanakhon' (OMA, 2009) project dismantles the typical tower typology by gradually dissolving the mass by spirally subtracting voxels. The degree of this decomposition can only be controlled by rules manipulated through parametric models.

Shape grammar, strongly influenced by mathematical logic and included as a track in eCAADe frequently since 2003, despite dating back to the 70's, has also explored the generation of different possibilities or topologies based on a set of rules (Singh, 2011). However, the idea of using design rules to generate alternatives has only become widespread thanks to parametric modeling technology. Although since its inception parametric design has generated conflicts regarding its use in early stages since the level of variation is limited to its topology, limiting the generation of options by defining a finite number of design alternatives.

As an alternative exploration, biomimetic design, also sometimes labeled biological-inspired design, references nature's models to solve problems (Torreblanca, 2020). Although it is rooted in the 1970s, even with experiences in the 1950s, it is only included in 2013 by eCAADe. Along that same line research, agent-based design is based on intelligent and dynamic systems based on programming of simple agents that interact in apparently chaotic self-organized behavior. This approach bases his discourse heavily on chaos theories in search of emerging patterns of organization resulting from the interaction of singular units. Although it dates from the late 80's, it was consolidated as track topic at ACADIA 2014 Conference. An example is the project "A systematized aggregation with generative growth mechanism in solar environment" (Lee, 2015) that generates propagation rules based on solar radiation.

Evolutionary design makes its first appearance at CAADRIA 2014. It is an iterative and incremental feedback approach (Frazer, 2009). Its predecessor, algorithmic design seeks to solve problems through the execution of a protocol (Kleinberg et al, 2005) not necessarily motivated by optimizations. Both approaches rely heavily on parametric modeling platforms for geometric manipulations, although there are also examples that rely on simple CAD software.

More recently, in response to these limitations of parametric design and the hierarchical representation of the topological structure of CAD models, an interest in topological modeling approach emerges. Included in Digital Futures 2020 Conference and with sporadic appearances in SIGraDi articles since 2016, this approach expands the design space through questioning the hierarchical structure of parametric modeling and, thus, extending the field of exploration of alternatives. It encourages the generation of alternatives based on topological mutations or variations where each topological model is a potential parametric model subject of geometric variations. Finally, since 2018 machine learning has incorporated supporting methods based on artificial intelligence that from existing design catalogs can generate new populations of alternatives not necessarily topologically correlated. The "Discrete Sampling" project presented by Immanuel Koh at Digital Futures 2020 explores the potential of deep learning in the generative design of three-dimensional shapes by automating and exploring a wide variety of cases. Although the validity of the designs produced is still in evaluation stages, the advances to get rid of the restrictions of parametric models are dramatically expanding the production of radically different alternatives in topological and geometric terms.

3.2. ANALYSIS - FROM SIMULATION TO PREDICTION

The notion of computational analysis in academia (Figure2) dates from the 90's (Abbo et al, 1992). eCAADe 2001 included simulation as a regular topic from 2001, before the other CAD conferences. On the CumInCAD platform, 1616 entries can be found under the keyword simulation. The SIGraDi 2013 Conference included performance-based design for the first time in the tracks, 13 years after its european pair eCAADe. This approach seeks to reduce uncertainty by applying dynamic simulation methods to find the options that better respond to the objectives set at the beginning of the process.

The performance simulation capabilities of different aspects have promoted approaches such as responsive design, which seeks to adapt the design to adapt to different conditions depending on the feedback of the results in a process of continuous improvement. Its consolidation as a topic in CAD conferences has a time gap between practice and academia of at least half a decade. For example, the installation of the architect Philip Beesley the "Radiant Soil" from 2008, generated a responsive and immersive lighting environment reacting to the movement of the audience, while the topic was only included for the first time in ACADIA 2012 Conference.

Since the 2010's, parametric analysis emerges from the convergence between simulation software and parametric modeling technology. Vast populations of alternatives are evaluated producing abundant data for each design. Sensitivity analysis has been used to correlate inputs and outputs and help to define priorities (Bernal et al, 2019). In turn, parametric analysis applied in different areas with different analytical models (i.e. Energy, lighting, costs, acoustics, among others) sustain multi-objective optimization processes that seek balancing performance of oftentimes conflicting objectives.

Regardless of the expansion of analysis methods for different aspects, whether for single-objective or multi-criteria optimization, since 2018 the use of artificial intelligence promises reducing response times. This technology is based on algorithms capable of learning from existing data from dynamic simulations. The use of machine learning requires a data set to train different

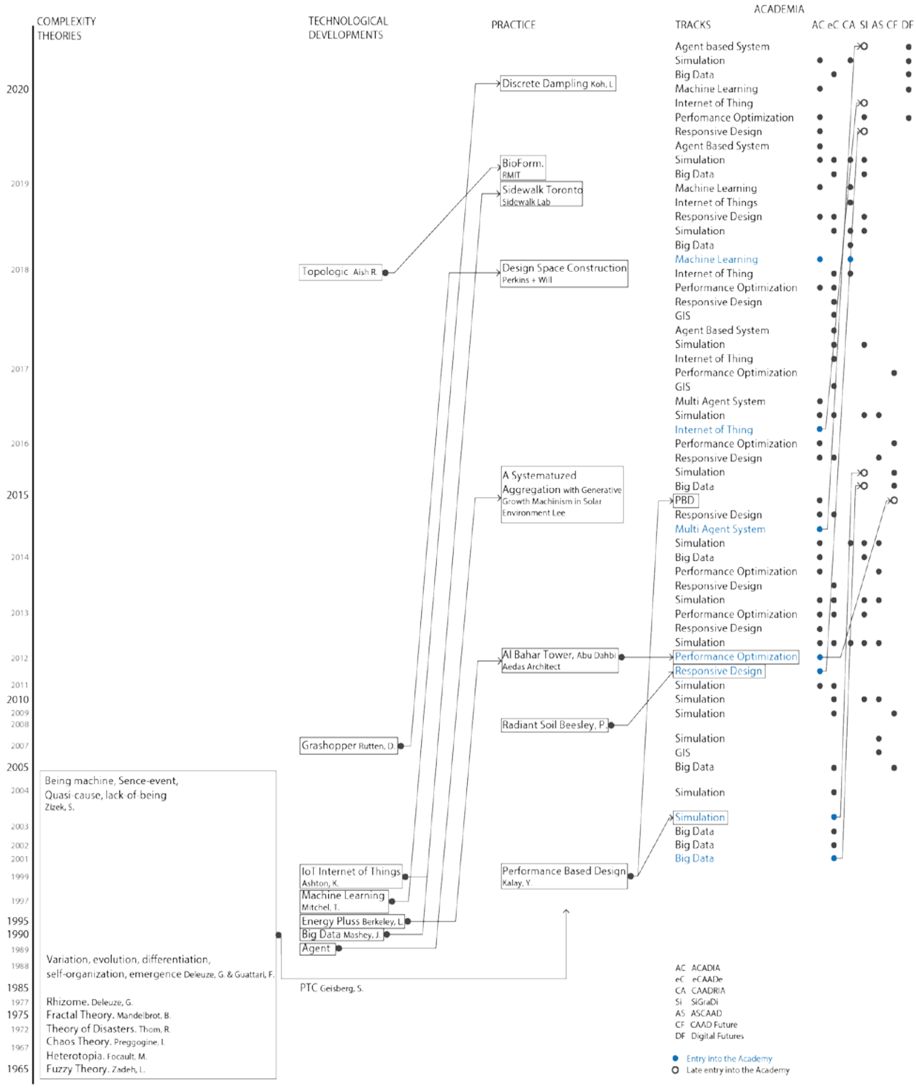

Figure 2: Analysis timeline.

algorithms (i.e neural networks, multi-layer perceptron, random forest, or simple regression) that build mathematical models capable of making predictions with acceptable levels of error about alternatives not dynamically evaluated. The "Sidewalk Toronto" project (Sidewalk Labs, 2020) combined internet of things and machine learning to generate an intelligent master plan in a constant feedback. Currently, there are 1681 publications in CumInCAD that respond to the machine learning search, of which 113 are related to prediction.

3.3. SELECTION - FROM HEURISTIC TO DATA DRIVEN DECISION MAKING

There are different techniques that support the selection of design alternatives (Figure3). In 1990 developed the analytic hierarchy process by doing pairwise criteria comparisons. Choosing by advantages, or CBA described in 1999, assigns a grade or advantage to each attribute to be compared. Between 1999 and 2006 multi-attribute utility theory determined the best alternative by assigning preferences to attributes that are combined by weighting averages. On the other hand, robust decision-making focused on selection with incomplete information (Parrish, K. Tommelein, I. 2009).

Although theoretical frameworks for structured decision-making with complete or partial information exist in other disciplines such as economics, selection methods in architecture have traditionally depended on the use of previous experience. This design expertise operates as a decision-making tree that evaluates new problems according to similar previous solutions.

Decision-making methods attempt to reflect trade-offs, values, and preferences through quantitative indicators by incorporating weights into the criteria to be evaluated to reflect the designer's preferences (Bernal, et al. 2015). The theoretical approaches in architecture regarding selection have a sporadic presence in the academic conferences. Between 2006 and 2017 it has been included in conference calls only six times, However, surprisingly, decision-making is mentioned in CumInCAD 1872 times in English and 2286 in Spanish.

The first appearance of the decision support system methodology, that was born between the 1950s and 1960s

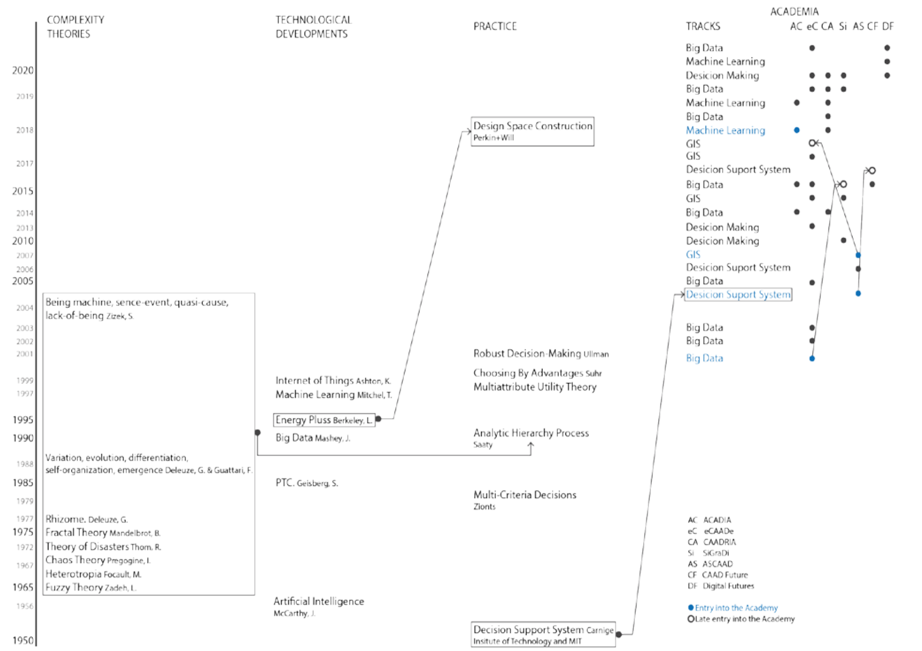

Figure 3: Selection Timeline.

at Carnegie Mellon University from a theoretical perspective and MIT from a technical perspective, was in CAADRIA 2006 (Keen, 1978). This approach is a computational support system for data analytics to objectively inform the decision-maker. Multi-criteria decisions, a term popularized by Zionts in 1979 in the field of the business, measures the fulfillment of multiple objectives by different design alternatives through comparative methods. Since ACADIA 2001, tracks dedicated to data visualization, big data and data mining explore methods for the interpretation of data derived from GIS, and more recently, from parametric analysis and predictions based on machine learning.

Heuristics have important limitations to discriminate design alternatives among vast populations of alternatives. Approaches for data driven decision-making based on statistical methods such as design of experiments allow sampling, analyzing and predicting with acceptable levels of confidence (Dhariwal et al, 2017), reducing response times. These sampling techniques, combined with sensitivity analysis quantify the influence of each parameter on the result, allowing the definition of priorities and streamlining the decision-making process.

There are two branches with respect to decision making, the one based on experience and the one that relies on data analysis. The latter show irregular presence in CAD conference calls since 2006, but with a great interest in

3.4. FABRICATION - FROM CUTTING TO PRINTING

The first dialogue between CAD and CAM technologies is attributed to the design of the Galaxy bomber between 1968-1975, although research in numerical control has been recorded since the late 1950s. This approach impacted the field of digital design for the first time in 1995 during Bernard Cache's "Objectile" exhibition where smaller scale non-standard architectural pieces were exhibited. A few years later, the Walt Disney Concert Hall project by Gehry in 2000 validated the use of this digital fabrication in large-scale architectural projects. During that same year, this manufacturing methodology began to be part of the programs of the schools of architecture (Gutiérrez de Rueda, 2017), promoting material and formal experimentation. Five years later, a digital fabrication track was included in eCAADe, followed by CAADFutures in 2009. Currently, this trend shows 5,698 papers in Spanish and 5,932 in English on the CumInCAD platform under this keyword.

During the first years of consolidation, the predominant categories in digital fabrication refer to cutting and assembly techniques exploring the use of milling machines and laser cutters (Figure4). Projects such as the "Serpentine Pavilion" in London by Álvaro Siza and Eduardo Souto de Moura in 2005 and later in 2011 the iconic Jürgen Mayer Metropol Parasol in Seville, validate the utilization of this technology on large scale projects. Derived techniques dominated the scene for the next decade and are still in development to this day.

Since 2012 3D printing, also called rapid prototyping, has been recurrently included in the calls of CAD conferences. With the introduction of robotics into computational design another technique emerged, additive manufacturing. This technique combines additive and subtractive techniques with robotic arms. This topic, introduced in ACADIA 20012, then eCAADe 2017 and, finally, in CAADRIA 2018, dramatically evolved 3D printing techniques. The "3D Print Canal House" from 2013 proposes an innovation not only from the perspective of the technique, but also from the material one by combining ornaments, structures, interior and exterior façade (DUS Architects, 2014). Gramazio and Kohler (2017) experience additive manufacturing using robotic arms with different materials. In their project "Mainstone" they explored stone printing. Today, rapid prototyping and the use of robots in construction also focus on the feasibility of the process and the results evaluating performance in terms of material and energy optimization.

In recent years digital fabrication incorporated new technologies. The 2019 "Terramia" project by MUD Architects uses drone spraying building facades, to structure an emergency home. Implementations based on computer vision combined with robotic automation can be seen since CAADRIA 2018 incorporating pattern recognition. Pinochet (2020) in the "Smart Collaborative Robotic Agents" workshop integrates the recognition of body gestures in the control of experimental manufacturing processes.

Retsin (2019), Gramazio, Kohler (2019) and Fologram last year have experimented with mixed reality or augmented construction. This hybrid approach between augmented reality and digital fabrication optimizes processes by accurately overlapping design and construction information

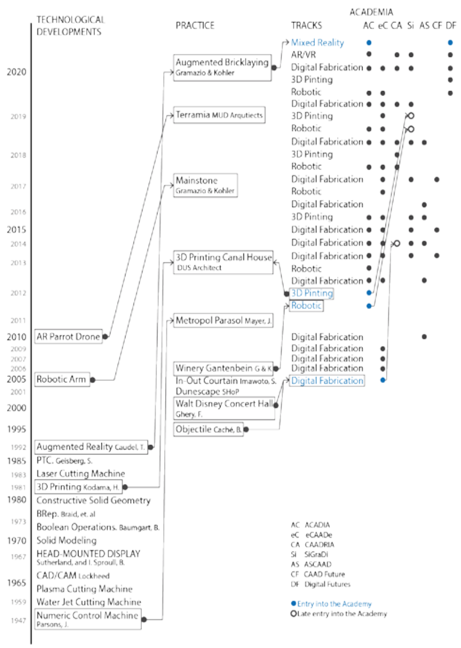

Figure 4: Fabrication timeline.

through virtual reality devices. This technique was implemented in the "Designing for Mixed Reality Fabrication" workshop taught by Fologram at Digital Futures 2020.

Digital fabrication has become one of the most recurrent tracks in CAD conferences. Research and exploration of techniques and technologies in this area have branched out into sub-theories, each applying different technology at different scales. In this trend the practical time gap practice-academia decreases until reaching almost convergence nowadays.

DISCUSSION

The main contribution of this study is shaping a framework of computational design theories that organizes from a historical perspective trends of theoretical developments and their intricate relationships. Through a hybrid pseudo-philosophical and pseudo-technical language and glossary of terms, this research seeks to provide meaning to the adoption of technologies from other disciplines, a process which continues actively evolving nowadays. Moreover, this study also visualizes through time the convergences between theory, practice, technology and academia, hardware and software adoptions, possible coincidences and relevant events that configure the brief and prolific history of computational design.

The study exposes a historical diagonal across three specific moments: the creation of technology, the exploration in practice, and the adoption in academia. Specifically, the consolidation in academia through tracks shows a chronological gap of around ten years compared to the first experiments in architectural practice, which in turn are up to two decades away from the beginnings of technologies until the 2000s. This gap has been decreasing dramatically in the second half of the last decade. During the last five years, the emergence of new design theories and related methodologies seem to arise from technological influences without a reference to a theoretical framework with philosophical roots such as the case of the 90's. This is the case of prediction or mixed reality. Each one arises purely from the potential and opportunities of technologies. This almost combinatorial phenomenon, without major theorizing, is revitalizing the proliferation of new methodological approaches in computational design.

Complexity has evolved from capabilities of technology decreasing the protagonist of a theoretical philosophical framework that in the beginning allowed us to name formal complexity. Concepts like blobs or genetic algorithms only remain in the nostalgia of some. The new generations are formed from the possibilities of the software and hardware, ignoring in many cases the roots and discourses behind their creations. The general questions that arises from this study are what are those current technological developments in other fields that are about to impact architecture in the near future, and how the discipline can anticipate and accelerate these changes.

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