Rethinking Computer-Aided Architectural Design (CAAD) – From Generative Algorithms and Architectural Intelligence to Environmental Design and Ambient Intelligence

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Abstract. Computer-Aided Architectural Design (CAAD) finds its historical precedents in technological enthusiasm for generative algorithms and architectural intelligence. Current developments in Artificial Intelligence (AI) and paradigms in Machine Learning (ML) bring new opportunities for creating innovative digital architectural tools, but in practice this is not happening. CAAD enthusiasts revisit generative algorithms, while professional architects and urban designers remain reluctant to use software that automatically generates architecture and cities. This paper looks at the history of CAAD and digital tools for Computer Aided Design (CAD), Building Information Modeling (BIM) and Geographic Information Systems (GIS) in order to reflect on the role of AI in future digital tools and professional practices. Architects and urban designers have diagrammatic knowledge and work with design problems on symbolic level. The digital tools gradually evolved from CAD to BIM software with symbolical architectural elements. The BIM software works like CAAD (CAD systems for Architects) or digital board for drawing and delivers plans, sections and elevations, but without AI. AI has the capability to process data and interact with designers. The AI in future digital tools for CAAD and Computer-Aided Urban Design (CAUD) can link to big data and develop ambient intelligence. Architects and urban designers can harness the benefits of analytical ambient intelligent AIs in creating environmental designs, not only for shaping buildings in isolated virtual cubicles. However there is a need to prepare frameworks for communication between AIs and professional designers. If the cities of the future integrate spatially analytical AI, are to be made smart or even ambient intelligent, AI should be applied to improving the lives of inhabitants and help with their daily living and sustainability.

Keywords: Artificial Intelligence (AI) · Computer-Aided Architectural Design (CAAD) · Architectural intelligence · Generative algorithms · Environmental design · Ambient intelligence

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1 Introduction

The new developments in Information and Communication Technologies (ICT) and Artificial Intelligence (AI) bring revelations of emerging smart cities. AI and robotics, bits and bricks, are becoming integral parts of architecture lexicons [1] and paradigm for smart cities (Michael Batty discusses the role of AI in smart cities and informing urban planning and design [2]). Artificial Intelligence (AI) can be defined as the capability of machines to work intelligently with complex tasks. Intelligently is typically used when the level of tasks reaches some complexity threshold, especially in being able to somehow adapt to unforeseen circumstances. This paper looks at how architects and urban designers can use new computational paradigms in AI and reflects on the role of AI in future digital tools and professional architectural and urban design practice. Computer-Aided Architectural Design (CAAD) can be defined as the application of computational science and technology in the field of architectural design. There are no discussions about Computer-Aided Urban Design (CAUD) even though there are new digital tools for urban design and planning e.g., City Information Modeling (CIM) [3].

CAAD research is characterized by pursuit of architectural intelligence and the development of generative algorithms for buildings and cities. Molly Wright Steenson [4] narrates the story of developing architectural intelligence in the mid-1960s and through the 1970s [5–7] when architectural machines and automated architects became of interest. Inspired by this technological enthusiasm, William J. Mitchell provided a theoretical framework in the book *Computer-Aided Architectural Design* [8, 9], juxtaposing computer systems and architectural practices into algorithms for generative architectural designs and design problem solving. The generative algorithms progressed from parametric models to proceduralism (even applied in CIM for the generation of cities and digital urban planning and design [3, 10]). Commercial city procedural modeling software such as CityEngine (developed by Paskal Müller [11, 12]) and building and city procedural models at the academy (see SkylineEngine [13]) are available.

Architects do not use software that automatically generates buildings and cities, despite the advancements in generative algorithms and proceduralism. The digital tools for architects gradually evolved from Computer Aided Design (CAD) to Building Information Modeling (BIM). CAD is a generic term for programs used for designing, from design of images, logos and other graphics products to the design of machines, buildings and cities. BIM denotes software used by architects and engineers to design, construct, operate and maintain buildings and infrastructures. Even though advertised as BIM, Graphisoft ArchiCAD and Autodesk Revit are used to draw and visualize architectural projects as CAAD (CAD for Architects). This paper aims to broaden the perspective on CAAD (in relation to BIM apps and CAUD/CIM conceptualization) as software for architects that should closely resemble their practices in designing buildings and interiors, neighborhoods and cities. Architects and urban designers have a diagrammatic knowledge and work with design problems on a symbolic level. The digital tools gradually evolved from CAD to BIM software with symbolical architectural elements. The Machine Learning (ML) techniques that characterize development of AI must understand the symbolical architectural and urban elements as well as deliveries from interior design, floor plans, sections and elevations to master plans for neighborhoods. AI has the capability to process data with ML algorithms referred to as Neural Networks (NN) or

Artificial Neural Networks (ANN) and it can interact with designers. Training the various NNs and ANNs with symbolical representations and data from professional practices can create a generation of analytical and interactive AI that can aid design processes. These NNs or ANNs can link symbolical architectural representations with information flows, big data and virtual reconstruct environments. Architects would not only focus on shaping a building in a closed 3D virtual space, but they can harness the benefits of analytical AIs in creating environments.

The morphogenesis of CAAD tools follows advancements in digital technology. The computer and AI reemerge as leitmotifs in architecture and planning every 20 to 30 years with new innovations. The embryonic CAD phase started on mainframe computers in the 1960s with the first program Sketchpad. AI, architectural machines and automated architects were buzzwords in the mid-1960s and through 1970s [5–7]. The developments in Information Technologies (IT) and the widespread of personal computers in the 1980s shaped the CAD, BIM and GIS systems of today. William Gibson published the book *Neuromancer* in 1984. Cyberspace is defined as electronic, invisible space that allows the computer to substitute for urban space and urban experience [14]. The concepts of cyberspace and informational cities [15] became increasingly important. In the last decade, with the widespread use of mobile phones as Information and Communication Technologies (ITCs) there is globalization of cyberspace (as the virtual domain of artificial worlds or as codespace [16]) and AI gets a more prominent role (with learning from big data). The architectural intelligence becomes ambient intelligence that positions architecture globally and in cities. There is a need to prepare frameworks for communication between AIs and professional designers. The following two sections present the historical development of CAAD and digital tools for architects in three morphogenetic periods. The fourth section reviews new development of AI discussing possible application. The fifth section discusses environmental design and ambient intelligence, urban/environmental morphology and design theory. The six section summarizes the history of CAAD and digital tools and discusses future developments. The final section summarizes and concludes the paper.

2 Computer-Aided Design (CAD) and Generative Computer-Aided Architectural Design (CAAD)

Computer-Aided Design (CAD) is a generic term for programs used for designing (from the design of images, logos and other graphics products to designing machines, buildings and cities) or the application of computational science and technology in the field of design. In a context of CAD for Architects there are two histories. This section focuses on "automated design" and generative algorithms for designing buildings and urban environments. The following section describes transition to Building Information Modeling (BIM) as CAD for Architects.

The first CAD program Sketchpad was developed in 1963 by Ivan E. Sutherland [17] at Massachusetts Institute of Technology (MIT). The computational models and computer graphics conceptualizations from Sketchpad for representing points, lines, curves and surfaces remain until today. Sketchpad was developed as a human-computer communication system using the TX-2 computer at MIT Lincoln Laboratory. The human designer communicated with the computer with light pen on the screen that acted as electronic drawing board. Timothy E. Johnson [18] presented Sketchpad III in the same year as a CAD system that was capable of creating three-dimensional designs. Sketchpad was presented at the conference Architecture and the Computer organized in 1964 in Boston where it inspired a debate on automated design. The conference brought together architects like Christopher Alexander and Nicolas Negroponte together with engineers like Marvin Minsky, the cofounder of the MIT's AI lab, and Steven J. Coons who led the MIT's CAD initiative. Walter Gropius (whose assistant Ernst Neufert wrote the influential architecture standardization handbook Architects' Data) opened the conference and the discussion centered on the computer and AI in a context of architectural intelligence. The engineers discussed how computers will change architectural practices and automate designing. Marvin Minsky predicted that computer graphics systems that would be able to sketch, render and generate plans within 10 years. He envisioned that architectural offices would be able to use computer graphics and projected that within 30 years (cited in [4]):

> *"Computers may be as intelligent, or more intelligent, than people. The machine may be able to handle not only the planning, but the complete mechanical assembly… Eventually computers will have hands, visions and the programs that will make them able to assemble, buildings, make things at a very high rate of speed, economically. Contractors will have to face automation in construction just as the architects will have to face automation of design. Eventually, I believe computers will evolve formidable creative capacity"*

Steven A. Coons was professor of mechanical engineering and a researcher in interactive computer graphics. He was involved in advising Ivan E. Sutherland and supervised Timothy E. Johnson who developed Sketchpad. Coons saw CAD programs as digital design tools for engineers focusing on human-computer interfaces. Coons [19] writes:

> *"By "design" I mean the creative engineering process, including the analytical techniques of testing, evaluation and decision-making and then the experimental verification and eventual realization of the result in tangible form. In science and engineering (and perhaps in art as well) the creative process is a process of experimentation with ideas. Concepts form, dissolve and reappear in different contexts; associations occur, are examined and tested for validity on a conscious but qualitative level, and are either accepted tentatively or rejected. Eventually, however, the concepts and conjectures must be put to the precise test of mathematical analysis. When these analytical procedures are established ones the work to be done is entirely mechanical. It can be formulated and set down in algorithms: rituals of procedure that can be described in minute detail and can be performed by a computer."*

The research on CAAD can be tracked through two traditions. There is a critical CAAD tradition that emphasizes design theory and interactions between human designers and computer. Steven A. Coons prioritized computer graphics over automation. He worked on CAD systems that will augment the engineers with new modes of interaction with computers. He was furthermore skeptical of the notion of "automated design" where creativity is transferred from the designer to the creator of the program. He writes [19]:

> *"There is much talk of "automated design" nowadays, but usually automated design is only part of the design process, an optimization of a concept already qualitatively formed. There are, for example, computer programs that produce complete descriptions of electrical transformers, wiring diagrams or printed-circuit boards. There are programs that design bridges in the sense that they work out the stresses on each structural member and in effect write its specifications. Such programs are powerful new engineering tools, but they do not depend on an internal capability of creativity; the creativity has already been exercised in generating them."*

Nigel Cross [20, 21] shows a similar skepticism about automated design, pointing out that studies had suggested that using computers in design might have adverse effects, such as inducing stress, on designers. The only positive effect of CAD was to speed up the design process. In his doctoral thesis from 1974 [21, cited in 20) he concludes:

> *"The computer should be asking questions of the designer, seeking from him those decisions which it is not competent to handle itself. The computer could be doing all the drawing work, with the designer instructing amendments ... We should be moving towards giving the machine a sufficient degree of intelligent behavior, and a corresponding increase in participation in the design process, to liberate the designer from routine procedures and to enhance his decision-making role."*

Nigel Cross summarized his doctoral thesis in the book *Automated Architect*. The book concludes with a CAAD system checklist emphasizing human and machine factors, and their specific roles in the design process. In the same CAAD tradition, Thomas W. Maver founded the research group ABACUS (Architecture and Building Aids Computer Unit, Strathclyde) at the Faculty of Architecture of the University of Strathclyde, Glasgow. He set out a plan to develop CAAD emphasizing the relationship between the computer and the design activity of architects, and he has continuously referred to the "deadly sins" of CAAD [22]. In the 1970s, Tom and Nigel compiled the Bulletin of Computer-Aided Architectural Design (BoCAAD). BoCAAD consisted of a few sheets of Xerox-copied news reports, and they mailed it out free to people working in or interested in CAAD. Tom and Nigel also created TV programs on use of digital tools by architects. Nigel Cross concludes the preface of *Automated Architect* with the words:

> *"This book is dedicated not to the machines, but to the humans"*

The second CAAD tradition enthusiastically embraced "automated design" and developed generative algorithms for designing buildings and cities. William J. Mitchell led a CAD course at University of California Los Angeles (UCLA), and he developed the theoretical framework behind CAAD [8, 9]. He described computer systems and their relationship with architectural practices. He presented algorithms for generative architectural designs and generated floor plans of buildings automatically based on rulesets for archetypical buildings [23]. He continued writing about computers and the logic of architecture developing a unique design theory that moves from computer graphics to architectural symbolic thinking (as design elements and typologies) [24]. William J. Mitchell will establish the Smart Cities Group at MIT in 2000s expanding the scope from architecture to cities, sadly stopped by his early passing away in 2010. The term CAAD since then has been linked with computer and programming enthusiasm and generative algorithms that characterizes William J. Mitchell research. In the same tradition Philip Steadman [25–27] developed archetypal buildings and "morphospace". Morphospace defines the architectural elements and morphological transformations of an archetypical building.

Between the two traditions stands a group of avant-garde designers starting with Greg Lynn who experimented with digital architecture by using new 3D software [28–32]. Greg Lynn discussed folds and blobs to describe the results of new LOFT tools in 3D modeling software. This tradition furthermore links to the CAD/CAM integration that combines CAD with automated factories and Computer-aided manufacturing (CAM). The 3D printers and robotic factors that emerged in the 1980s helped to create new avant-garde furniture and architecture from the 1990s. Parametrism as a term for this architectural style was coined by Patrick Schumacher, studio partner to Zaha Hadid. The parametricism created stararchitect status e.g., for Frank Gehry and Zaha Hadid. Parametric modeling is simultaneously used for generative algorithms where human designers or computers modify parameters. It established 3D modeling parametric software such as Rhino (supported by Grashopper) as default in architectural education since the 2000s (ArchiCAD had an addon Profiler that acted as a LOFT tool). However, there are differences in the application of the 3D modeling parametric software. Frank Gehry and Zaha Hadid as many other architects used 3D tools to create a unique architectural design. Greg Lynn argued for using parametricism in designing variation (e.g., instead of producing one hundred copies of a same chair, small changes in parameters of furniture design would create one hundred similar, but original chairs). Greg Lynn envisioned "unique generativeness" by manipulating parameters, instead of optimizing design. Lynn's approach has never become the mainstream of parametricism and it is a worthy direction for future thinking and developing new CAAD tools. Sean Keller [32] writes.

> *"Greg Lynn, for instance, has said that his design was motivated by the desire to use computers in a way that was unpredictable, but not completely arbitrary; and has described the computer as a "pet" which is partially domesticated and partially wild."*

Even though CAAD has been used to describe critical approaches, the term predominantly links with computer and programming enthusiasm and generative algorithms that characterizes William J. Mitchell's research or the parametricism of stararchitects like Frank Gehry and Zaha Hadid in practices. A younger generation of researchers continued the parametric modeling and generative algorithm tradition particularly in a context of City Information Modeling (CIM). One research direction of CIM [3] links to generative city algorithms inspired by the shape grammars of George Stiny ([33]; e.g. [34–41]). Independently from CAAD historical developments, the pattern language of Christopher Alexander [42–44] and shape grammars of George Stiny [33] inspired computer scientists to develop procedural models for generating buildings and cities. The proceduralism links to morphological theories. Urban morphology dissects urban elements and factors and composes them in a hierarchical generic structure of streets, lots and buildings in a context of morphologically informed urban design [45–55]. The procedural models use the same generic morphological structure to automatically generate from building façades to entire neighborhoods [11–13, 56–59]. They use hierarchies of urban design and architectural elements and sets of rules to create buildings and urban environments in 3D at various Level of Details (LoDs) [60–62]. The procedural models generate 3D from Geographic Information Systems (GIS) data [13]. AI techniques such as Generative Adversarial Networks (GANs) were used to add geometric and texture details on procedurally generated buildings based on morphological elements [63]. Even though by Christopher Alexander (see the critique [64] and George Stiny moved away from CAAD and did not create computational models from their design theories, the pattern language and shape grammars have had a profound influence on programmers and computer scientists and architects who developed generative algorithms (even more than the works of William J. Mitchell and Philip Steadman that started and continued in the tradition).

3 From Computer-Aided Design (CAD) to Building Information Modeling (BIM) Apps for Architects

The first CAD system came in 1960s. Sketchpad and URBAN5 worked with a light pen as input. URBAN5 included AI as a conversional assistant that helped architects in the design process. The widespread diffusion of personal desktop computers with a computer mouse at the end of the 1970s and 1980s (e.g., Apple II, Apple III and Apple Lisa and x86 series processors by Intel) rendered both the light pen and AI obsolete. Autodesk AutoCAD was released in 1982 and it made possible to draw architectural projects with lines, arcs and dimensions. It recreated the drawing board of architects with the T-square in a digital form with a computer mouse. AutoCAD dominated architectural design practices until the emergence and spread of Building Information Modeling (BIM) software, namely ArchiCAD (initially developed for Apple Lisa in 1984 and transited to Windows in the mid-1990s) and Autodesk Revit (in the 2000s).

The history of BIM started as two parallel developments. Bojár Gábor founded Graphisoft, a programming company in Hungary in the 1980s. Graphisoft launched ArchiCAD, a 3D modeling software that aimed to create photorealistic visualizations of architecture. The difference between ArchiCAD and AutoCAD was that ArchiCAD used building elements as walls, slabs, doors, windows and so on as 2D symbols on a plan and created various 3D representations (including sections, elevations, architectural details, axonometries and perspectives). ArchiCAD digitized the famous handbook *Architects' Data* (often called Neufert, by its author Ernst Neufert) in its building elements that do not show only the 2D symbol, but also the spaces needed to operate (e.g., furniture elements in kitchens or bathrooms). ArchiCAD like AutoCAD worked as digital drawing boards, but the difference was that ArchiCAD created sections, elevations, architectural details, axonometrics and perspectives automatically from the 2D symbols on the plan.

In AutoCAD, architects draw sections, elevations and architectural details manually and they used elevations to create 3D visualizations.

Jonathan Ingram [65] narrates the second BIM history. An engineer by training, he programmed the software packages Sonata and Reflex in the 1980s and 1990s to make a building model. He sold the software to a company that went on to develop Revit. Sonata, Reflex and Revit, like ArchiCAD use architectural elements (walls, slabs, doors, windows and so on), together with generic CAD (lines, arcs, dimensioning, and so on). Autodesk purchased Revit in 2002 to create a competitor on the BIM market that brought success to Graphisoft and ArchiCAD making Revit currently the most popular BIM software. Revit inspired a BIM revolution in the 2000s. The vision of Jonathan Ingram was to create a software that will be used both for drawing architecture and managing construction works. Reflex was programmed to support project management, in contrast to ArchiCAD that could create a list of building elements with price tags, but it posed many difficulties in implementing them for project management. The Industry Foundation Classes (IFC) initiative was intended to create international inventories of building elements together with the construction industry, but the various contexts internationally and even locally never created databases or libraries with products and costs. The complex building models have disadvantages for managing construction projects. Contractors and engineers prioritize completing constructions and reality does not always correspond to architectural drawings and BIM representations. The construction sites are not as tidy as factory floors. Buildings do not work as machines in factories where every building element must be controlled. When constructed, some building elements e.g., walls might not change with centuries. In practice, the BIM model is more a virtual approximation than a digital twin for building management.

While there is evolution from CAD to BIM, the planners and urban designers keep to traditional design skills such as creating scale models, sketching, using notations and drafting over printed two-dimensional cadastral maps that derive from GIS. There is no Computer-Aided Urban Design (CAUD) as expansion of CAAD or BIM, but there is a second stream within the City Information Modeling (CIM) advocacy that aims to create digital drawing boards for urban designers [66–68]. Table 1 shows differences between CAD, BIM and GIS software that is used by architects while designing buildings and cities. The BIM software works with architectural design elements (walls, windows, doors, etc.) instead of geometric elements (points, lines, polygons and solids) as in typical CAD software. GIS like CAD uses geometric elements, but predominantly in two dimensions.

Table 1 shows that generative algorithms, procedural models and AI techniques are not used in the typical packages, even though tools as LOFT or various parametric design tools are integrated in BIM and 3D modeling software (they are available from the 1990s). The two traditions in CAAD, the critical and generative design can be summarized in a context of architectural intelligence as: the automated architect (researched as generative design by Nigel Cross [7]) and architect-machine symbiosis, as analytical and conversational AI who aids the architect (advocated by Nicolas Negroponte [5, 6]). The architect-machine symbiosis links to the critical tradition in CAAD, but it emphasizes AI. Nicolas Negroponte formed the MIT's Architectural Machine Group in 1967, aiming to create (soft) architectural machines that would work together with architects

Table 1. Architecture and urban design software and its linkages with architectural and urbanism practices and AI.

	CAD software	BIM apps	GIS software
Software packages considered	Autodesk AutoCAD, 3DS Catia, 3DS SolidWorks	Autodesk Revit, ArchiCAD	ESRI ArcGIS, QGIS, ESRI City Engine
Human-computer interface	Screen and computer mouse	Screen and computer mouse	Screen and computer mouse (with scripting box)
Programming interface	Not typical for CAD software. Dynamo and Refinery used for visual programming in AutoCAD	ArchiCAD uses GDL as programming interface for designing objects (not common)	Using scrips is common for GIS software e.g., VBscript and Python strips in ArcGIS- QGIS uses Python for scripting-
Design environment	2D (top, down, left, right) and 3D (perspective, axonometry)	2D (plans, sections, elevations, details) and 3D (perspective, axonometry)	2D in GIS. 3D in City Engine (axonometries and perspectives) and 2D-3D in CityGML[a]
Design toolbox	Generic 2D and 3D elements (lines, arcs, solids, nurbs, etc.). AutoCAD uses BLOCKS as generic design elements	Design elements (walls, columns, slabs, windows, doors, etc.) placed on plan	GIS uses generic 2D elements (points, polylines and polygons). City Engine makes hierarchy of streets, lots and buildings
Link to architectural practices	Generic 2D/3D software. AutoCAD uses BLOCKS as generic object	Digital drawing board, use of design (building) elements, visualization architecture	Not used by architects
Link to planning and urban design	Used for drawing master plans	Sometimes used for drawing master plans	GIS is used for drawing master plans and executing spatial and network analyses. CityEngine is sometimes used for visualizations
Procedural generation	Not included	Profiler in ArchiCAD can generate 3D from 2D shapes	CityEngine is a procedural generator of cities. GIS has no procedural models
Artificial intelligence	Not included	Not included	Not included. Some AI techniques are used

[a] There is no software for CityGML CityGML is a data model for storage and exchange of virtual cities aiming to integrate BIM and GIS by combining GIS data models (e.g. shapefiles) with Industry Foundation Classes (IFC).

and learn about architectural practices [5, 6]. In this context, the term "soft" refers not only to architectural intelligence of the computer, but also intelligent environment as evolving organism. Negroponte's architectural machine URBAN2 and URBAN5 were CAD systems who integrated a dialogue with an AI (the conversational program ELIZA), light pen and touchscreen as human computer interface. URBAN5 was an interactive graphic system that engaged in a dialogue with the human designer about the design process. The system was meant to adapt itself to the human designer thus becoming a design partner. However, the AI was not sufficiently sophisticated, and the experiment failed [4, 69]. The unsuccessful experiments with conversational AI discouraged new experiments, despite new developments in conversational and generative AIs.

Even though there was a half century of advocacy for integrating architectural intelligence, architects like Nicolas Negroponte created early CAD systems that interacted directly with a light pen and with the screen and had a dialogue with an AI, but they vanished in the 1980s with new CAD software that used computer mouse and monitors (these became larger and larger and replaced the drawing board). Today the computer pens and touchscreens are reemerging, but that has not influenced CAD, BIM or GIS software. At the same time, there are new developments with AI that can be applied to architecture and urban design.

4 New Developments in Artificial Intelligence (AI) and Possible Applications in Architecture and Urban Design

Artificial Intelligence (AI) can be defined as the capability of machines to work intelligently with complex tasks. The machine mimics humans in setting goals, making plans, considering hypotheses, recognizing analogies and carrying out various other intellectual activities [70]. Artificial neural networks (ANNs) or neural networks (NNs) are computational analogies of the human brain. The ANNs use concepts of logic and analogies to theorize and solve problems, learn from data and improve automatically. AI process data with Machine Learning (ML) algorithms. Training NNs and ANNs includes the input of data. Figure 1 illustrates the evolution from traditional approaches and Machine Learning (ML) to Deep Learning (DL). ML and DL algorithms can be used to achieve classification, regression, clustering and prediction by learning and analyzing large amounts of data. These results can, in turn, be used to help make engineers and designers (architects etc.) to make decisions. In general, ML and DL algorithms may be further classified into three machine learning paradigms, i.e., Supervised learning (S), UnSupervised learning (US) and Reinforcement Learning (RL). Supervised learning makes use of labeled input-output pairs as training data and derives a computational model between input and output data. In contrast to supervised learning, unsupervised learning makes use of training data. Unsupervised methods are appropriate in contexts in which it is difficult to obtain labeled data. More precisely, unsupervised learning can be used to cluster data into groups based on similarity of features, and to identify relationships between such identified clusters. RL is a different way where no training data is provided, and it does not have an explicit training phase. The algorithm builds and updates a DL model based on an agent's interaction with its own environment and develops a strategy to maximize a predefined reward. Figure 1 illustrates AI approaches and applications. Various ANNs or NNs, ML and DL techniques are often used across the S, US and RL spectrum.

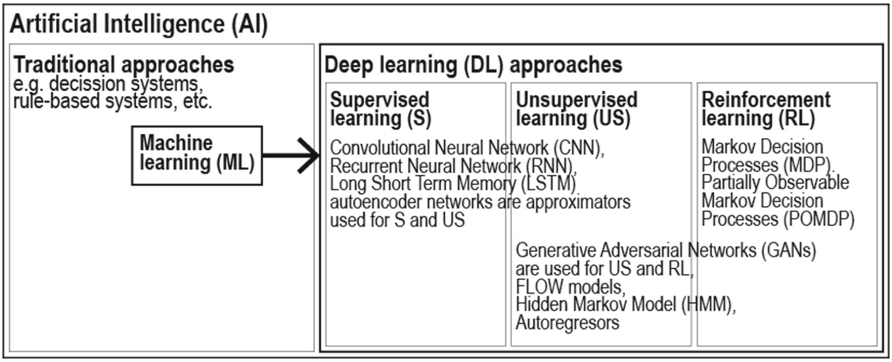

Fig. 1. Evolution of traditional Artificial Intelligence (AI) and Machine Learning (ML) approaches to Deep Learning (DL)

The smart city inspired research on big data and AI in various applications from the scale of the home [71] to the city [72, 73]. DL algorithms have been significantly advancing smart city applications. However, they have not been integrated in the practices of designing buildings or cities. Their application is mostly analytical. Compared to traditional AI approaches; DLs provide improved capacity to deal with big data and to detect and extract more patterns and features. Convolutional Neural Networks (CNNs) have been used for computer vision-based perception and recognition of design elements [74]; procedural modeling and urban simulations [75]; and Deep Graph CNNs for analyzing 3D topological graphs of buildings [76]. ML methods have been applied for predicting land uses [77]. Generative Adversarial Networks (GANs) has been widely used for creating new virtual images and 3D shapes. GANs were firstly introduced by Ian Goodfellow [78] and applied in generating 2D images, videos and 3D content, and image to image translation. Deep Conditional Generative Adversarial Networks (DCGAN) [79] are trained on an objective function that is conditioned on some class labels. GANs are currently being used in digital cities [63], for style transfer of architecture, which extracts a 3D architecture model from the ML generated 2D image. GANs are also used for depth estimation of architecture [80], for generating synthetic building mass models [81] and for generating street scape images [82]. Despite these experiments, the new AI approaches have not been integrated in the CAD or BIM software (or CAAD) that architects work with in their daily practices.

5 Environmental Design and Ambient Intelligence

The computer and AI reemerge as a leitmotif in architecture and planning every 20 to 30 years with new innovations. We are in a new wave of enthusiasm for digital tools. AI gets a more prominent role (with learning from big data) and it can analyze environments (computer vision and image recognition) and text (for example in search engines). Architects can harness the analytical capabilities to deliver not only floor plans and sections of buildings, but environmental designs. AI can improve the lives of inhabitants and help with their daily living and sustainability, by identifying problems at design stages and informing architects and urban designers. However, there is a need to prepare a framework for communication between analytical AIs of environments and professional designers. Architects and urban designers have diagrammatic knowledge and work with design problems on a symbolic level and the data input for ML algorithms and the structure of NN/ANN must follow. Christopher Alexander criticized the application of computers (and AI) as an end [64] developing an architectural and urban design theory emphasizing design problems [42–44, 83]. Architects work with design problems on a symbolic level between context and form (Fig. 2). ML algorithms and the structure of NN/ANN work at a scale of geometry, metrics and attributes (F2/C2). They also work at a level of symbolic representations and patterns, elements and rules that are not always measurable (F3/C3).

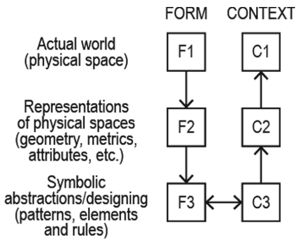

Fig. 2. Understanding the design process/abstractions of the city [83]. Urban designers work with symbolic abstractions.

The concept of design worlds describes the process of designing. The design worlds are environments inhabited by designers when designing. Design worlds act as holding environments for diagrammatic design knowledge [84, 85] where urban design and morphology are entangled [86–89]. The current BIM apps create design toolboxes with geometric elements (points, lines, polygons and solids) and architectural design elements (walls, windows, doors, etc.) that are used in designing and the architectural design elements in BIM represent a symbolic level. However, the symbolic abstractions that are used by architects for urban design are not common in CAD or GIS. There is no Computer-Aided Urban Design (CAUD) that expands the digital toolbox of BIM. GIS has very limited design capabilities and it is in 2D. The symbolic abstractions (referred to as patterns by Christopher Alexander) are complex and involve spatial practices (knowledge/behavior). Ambient intelligence is defined as the capability of humans, computer and robotic systems to understand and represent the environment and the spatial knowledge/behavior of humans. The spatial/spatial behavior includes perceptional layers of nested environments (Fig. 3). Urban morphologists have worked on a morphological structure of cities to inform urban designers [45–53]. Figure 3 illustrates one example of morphological structure (Fig. 3C) supported by three representations (Fig. 3E). The diagrammatic knowledge and expressions of urban designers often implies transforming 3D spaces into 2D symbolic representations. Urban designers in practice commonly combine theories and representations to create design toolboxes.

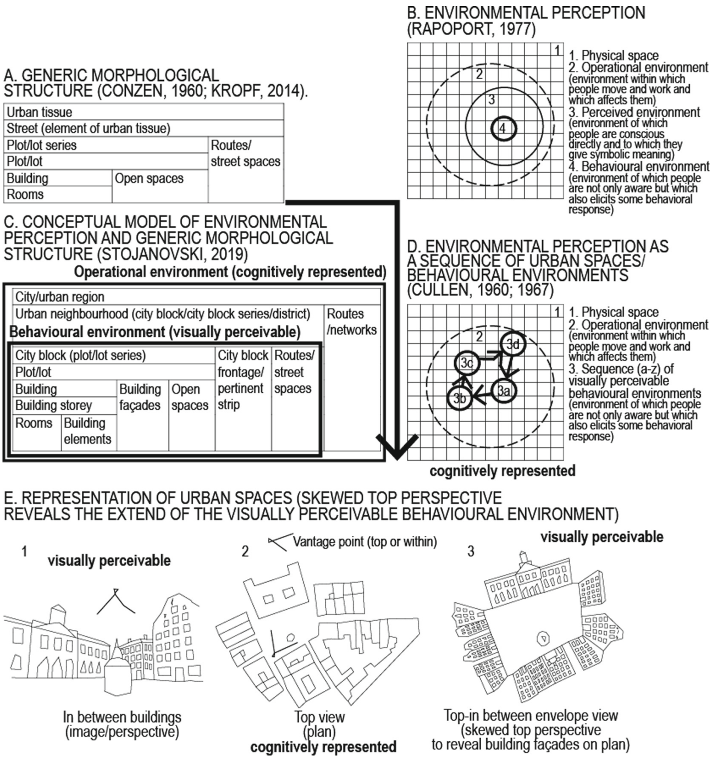

Fig. 3. Understanding generic morphological structure and environmental perception as morphological information for ambient intelligence and environmental design [48, 52, 66, 90–92].

In the generative tradition of CAAD, William J. Mitchell and Philip Steadman started to develop computational and morphological methods and programs for algorithms to generate buildings and cities. Figure 4A illustrates the typical generative algorithm [see 8–9].

A generative algorithm can create millions of variations (in a context of Greg Lynn originality parametric design advocacy), but this produces the "problem of 10 000 bowls of oatmeal" that conflicts the parametricism. Kate Compton, a computer scientist and expert on procedural generation writes on her blog:

> *"I can easily generate 10,000 bowls of plain oatmeal, with each oat being in a different position and different orientation, and mathematically speaking they will all be completely unique. But the user will likely just see a lot of oatmeal. Perceptual uniqueness is the real metric, and it's darn tough."*

The second aspect of generative CAAD is the automatic design process within a computational model as design environment. Table 1 shows the typical design environment for CAD, BIM or GIS that do not go from geometric elements (points, lines, polygons and solids) and architectural design elements (walls, windows, doors, etc.) to a hierarchy of environmental elements. There are various hierarchies and elements. There lies

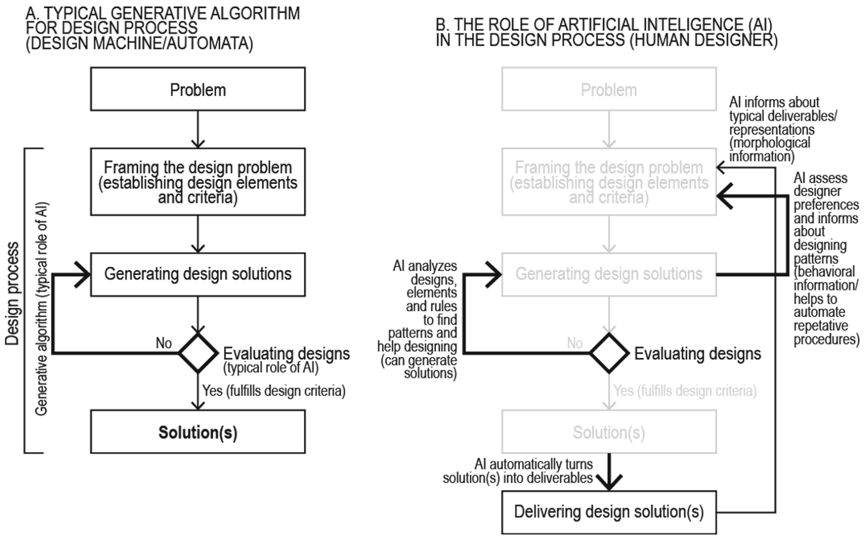

Fig. 4. Artificial Intelligence (AI) in generative algorithms and proposed new roles of AI in informing environmental design, morphological consideration and sustainability [66]. The AI does not deliver solutions, but informs the human designer in a symbiotic relationship as advocated by Nicolas Negroponte [5, 6], but unsuccessfully tested with older conversational AIs [4, 69].

a great potential to use AI not as design machines, but as analysts and programmers of these design environments. While todays CAD, BIM and GIS software acts as IT (closed system), the ICT revolution in the last decades allows to network computers and create AI that can aid designers across the globe. The buildings are nested in layers of environments from the morphology of the plot and adjacent street spaces, location in the neighborhood, city and region, to the global scale from which they draw their resources. While this can be overwhelming to a human designer, AI does not need to deliver the right “oatmeal”, but bring analytical information to cook it. AI can link isolated CAD and BIM drawing boards and with analytical algorithms in GIS, and big data analyses of information flows that circulate around smart cities. This can bring environmental layers in architectural design. The AI that works with elements of buildings, cities and environments as human designer will develop ambient intelligence as spatial knowledge. AI mimics humans in setting goals, making plans, considering hypotheses, recognizing analogies and carrying out various other intellectual activities. ANNs/NNs are computational analogies of the human brain that use concepts of logic and analogies to theorize and solve problems, learn from data and automatically improve [70].

6 Discussions

This paper presents two traditions in CAAD. Steven A. Coons, Thomas W. Maver and Nigel Cross are critical to “automated design” and discuss CAD/CAAD that emphasize the human-machine interfaces and the relationship between the computer and the design activity of architects. William J. Mitchell and Philip Steadman started a CAAD tradition to develop morphological methods and programs for algorithms to generate buildings and cities. Between the two traditions stands a group of avant-garde designers starting with Greg Lynn who experimented with digital architecture by creatively using digital tools. This tradition furthermore links to the CAD/CAM integration that combines CAD with automated factories and Computer-aided manufacturing (CAM). CAAD in the future must escape the historical precedents as generative algorithms and create software that enables environmental design and integrates various design and morphological theories and AIs capable of ambient intelligence on various resolutions, from the room as architectural space to the street aligned to the building and its wider local, regional and global context. As a human designer it is impossible to process the large amounts of data and information flows that are currently circulating, but AI has new capability to both analyze data and communicate with human designers.

Even though there was a half century of advocacy for integrating architectural intelligence or automating architectural practices, many architects and urban designers remain reluctant to use software that automatically generates architecture and urban designs. Architects instead use digital tools that gradually evolved from Computer Aided Design (CAD) to Building Information Modeling (BIM) software. A good start for developing computational models are the BIM apps which have integrated building elements and rules on a symbolic level. Architects and urban designers have a diagrammatic knowledge and work with design problems on a symbolic level. The digital tools gradually evolved from CAD to BIM software with symbolical architectural elements. The Machine Learning (ML) techniques that characterize development of AI must understand the symbolical architectural and urban elements as well as deliveries from interior design, floor plans, sections and elevations to master plans for neighborhoods. AI has the capability to process data with ML algorithms that can grasp the symbolics of patterns, elements and rules, if the data input includes hierarchical morphological structures (from a scale of a building with its elements, the city with urban elements, to the environment that includes landscape and transportation flows).

BIM denotes software used by architects and engineers to design, construct, operate and maintain buildings and infrastructures. The BIM representation ideally also creates a digital twin that closely resembles the physical building. However, the BIM application does not correspond closely to the practices of construction engineers. Construction engineers can program and tend to code their own structural models. When leading and managing construction projects they rely on their expertise and professional networks. The buildings do not work as machines and the construction sites are not tidy as factory floors. Contractors and engineers can experience more problems with complex BIM representations for managing construction projects, than architects who need to deliver renderings and technical drawings. In practice, despite the broad BIM applications, the software (as ArchiCAD or Revit) is used like CAAD (CAD for Architects), but without use of generative algorithms or AI techniques that should be integrated in the future and not only to analyze building elements, but also elements of the environment.

This paper describes architecture from a perspective of environmental design (its structure and elements). Ambient intelligence is defined as the capability of humans, computer and robotic systems (that will be embedded in cities) to understand and represent the environment and the spatial knowledge/spatial behavior of humans. The spatial knowledge/spatial behavior includes environmental perception layers of nested environments (Fig. 3). The BIM apps create a hierarchy or structure of building elements, but CAD, CAAD (generative algorithms) or GIS software does not support it. Furthermore, these structures can be very complex, but they are patterns and AI can help in creating a hierarchy or structure if the data is labelled. The CAAD and CAUD must expand to integrate a larger morphological structure (Fig. 3). The current CAD and BIM apps create a building information model where buildings are designed in isolation. The architectural scope of an isolated building excludes the broader environmental design context (a CAAD sin of unsustainability [22]) or insights in the urban/environmental morphology such as relations to adjacent streets and surrounding buildings. Today architects work on buildings in the isolated 2D or 3D virtual environment, while planners and urban designers either manually execute spatial and network analyses in GIS or they sketch over printed GIS backgrounds. Procedural models and AI techniques are not used and they can help with integration of the data. However, there is a need to integrate and label the input data for ML.

To grasp the complexity and symbolics of architecture and urban design the ANNs/NNs must be supervised, meaning it will start with data with predetermined concepts and definitions. Though experience and interaction with humans, machines can be supervised in understanding human concepts and definitions. These machines acquire their data through processing images or text (or code) and there is a need to frame not the problems, but the structure of patterns, elements and rules (that create the diagrammatic knowledge and design symbologies). The following section discusses architects and urban designers in future AI interactions and reflects on the role of AI in future digital tools and professional architectural and urban design practice.

The application of Artificial Intelligence (AI) spans from the scale of the human body (including medicine and bionics) to humanoid robots and artificial humans and control systems for environments including surveillance. Architects and urban designers have also looked at designer AIs not purely from a technician's perspective, but as a competitor (artificial human) that designs buildings and cities. The AI is not the competitor, but programmers who create NNs (that enable generative designs). Architects like Nicolas Negroponte created early CAD systems with conversational AI that interacted directly with a light pen with the screen and had a dialogue with an AI, but they vanished in the 1980s with new CAD software that used computer mouse and monitors (that became larger and replaced the drawing board). Today the computer pens and touchscreens are reemerging, but that has not influenced CAD, BIM or GIS software. The conversational AI are also not preferred and probably might be considered as nuisance. Design studies [20] had suggested that using computers in design might have adverse effects, such as inducing stress, on designers. The only positive effect of CAD was to speed up the design process. The future digital tool should consider the role of AI in human-computer and programming interfaces, design environments and toolboxes (Table 1), but not use design theory as a procedure to generate designs, but to help and interactively automate boring parts of architectural and urban design process.

CAAD as digital tool for architects (even BIM that goes into symbolic representations and inventories of building elements) does not consider the worlds of human designers (theorized by Donald Schön [84] and discussed as computer and human designer factors by Nigel Cross). Architects and urban designers envision and illustrate building and cities artistically. Through practice, they develop unique design toolboxes and worlds. The programmers of BIM and CAD software do not focus on unique design toolboxes and worlds. They tend to be rational problem solvers before eccentric stylists. The digital tools, ICTs and AIs have not addressed the uniqueness and artistry as well as the trademarks of architects and urban designers as artists. Greg Lynn's parametricism in designing variations and use of folds and bulbs is an example of a unique application of the available design toolbox, but it is very difficult to create a unique element (e.g., a series of façades from Gordon Cullen's [91, 92] townscape analyses). Greg Lynn envisioned "unique generativeness" by manipulating parameters, instead of optimizing design. Lynn's approach has never become a mainstream of parametricism and it is a worthy direction for future thinking and developing new digital tools (or creatively using the existing). Lynn worked with tools (LOFT) that were programed before. There is sometimes a need of a typical design toolbox, tailor made, that has not been addressed by programmers But future conversational AI can help not only with analyzing, but also programming design elements and toolboxes.

In the end, the digitization challenges require ethical consideration. Every technology has the potential for both positive and negative impacts on society and this is especially true of inherently disruptive technologies such as AI, pervasive computing and ambient intelligence. When a new technology is applied without due consideration, unintended negative impacts may emerge despite the best intentions of its designers. It is therefore important that the application of such technologies to future cities be considered carefully and comprehensively from ethical perspectives involving a diverse range of actors. Potential misuses or unintended implications of the application of technologies should be considered in addition to their anticipated benefits. There are many challenges for the responsible practical deployment of AI supported tools and infrastructures. These include *transparency,* or how to make artificial systems that enable a better understanding of how they reach decisions, how and why they may fail and what the implications of those failures will be. *Bias*, in which the decisions made by an AI are biased due to limitations in its training data or the assumptions encoded in its decision-making processes. *Privacy*, the need to ensure that individuals from whom data is collected have consented to it and to limit unintended uses of the data. If the cities of the future are to be made *smart* or even somehow *ambient intelligent*, in which they are not just a passive backdrop to inhabitants, but actively shape their lives, then a key question is to what degree should that influence be allowed to extend, how apparent it should be and how to ensure that it will be applied to improving the lives of inhabitants, rather than becoming a means with which to control or exploit them.

7 Conclusions

This paper presents a historical record of Computer-Aided Architectural Design (CAAD) and juxtaposes current digital tools for CAD, BIM and GIS. The term CAAD is closely linked with generative algorithms and architectural intelligence while many architects and urban designers remain reluctant in using software that automatically generates architecture. A generative algorithm can create millions of variations (in a context of

Greg Lynn's original parametric design advocacy), but this produces Kate Compton's "problem of 10 000 bowls of oatmeal" that conflicts with the parametricism. Architects instead use digital tools that gradually evolved from CAD to BIM software, that represent symbolical architectural elements. Architects work with design problems on a symbolic level including unique patterns, elements and rules that are seldom available in CAD. BIM has a large inventory of building elements, but it cannot be used in designing cities. Urban designers tend to sketch over 2D maps printed from GIS. The design elements and symbolic abstractions are not common in CAD or GIS. BIM corresponds to the needs of most architects who design buildings, but this is done in an isolated 3D cubicle without considering the wider environmental context (the morphological structure including adjacent street, the neighborhood, the transportation flows and the city and the global reach). The architects who design buildings do not see the wider environmental layers (as CAUD or environmental design/the cities have global reach today with factories in China and wastelands in the Pacific). The future digital tool should consider the role of AI in human-computer and programming interfaces, design environments and toolboxes (Table 1), but not use design theory as procedure to generate designs, but to help and interactively automate boring parts of architectural and urban design process (e.g., searching for a map in GIS and printing it as a background).

In the future of CAAD must move away from the historical precedents such as architectural intelligence and generative algorithms and perhaps embrace BIM apps as good example of digitizing the design environments and toolboxes for architects who create building plans. But BIM is limited to isolated buildings that are modelled in detail to be further managed. CAAD and CAUD should bring in urban and environmental elements to enable architects in producing environmental designs. There is a need to prepare frameworks for communication between professional designers and AI. This paper presents urban morphological conceptualizations that are start to conceptualizing input data for AI that can learn about environmental design and ambient intelligence. The environment structure includes a layer of nested environments. Ambient intelligence is defined as capability of humans, computer and robotic systems (that will be embedded in cities) to understand and represent the environment and the spatial knowledge/spatial behavior of humans. The morphological/environmental structure of elements should be conceived as data input to AI with ambient intelligence/spatial knowledge across layers of nested environments. The software should integrate various design and morphological theories and AI capabilities to link to big data and develop ambient intelligence at various resolutions, from the room as architectural space to the street aligned to the building and its wider local, regional and global context. As a human designer it is impossible to process large amounts of data and information flows that are currently circulating, but AI has a new capability to both analyze data and communicate with human designers.

In the end, the digitization challenges require ethical consideration. Every technology has the potential for both positive and negative impacts on society and this is especially true of inherently disruptive technologies such as AI, pervasive computing and ambient intelligence. If the cities of the future are to be made *smart* or even somehow *ambient intelligent*, AI should be applied to improve the lives of inhabitants and help with their daily lives and sustainability.

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