Journal of Architectural/Planning Research and Studies (JARS) Vol.22(1).2025
https://doi.org/10.56261/jars.v22.269892

The Silicon Architect: Transformation Towards a Data-Centric Mindset

Wasin Kemkomnerd[1]* and Chamnarn Tirapas[2]
[1,2] School of Architecture and Design, King Mongkut's University of Technology Thonburi, Bangkok, Thailand
*Corresponding author email: wasarticletwo@hotmail.com
Received 29/04/2024 Revised 5/06/2024 Accepted 15/07/2024

Abstract

This paper investigates the emergence of a novel 'data-centric' mindset within architecture and its implications for the architectural design process. Defined by engagement with new technology (Data Science, Big Data, Machine Learning) this mindset is driving new insight toward novel aesthetics and ultimately new disciplinary hypotheses. The literature review first tracks distinguishable transitions in the architectural mindset through the architects that have embodied them (Master Builder, Beaux-Art, Modernist, and Parametric Architect) culminating with what is here termed the 'Silicon Architect'. Next, three archetypal case studies reveal how the architectural design process is re-potentialized through a data-centric mindset, allowing architects to ultimately escape their imaginative limits and arrive at new disciplinary ambitions. The data-centric inclinations of these architects have resulted in a fusion of human-machine cognition. Through this 'composite' cognition, architects can now push beyond more typical ambitions (i.e. the creation of novel forms) toward an encounter with notions of 'hypotheses generation' and 'disciplinary prospection' via non-human cognitive input. This new mindset emerging in the Silicon Architect is set to re-direct the architectural design process, and in doing so, help the discipline escape the limits of its own paradigmatic imagination in ways that operate beyond human cognitive capabilities. In this sense, research sheds light on the influences that may shape future architectural design processes and the architects who may evolve.

Keywords

Data-centric Mindset; Silicon Architect; Design Process; Composite Cognition; Machine Learning

1. Introduction: The Data-Centric Mindset and the Architectural Design Process

As the architectural design process undergoes an increasing level of digitalization, architects are shifting their mindset to exploit the abundance of data being made available (Knippers et al., 2021). This digitalization is occurring through the greater inclusion of ‘data-centric’ approaches into the architectural design process (i.e. Data Science, Big Data, Data Mining, Machine Learning, Augmented and Virtual Reality, Artificial Intelligence, Digital Twins, Large Language Models, Image Generators etc.) transforming its capacity to achieve ever-greater complexity of building design and performance (Almusaed & Yitmen, 2023; Ploennigs & Berger, 2023; Manzoor et al., 2021; Limchutrakul & Srisutapan, 2021).

Architects have themselves been incubating within this progressive digitalization of the architectural design process, maturing a mindset able to capitalise on data and extract architectural value from it through data-centric virtuosity. These architects have begun instrumentalising their mindset, using it to amplify the potential of the architectural design process and the complexity it can deliver. The simplest expression of this desire can be seen in the analysis of continuous data streams to enhance building performance (Ochiai et al., 2011). This has evolved into the automation of software that instantaneously generates optimal floor plans in real time (Zhu & McArthur, 2020). A further step in complexity has seen the creation of pattern recognition algorithms used to support the re-generation of building façades (Bacharidis et al., 2020). Recently, in more sophisticated actualizations a predictive capacity has been developed to infer, from initial architectural conditions, data on future urban air-flow (Xiao et al., 2019) and resource consumption via Digital Twin (Ke et al., 2019). Ultimately, this data-centric aptitude has incorporated Machine Learning into the architectural design process, resulting in an ability for architects to bypass their imaginative limits towards the generation of new disciplinary insights (Andrasek, 2019).

Given this scenario, our work questions how the emerging data-centric mindset is engaging with contemporary technology to advance the design process and drive disciplinary development. This seems ever-more relevant with the allure of recent Artificial Intelligence software, particularly the capacity of Machine Learning. Its successes have shown that “it’s already way beyond what humans can do” (Wainwright, 2023). Moreover, Mrosla et al. (2019, p. 48) express how “data can be connected to one another in ways humans have never thought”. The “surface-deep” images achieved through text-to-image software (i.e. Midjourney, Dall-E, Stable Diffusion etc.) have already announced ideation that “humans haven’t thought of yet” (p.53).

This rich spectrum of data-centric approaches epitomises the mindset crystallizing in the architect and what can be achieved through it. Its success is drawing attention to the ‘under-delivery’ of a more orthodox architectural design process, one whose existing conventions reveal it as outdated and in need of transformation (see Table 1).

Table 1. Orthodox design conventions contrasted with data-centric alternatives**

	Existing conventions (traditional mindset)	**Replaced conventions** (data-centric mindset)
DESIGN PHASE **Conceptual design:**	■ Design direction dictated by personal preference and experience of architect ■ Use of 'analogue' data collection methods i.e. interviewing, case-studies, magazines, photography etc. ■ Existing images for inspiration sourced online (Architizer, Dezeen, Pinterest, Instagram etc.)	■ Diverse and multiple sources contributing to design direction (Prime Weber Shandwick, 2015) ■ New digital data collection methods (i.e. apps, sensors, avatar), with rapid AI data analysis to respond to contingencies (Darko et al., 2020) ■ Image Generators (i.e. Midjourney, Dall-E etc.) to instantaneously create inspirational ideation (Euchner, 2023)
Schematic design:	■ User experience typically assessed post-occupancy leading to the costly amendment of previously undiscovered building errors ■ Energy, finance, pollution profiles etc. assessed retrospectively once a building becomes fully operational	■ User experience investigated prior to construction via immersion to adopt a user's perspective (i.e. disabled, elderly etc.) (Herrera et al., 2018) ■ Predict possible scenarios for energy profiles, finances, pollution footprints at design stages (Seyedzadeh et al., 2018)
Design development:	■ Digitally-unconnected representational drawing limiting data sharing from design phase to consecutive phases ■ Future operational issues estimated from drawings, interviews, expert opinion etc. ■ Single design solution imagined, communicated, and executed	■ Digital data created in the design phase re-used in following phases of construction and building operation (Jupp & Awad, 2017) ■ Immersive environments allow investigation of potential future issues (Paes et al., 2017) ■ Multiple simulations run to find the optimal design solution (Behzadan et al., 2015)
CONSTRUCTION PHASE **Pre-construction:**	■ Architect's and contractor's individual experiences used to avoid potential construction complications ■ Construction issues tackled post-construction	■Buildings tested by avatars prior and during construction stage to locate construction issues (Eiris & Gheisari, 2017) ■ Construction methods tested virtually ahead of time (Sun et al., 2021)
Construction:	■ Unexpected performance problems in building dealt with when appearing in the real-world (unable to anticipate)	■ Able to predict and anticipate performance prior to full construction (Alambeigi et al., 2017; Pratama & Dossick, 2019)
OPERATION/ MANAGEMENT PHASE **Building Management, Operations and Maintenance**	■ Collecting data for the appraisal of a building's performance currently comes with a time-gap following post-construction ■ Effective decision-making data collected from users 'post-construction' to provide future management directions ■ Primarily analogue methods used to collect operational data (i.e. interview, photos, surveys etc)	■ Uninterrupted real-time data streaming via sensors enabling facility managers to instantly assess and respond to volatile conditions (Dinmohammadi & Wilson, 2021) ■ Opinions crowdsourced and assimilated from the opinions of the many, not the few (Wilson et al., 2018) ■ Continuous data streams allow the inference of patterns from data to predict building behaviour (Ahmed et al., 2017)

****Note.** The direct comparison shows areas of underperformance in the traditional design process through dated conventions and their more contemporary replacements.

From a pragmatic perspective, engagement with data-centric technologies like AI offers the potential for both automation and augmentation. Yildirim (2022, p. 111) states "automation seeks to replace humans in executing tasks, whereas augmentation seeks to enhance human capability". As these methods continue to gather momentum, they commensurately reveal the redundancy of current design traditions and a contemporary cluster of architects that are "disillusioned with what they [see] as an outmoded way of working" (Wainwright, 2023, para. 6). Thus, as this novel mindset extends the potential of the architectural design process, a former traditional approach to design is being exposed for its limitations and superseded.

Such alternatives are out-competing existing architectural conventions for design, construction, and operation of buildings. Adherence to a traditional architectural design process, accomplished through a set of digitally-unconnected representational drawings is becoming increasingly untenable (Tamke et al., 2018, p. 1/25). As the architectural design process irrevocably transitions toward the use of highly-exchangeable, data-intensive digital representations of buildings, the need to exploit data-rich methodologies is set to guarantee the future presence of architects, with their data-centric capacities, and novel mindset.

2. Literature Review

A systematic on-line review of reputable academic journals was undertaken to provide a theoretical grounding for the emergence of a new mindset. This involved identifying relevant keywords, curating a list of credible academic sources, and synthesizing the collected information to form a coherent narrative for each mindset. Evidence for the potential emergence of this novel mindset was then progressively inferred as an undercurrent across extensive academic literature and documented design processes taking hold in the field. Although this research is comprehensive, it has several limitations. Investigating historical changes in architectural mindsets depended on available and complete sources. Historical records were at times fragmented, hindering comprehensive understanding. Additionally, the interpretation of historical data, by different authors, could result in divergent interpretations and potential conclusions. To address these issues, we attempted to corroborate data through multiple sources, avoiding reliance on any one singular source.

2.1 Embodied Mindsets: From Master Builder to Silicon Architect

Kramer (2016, p. 31) refers to 'mindset' as "a worldview, mental model, or set of beliefs and assumptions we hold about ourselves, our organizations and the challenges we face". As such, mindsets clearly can be transitioned into and out of, whereby as a previous mindset is shed, so too are the limits of "how we see, think, feel and act" (p.32). In leaving an existing mental model, one is free to rethink others.

In this narrative review, the mindset of the architect is similarly understood as a temporary assemblage, consolidated over time, then reconfigured in response to new influences. Thought of in this way, it is possible to trace a series of former embodiments that have chronologically emerged, endured, and subsequently been relinquished. The mindset of the architect has been influenced and transformed by the hand-craftsmanship of the late 19th century, the mechanization and industrialization of the 20th century, and most recently 21st century digitalization. It has been in a reciprocal transformation with architecture's disciplinary evolution and made distinguishable through the architects that have come to embody them. As technological advances have migrated from other disciplines to influence the architectural design process, the architect's mindset has continuously reconfigured in response to them. A discernible series of prior transitions are here characterized via Master Builder; Beaux-Art; Modernist; and Parametric Architect. The review culminates with the inclusion of the 'Silicon Architect' and their expression of a data-centric mindset.

2.1.1 The Master Builder

The early Master Builders exercised a broad range of architectural knowledge through a holistic mindset. Characterised by its intuitive, resourceful, and problem-solving nature (Holm & Schaufelburger, 2019, p. 14) this mindset was forged through centuries of trial and error, permitting a “seamless service” from initial vision to completed construction (Beard et al., 2001, p. 13). The Master Builder’s all-encompassing approach was the predominant method for building in the Western world prior to the industrial revolution (Abrams, 2008, p. 143).

The modern Master Builders of the early 19th and 20th centuries were equally distinguishable by a holistic mindset (Figure 1). Both imaginative and pragmatic, they orchestrated the entirety of a project from inception to completion.

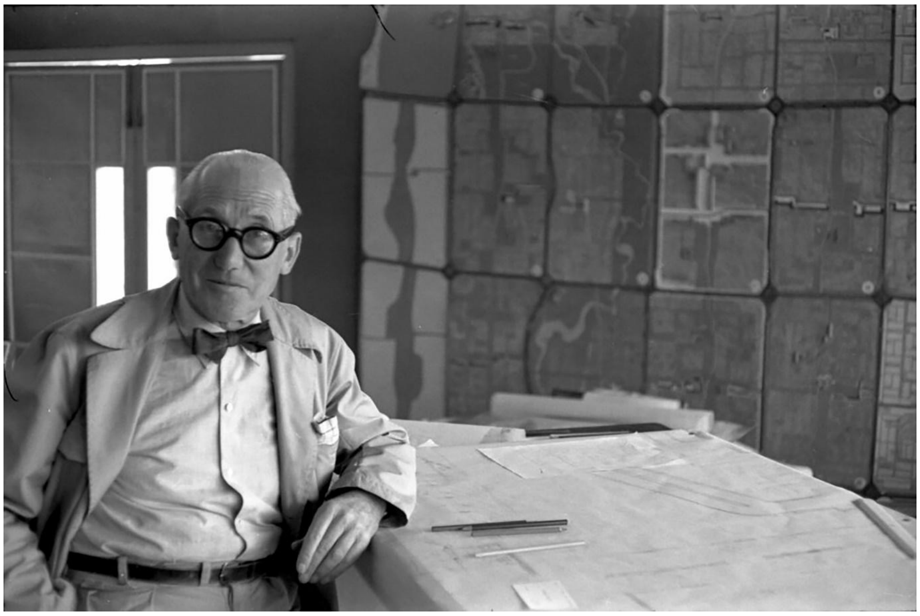

Figure 1. The visionary Le Corbusier in Chandigarh. (Source:Harrouk, (2021))
Wim Dussel, IISC on Flickr Creative Commons, CC BY-SA 2.0 Deed)

However, as the sophistication of architectural projects increased, so did the technology and techniques required to execute construction (Burr & Jones, 2010, p. 1). The Master Builders inability to maintain a previously broad scope of expertise led incrementally to specialization, and as a result, the earlier holistic mindset of the Master Builder was compelled to separate into two distinct domains, designer and builder (Burr & Jones, 2010, p. 2). As design split from construction, the designer’s attention on drafting (to communicate the appearance, function and assembly logics of a building) and the builder’s focus on construction methodology (needed to successfully execute it) consolidated the demise of the holistic mindset underpinning the Master Builder.

2.1.2 The Beaux-Art Architect

According to Kaltenbrun (1924, p. 17) “the French realized long ago, the ideal method of developing architectural talent in the men of tomorrow”. The Beaux–Arts architectural system emerged from the Ecole des Beaux-Arts in 1819, enduring through to the 1930s. Its early period shaped the mindset of elite French architects, who upon graduation, possessed the knowledge base, skillset, and competency in design to envisage prestigious national-scale projects.

The Ecole des Beaux–Art prioritised artistic discipline and its architects were encouraged to mature an aesthetic mindset. This involved developing their illustrative talent through regular competition in preparation for the ultimate competitive prize, the 'Prix De Rome' (Gournay, 2019). The Beaux–Art approach actively dissociated the architect from the competencies of engineering and science, relegating the learning of these pragmatic construction and engineering skills to professional practice. Instead, through rigorous training, architects elevated the expression of their ideas as the highest-quality of artistic expertise and exquisite draftsmanship (Figure 2).

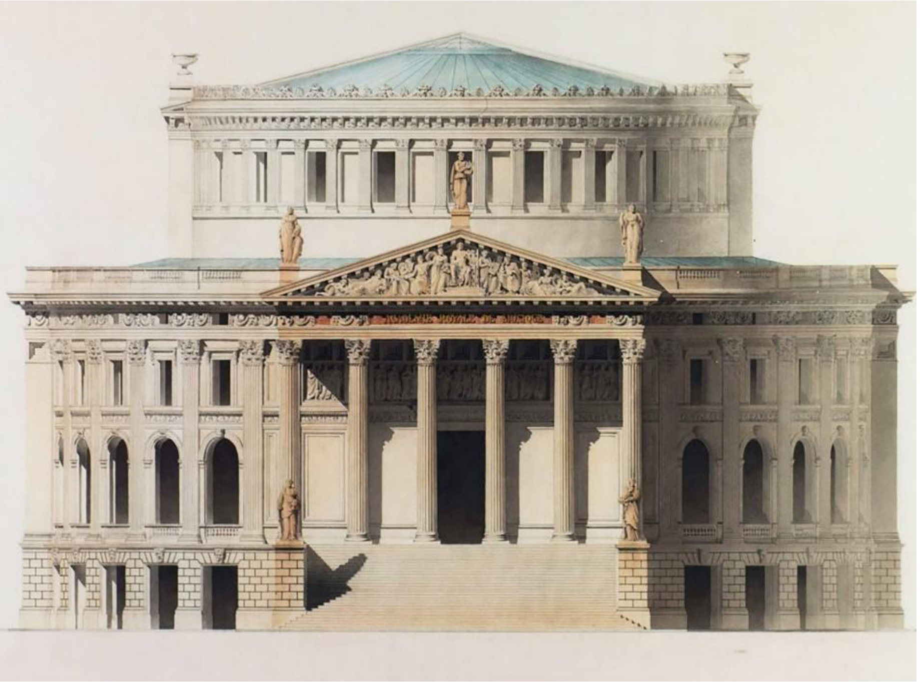

Figure 2. Beaux-Arts training and its emphasis on exquisite drawing. (Source: 1stDIBS (2015))

Although parallel approaches to architectural training also were promoted (most notably the École Centrale and École Polytechnique prioritizing construction and engineering knowledge) they were never as prestigious or influential in the moulding of the architect as the École des Beaux-Arts (Garric, 2016). The Beaux-Art's fostering of a well-disciplined, traditional, artistic mindset remained an influential model for the training of architects up until the 1930s (Mađanovic, 2018, p. 10). At this time, a competing Modernist ideology began supplanting its longstanding orthodoxy. It would take a further 30 years for the Beaux–Art mindset to be fully-eclipsed following the arrival of a new generation of post-World War II architectural students that were "brimming with dissent and unwilling to submit to academic authority" (Garric, 2016, p. 8).

2.1.3 The Modernist Architect

To depart the architectural hegemony of the Beaux-Art tradition (understood as a conservative force) in 1939, Harvard University invited Walter Gropius to the United States to teach history, effectively introducing Bauhaus instruction to American institutions (Jordy, 1969, p. 485). At this point, Gropius' manifesto "Training the Architect," set-out new pedagogical underpinnings that would re-direct the attitude and practices of architects toward a wholly novel and contemporary mindset. His academic work contributed to the proliferation of the modernist rationale (Blake, 1976, x.iii) one stamping a deep authority on the architect's attitude and beliefs and compelling a change in their ambition and that of architectural practice. Bauhaus theory gained rapid traction in the architectural departments of American universities (Simon, 1996, p. 324). Consequently, as form began to follow function, 'modernist' architects shed the decorative exuberance instilled in them by their predecessors and remodelled architecture into utilitarian simplicity (Nia & Rahbarianyazd, 2020).

This shift in the prevailing mindset led to the uptake of construction efficiencies afforded by advances in new technology (Cobley, 2009). From WWII onwards, the vision of modernity exposed architects to ideas of mass-production, new technology, and egalitarian ideology (Mallgrave & Goodman, 2011). A new vocabulary of glass, steel, and reinforced concrete arose and gained popularity (Mindrup, 2014). With Bauhaus methodology underpinning the training of architects, its tenets would form a near-global academic and professional agenda for them, defining their role and homogenizing the aesthetics of architectural output (Figure 3). The modernist mindset - matured in the architect of this period and exercised in their design and construction methodologies - prevailed until the early 21st century, succumbing only recently to change through digital innovation (Poole & Shvartzberg, 2015, p. 69).

Figure 3. The modernist mindset driving of a global architectural aesthetic. (Source: CC image: Leen (2020))

2.1.4 The Parametric Architect

During the 1960s and 70s, the commercial architect held a predominantly analogue mindset. At this time, computer technology was perceived as "constraining and stifling to creativity" (Rocker, 2008, p. 159). In addition, the technological limitations inherent to computing (i.e. file size, data storage, portability etc.) meant architects had little to do with computers as they could not be engaged productively (Carpo, 2019).

The architect's deeper engagement with computers was tied to a shift in mindset, one triggered by a belief in the computer's ability to avoid duplication of labour and accelerate the design process. In the 1980s, the idea that architects might short-circuit labour-intensive architectural conventions i.e. orthogonal, sectional and perspectival hand-drawing, popularised a transition from analogue to digital (Carpo, 2019). Subsequently, as computing potential extended to offer new design possibilities such as mass-customization, the lure of designing and manufacturing architectural objects with 'variability,' at no extra cost, galvanised digital commitment. To capitalize on this new potential for variability, architects committed to a shift in skillset towards programming and scripting (Burry, 2011). These newly-acquired skills allowed the architect to escape a longstanding 'modernist' mindset, particularly its prevailing design and construction logics tied to economies of scale (i.e.

the cost of identical building-units decreases as number of units produced increases). Instead, novel digital fabrication logics, now engaging subtractive/additive methods of construction, began rendering repetitive formwork redundant (Figure 4). The ability to employ mass-customisation via computation justified the architect's earlier shift in skillset. As a 'digital turn' (Carpo, 2013) gained momentum, the increased availability of computer software (i.e. Adobe/Autodesk) saw architectural schools in Europe and the United States prioritize the cultivation of digital skills in architects (Carpo, 2019). By the early 21st century, the escalating use of digital software had translated into a heightened control over design and fabrication processes.

Figure 4. Economy of scale with pre-cast wall units minimizing construction cost (left). 3-D printed wall elements eliminating the need for formwork in new fabrication logic (right). (Source: left - -Sokołowski, (1970, as cited in Tsimer, 2018) / PAP; right - Vu and Iso (2022))

In addition, the appearance of scripting in architectural software meant many architects deepened commitment to programming and coding to realise more complex architectural proposals (Arantes, 2019). At this point in the evolution of the architectural design process, the lineaments of a design were being "calculated numerically" not drawn (Marcos, 2020, p.605). Under the incoming 'parametric' paradigm, the ambition of the newly-coined 'Parametric Architect' was re-calibrated towards seeking novelty of form via the geometric flexibility and control afforded by computation (Al-Azzawi & Al-Majidi, 2021). Through newly-available parametric software, the architect could specify key parameters of a design, gaining access to innumerable variations for a building's form (Figure 5).

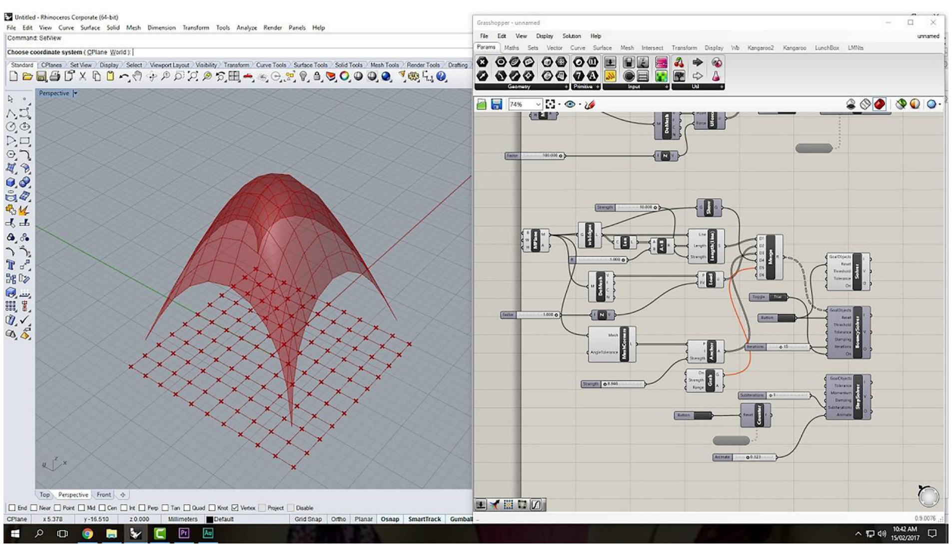

Figure 5. Parametric Architect interface providing precise numeric manipulation of design parameters for generation of complex architectural geometries. (Source: Christev, (2017))

With instantly-modifiable parametric processes, final architectural solutions could be rapidly customized and efficiently fabricated (Cudzik & Radziszewski, 2018, p. 78). This computational trajectory pursued by the Parametric Architect profoundly altered the mindset of the architect and their relationship to the computer, seeing it beyond a tool for time, cost, and labour savings, towards it becoming an active partner or “advisor” (Dimcic, 2017, p. 205) in the design process. In a continued intensification of this idea, a decade on, this theme of ‘partnership’ with the computer has now intersected with data-centric technologies (via Machine Learning, Data Science, Big Data etc.) inviting the emergence of what is here termed the novel Silicon Architect and their data-centric mindset.

2.1.5 The Silicon Architect and Data-Centric Mindset

The Silicon Architect’s novel mindset emerges to assimilate the potential of data-centric methodologies into the architectural design process. Its appearance is driven by the desire for architects to exploit the abundance of newly-available data emerging from people, buildings, and environment (Tao et al., 2020; Holzwarth et al., 2019; Kocaturk, 2017; Deutsch, 2015). This digitalization of the built environment is enabling architects to respond to a demand for peak architectural performance via ‘real-time’ measurement, monitoring, automation, and prediction (World Economic Forum [WEF], 2021; Chaiyakul, 2020). The Silicon Architect thus is characterized by their ability to employ the advantages of a data-centric design process over a more conventional and mainstream architectural process, to potentially provide:

a) ‘virtual’ data-rich architectural design processes that use ‘real-time’ analysis, from which to predict future building performance, prior to full-construction;
b) infinite numbers of ‘inhabitable simulations’ to virtually suggest and validate future design directions and/or proposals; and
c) analysis of complex data leading to ‘novel design insights and design directions’ that might otherwise remain undiscovered through analogue means.

With such potential, the traditional architect’s earlier more artistically-calibrated mindset - one built-upon a Beaux-Art and Modernist lineage - appears increasingly irrelevant. Instead, the Silicon Architect’s mindset is re-oriented towards engagement with data-centric methods (i.e. programming, coding, LMM prompting, statistical analysis, predictive modelling, machine learning, etc.) using them to ‘re-structure’ the architectural design process towards fulfilling more complex design ambitions. This ‘restructuring’ lies at the heart of its divergence from the parametric mindset. The Silicon Architect’s data-centric mindset emerges from the parametric and its associated processes (i.e. generative design, algorithmic design etc.). However, the data-centric architect promotes novelty through ‘unconventional’ use of data within an altered design process. Instead, parametric novelty holds more to systematic variation of pre-established parameters. Both design processes prioritize data, yet their treatment of it are quite distinct. One is an open-ended, prospective search through data for conspicuous novelty to drive design. The other is foreclosed, focusing on refinement and optimization within predefined parameters. The Silicon Architect’s mindset differs in how it obtains data, the purpose of its use, and the value it generates from the data.

This re-potentializing of the design process (driven by its constant modification) reveals the Silicon Architect’s commitment to invention when delivering an architectural project. As Silicon Architects further mature this contemporary mindset and deepen their understanding of data-centric tools, it is likely they will collectively affect an expansion of their discipline and its ambitions, helping it to discover new architectural initiatives. Data-centric methods promise novel design paths to explore, unattainable from within traditional design approaches. This is allowing the Silicon Architect, with their novel mindset and data-centric repertoire of skills, a context in which to flourish.

The Silicon Architect thus epitomizes the most contemporary expression of mindset, one emerging in dialogue with contemporary technology and its ability to advance the potential of the architectural design process. Such dialogues are considered accountable for the diverse formations in mindset depicted here. Beginning with Master Builder, one sees a previously holistic mindset compelled into specialization through the overwhelming technological sophistication of the modern design process required to deliver a building. A following formation is made visible through the Beaux-Art's engagement with a design process promoting a more artistic mindset through the elevation of exquisite draftsmanship. A modernist mindset next takes shape, characterised by a design process that emphasises utilitarian simplicity achieved through exploitation of construction efficiencies and new materiality. Thereafter, a parametric mindset comes into being as digital technologies are incorporated into the design process providing the architect with a depth of control to oscillate between potential architectural solutions. Finally, the Silicon Architect mindset is actualised to take advantage of data-centric technologies (i.e. Machine Learning, Data Science, Big Data, Text-to-Image) in a design process that can exploit data toward new insights, otherwise impossible through a typical representational design process.

3. Case Studies in the Emergence of the Silicon Architect

The impact of the Silicon Architect's data-centric mindset on the architectural design process can be exemplified through a range of recent architectural projects. These projects locate architecture's increasing overlap with data-centric methodologies, revealing how such methods are integrated, embedded, and re-purposed to create alternative models for project delivery. The architects implementing these projects (designated here as 'Silicon Architects' in recognition of their in-depth engagement with data-centric technologies) demonstrate the uses of such approaches toward highly-diverse ends.

3.1 House of Clicks

The clearest example of the Silicon Architect's impact on the traditional architectural design process is seen in the 'House of Clicks' (Prime Weber Shandwick, 2015). In this design for a Swedish home, the architects (Tham & Videgard Arkitekter) altered the traditional design process using on-line technology to crowdsource data.

In a near-global invitation for public opinion, the House of Clicks' entire design was undergirded by the personal preferences of an immense number of people. This data-centric approach produced more than 460,000 unique visitors from 187 countries and surfaced at a scale and speed never before attainable. From a vast on-line visual dataset, its architects analysed over 200 million clicks across 86,000 diverse Swedish properties (Weber Shandwick, 2014). Their unorthodox design process resulted in Sweden's most statistically sought-after-home (and consequently led to over 600 people from all over the world expressing interest in buying the house). This data-rich analysis informed the aesthetic appearance and design direction of the house via insights that would otherwise have been unobtainable through a more conventional design approach (Figure 6).

Figure 6. House of Clicks: Sweden's most statistically sought-after home created through a data-centric design process generated from 460,000 clicks across 187 countries. (Source: Weber Shandwick (2014))

This unorthodox design process reveals the data-centric inclinations now being expressed by architects through their modification of a more traditional and typical architectural design process (in this case through statistical analysis of Big Data) and is highly-indicative of the Silicon Architect's novel mindset and aptitude. The 'House of Clicks' remains an exemplary design project in that it reflects the contemporary architect's data-centric appetite to create and implement novel trajectories for the delivery of architectural projects.

3.2 Foster+Partners: Design Assistance Modelling Process

Tsigkari et al. (2021) recently engaged a data-centric approach to develop what they now term 'Design Assisted Modelling' (DAM). In their constant pursuit to improve the architectural design process, their adoption of 'Machine Learning' and 'Statistical Analysis' has led to a new tool in the armoury of the architect. DAM shows how a data-centric mindset can re-wire the architectural design process to obtain greater architectural complexity and increased productivity. This ambition is made explicit in the office's recent project for a building façade.

Foster+Partners investigated the design of a passively-actuated building façade achieved through a material that alters its shape under changing environmental conditions (i.e. temperature, humidity and sunlight). Their goal was to steer the movement of the façade to create shade, prevent overheating, and control privacy with zero-energy demand (Tsigkari et al., 2021).

To accomplish this task, the façade's shift between a desired beginning-and-end state needed to be precisely predicted and controlled. A typical approach to such a complex design problem might have been to digitally-model each step of the façade's transition in a repetitive process that edged toward an acceptable solution (Levitskaya, 2021). The time and labour involved with this standard approach led architects to instead create in-house, custom-written software, able to analyse façade data "tens-of-times faster than commercial modelling software" (Figure 7). Eventually, the Foster+Partners architects created a general adversarial network (where two machine-learning networks compete to refine each other's output) to move towards the most appropriate architectural solution. This advantageous partnership with data-centric methodology restructuring the prototyping phase, reduced time and labour costs, and provided a new design process for architects to employ.

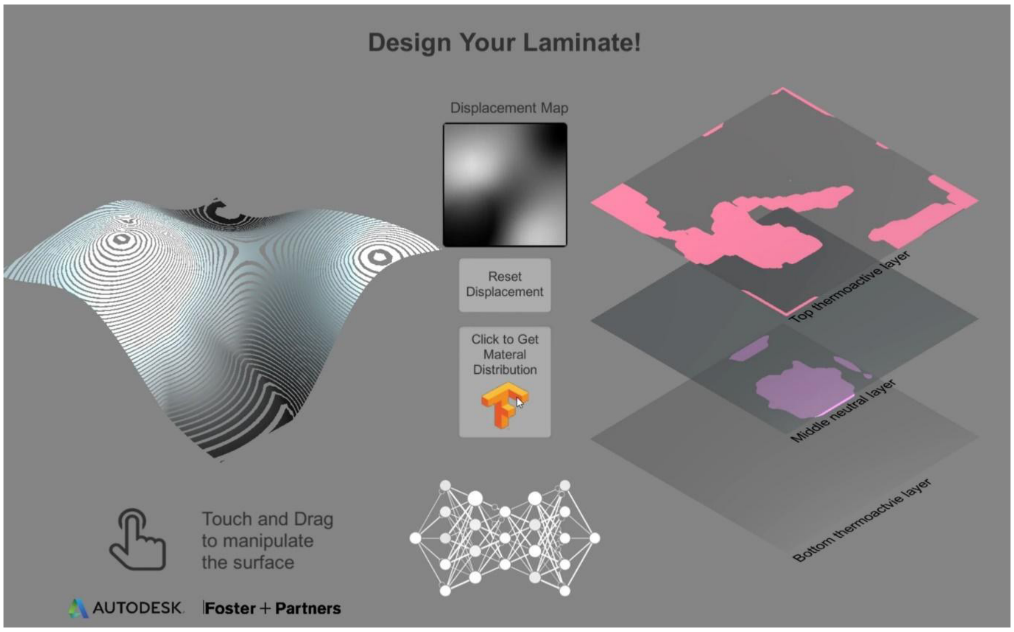

Figure 7. In-house custom software creation for passively-actuated façade analysis.
(Source: Tsigkari et al., (2021))

Through an embracing of data-centric methodologies, Foster+Partners invite their architects to redefine their knowledge base, augment their repertoire of digital skills, and open themselves to a newly-emerging mindset. In pursuing such projects, Foster+Partners simultaneously support proliferation of data-centric design processes and mature the type of future architects needed to implement them. This pursuit promotes a newly-emerging Silicon Architect, whose ability to manipulate data-centric technologies enables them to explore novel ideas and undertake as-yet-unthought-of trajectories for the design and manufacturing of buildings.

3.3 Surpassing Cognitive Limits

In the most ground-breaking example of partnership with data-centric technology, the Silicon Architect re-purposes the architectural design process by taking it beyond its more typical ambitions (i.e. labour-saving automation, construction of increasingly complex forms, optimization of future building performance etc.) and instead uses it to overcome their own imaginative limits and gain new disciplinary insights.

Andrasek (2019) best demonstrates the potential of such an ambition. Her integration of ‘Machine Learning’ into the design process provides the example ‘par excellence’ of a new data-centric mindset, one she believes will enable architects to overcome their own imaginative limits and subsequently those of their discipline, to arrive at novel aesthetics and new disciplinary hypotheses.

Andrasek’s architectural design process far-exceeds the use of data-centric technology to fulfil an already-established aim for the architect (as seen earlier in the Foster+Partners façade transition). Instead, her design process is used to augment the imaginative potential of the architect. In her 2019 article entitled ‘The Unseen,’ she describes the architect’s cognition - on its own - as being “overwhelmed by an increasing complexity” (p.115) and in need of augmentation. Referencing all architects, Andrasek states “to exceed ourselves” will require “upgrading our cognitive capacities and expanding our imagination” (p.115).

To achieve this upgrade, Andrasek partners with Machine Learning, inviting cognitive input that is “...not only of human origin” (p.114) in pursuit of a ‘new cognition’ that is “...likely to be deeply non-human” (p.115). Andrasek’s architectural design process is no longer elaborated through representational drawing and its output is not prefigured visually. She instead operates outside of conventional drawing, working ‘numerically’ with vast data sets which in essence is a mathematical abstraction that is ‘unseen’.

Having highlighted the cognitive limit reached by architects, Andrasek engages in its transcendence by training machine-learning programs to rapidly create, search through, and inventory valuable-from-spurious design output (i.e. computer-generated objects or 3D patterns with potential design value) in ways that are beyond human capability (Figure 8). In pursuing this process, she gains access to aesthetic results that would otherwise remain “out of reach” (p.118) or literally inarticulable via a typical analogue design process (Figure 9).

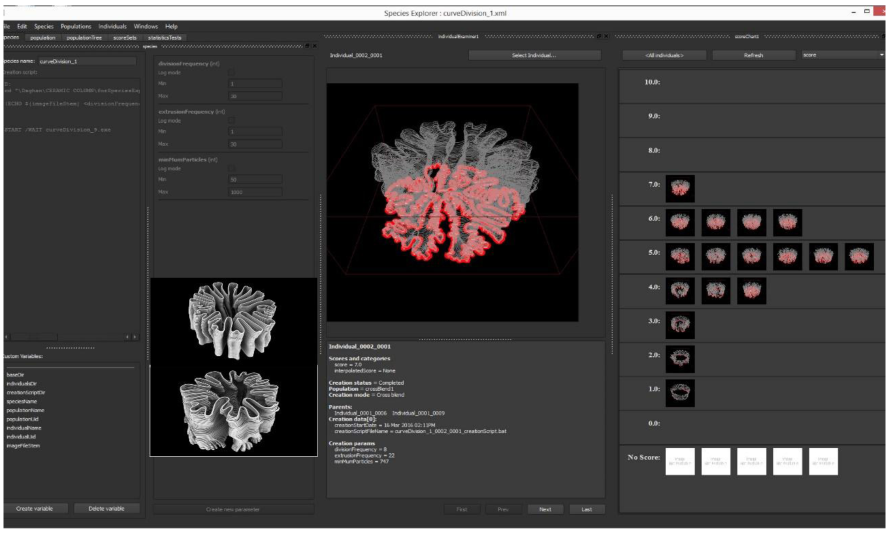

Figure 8. Search assistance via rapid supervised machine learning (candidates appear on right-hand-side). (Source: Andrasek, (2018, pp. 200-201))

208-209

Figure 9. ANDRASEK: Morphocyte: previously unseen architectural design vocabulary- generated at an extreme level of resolution. (Source: Wonderlab (2023))

This machine learning capability capitalised upon by Andrasek in her recent research is not without precedent. It was first conceptualized in the 2017 ‘AlphaGo’ project (Kohs, 2014). The highly-publicized project provided a platform on which to test the current potential of machine learning programs to defeat humans at the adversarial game of ‘GO’. Of significance here is the machine learning program that - having been trained to play the ancient game of ‘GO’ - began making moves that its creators could not attach a logic to.

The program performed its now infamous MOVE 37 in GAME 2 (Figure 10) which was declared ‘unimaginable’ in the more-than 3000-year history of the game (Zarkadakis, 2016, para. 1). The machine had intuited a winning strategy through a move that “no human would ever think of doing” (Peri, 2020, para. 4). Upon re-examination of the metrics determining the validity of moves (i.e. Monte Carlo Tree Search), its creators rationalized that the program’s extensive training sets (that included games played against humans and subsequent games against itself) had allowed it to consider moves that would not have occurred to a human, put simply, moves situated beyond their imaginative capability.

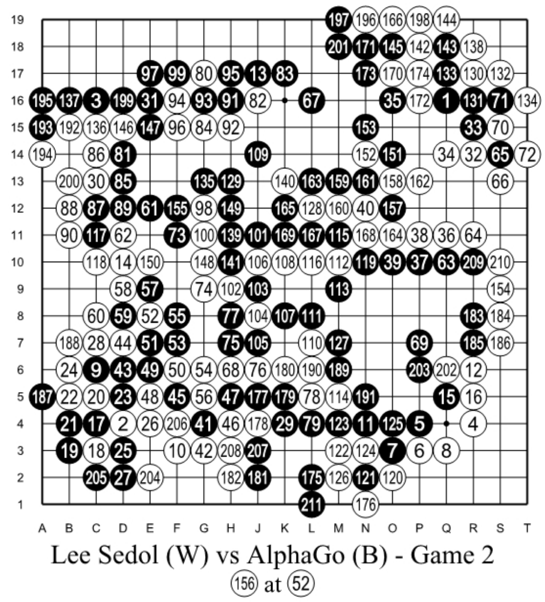

Figure 10. AlphaGo documentary poster (left: Wikipedia, (2021)) Lee Sedol vs AlphaGo Game 2 (right: Wikimedia Commons, 2018)). Note Move 37. (Source: AlphaGo Wikipedia)

A similar ambition can be detected in Andrasek’s design process. Built into this process is the instruction for machine-learning to seek-out potential ‘candidates’ for a design solution; candidates that would never otherwise emerge through human cognition alone. The inability of human cognition to locate these latent design possibilities hidden within vast data sets, in effect renders them ‘inconceivable’. This breaching of the human cognitive frontier by Andrasek is expected to heighten urgency in machine learning’s contribution to the architectural design process and accelerate transformation toward a data-centric mindset in the architect.

3.4 The Scope of the Imaginable

The scope of what can be typically thought of or imagined is expanded by Andrasek’s machine-learning approach. Her process yields ‘extraordinary’ designs that are inconceivable through human cognitive effort. When conducting a 3-dimensional search, some designs are adopted, others discarded, yet some appear ‘propositional’, suggestive of new starting points, new openings for thought far-removed from any existing territory of expectations. Through such output the architect’s previously held assumptions (assumptions defined by their prevailing mindset) are reframed as their imagination builds a new discourse around them.

This fabrication is the genesis for new directions in architectural thought, 'alien' directions that might otherwise never have been detected, considered, or undertaken. Andrasek describes this phenomenon as "counterintuitivity," using it in her search for 'unseen' aesthetics (Andrasek, 2019, p. 115). In this sense, machine learning cognition acts as a differentiator, creating difference that when interpreted by the architect, leads to completely different imaginative territory. Experiencing this design process allows the architect's thought to be moved from where it is entrenched. Andrasek posits that from such new positions - afforded by this process - architects can re-think the field of architecture and re-originate architectural design onward from this point (Center for Augmented Computational Design in AEC, 2020).

This use of 'composite cognition' signals to the architect an emancipation from their imagination (and by extension architecture's disciplinary imagination). It offers imagination a way out of its habitual circuits, freeing it to contemplate new ambitions, employing it beyond the generation of novel architectural forms, and potentially toward the generation of new 'disciplinary hypotheses'. This potential for hypothesis generation, newly-installed in the architectural design process through machine learning, should not be underestimated or trivialised. It already has been corroborated and used to "inspire scientific insight and accelerate conceptual discovery" (Friederich et al., 2021, p. 1). Friederick et al. reveal that their work with machine learning has led to as-yet-unknown postulates in their field and the contradiction of current understanding (p.8). Institute for Ethics in AI Oxford (2022) further testifies to the potential of machine learning cognition due to its instrumental application in diverse fields (i.e. chemistry, mathematics, material science, weather prediction) leading to new scientific discoveries.

Surprisingly, architectural discussion of non-human contribution to the design process initially has coalesced around arguments of authorship (Doyle & Senske, 2018; Tönissen, 2013). This seems a rather juvenile concern. Instead, an emerging Silicon Architect, equipped with the skillset and competency to navigate data-centric technologies, could soon begin operating beyond the limited processing capacity of human cognition (as described by Andrasek) resulting in output, logics, and ambitions that "will exceed our imagination" (Malaeb & Wenjun, 2019, p.11) opening architecture to new disciplinary premises.

Andrasek's cognitive partnership with machine learning thus offers a new creative vector for architects and endorsement of a data-centric mindset. In her re-structuring of the architectural design process, she offers an example of how the Silicon Architect's novel mindset is facilitating an escape from imaginative limitations, a mindset poised to influence future architectural design processes and the types of architect who may evolve.

3.5 New Dialogues for Adoption

Figure 11 provides an overview of each research project regarding the shift towards a data-centric mindset. In particular, Andrasek's work places emphasis on an interactive and evolving provocation between human and non-human cognition for design. This identifies non-human cognitive support as increasingly enriching the design narrative.

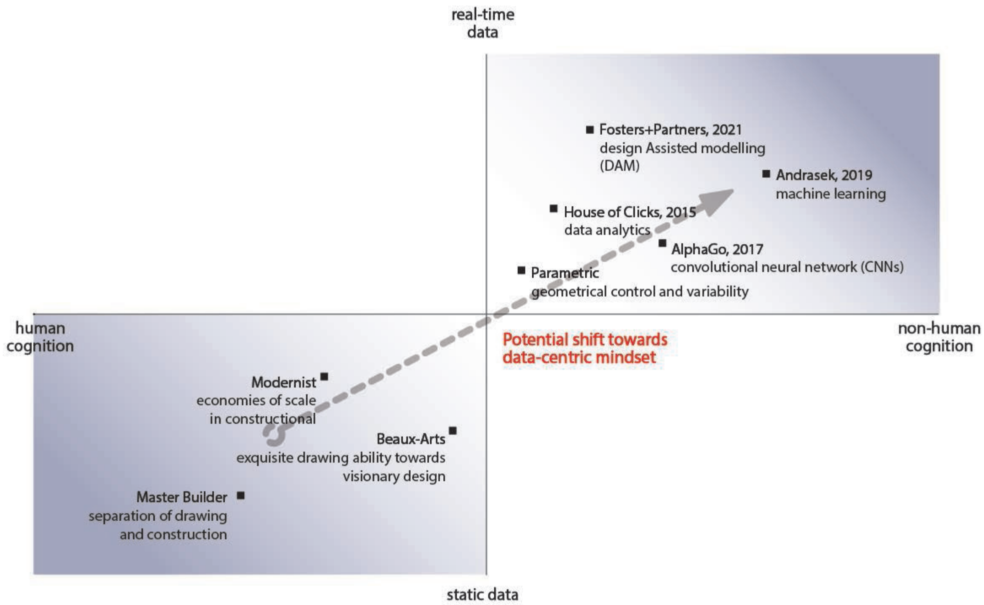

Figure 11. Research case studies showing potential shift towards Silicon Architect mindset. (Source: Authors Notes 2023)

Andrasek has, however, progressively advanced her design process, recognising the need to effectively incorporate three-dimensionality. In contrast, today's more popular (AI-driven) image-based software promoting a shift in mindset (i.e. Stable Diffusion, Midjourney, Pika, Krea, etc.) remains limited with regard to this. Available software does not yet enable architects to translate designs into physical forms "to examine ideas in the third dimension" (del Campo et al., 2019, p. 5). Progress is being made in this area (notably He et al. (2022)) in design development and construction stages) via innovative software (XKool). The issue remains a significant obstacle to shifting mindset away from more traditional approaches as the underwhelming translation of these outputs into physical form is still found limiting by architects.

In this regard, the novel mindset emerging in the Silicon Architect may not resonate for architects. Not all architects will find it valuable, or suitable to embody it. However, it remains a prospective model for the architectural profession to embrace, particularly as data become more prevalent and impactful on the design process, and AI-driven technologies eliminate 'coding' for greater access. As the benefits of these design approaches become more widely recognized, a greater adoption of this mindset is anticipated. In the interim, more attempts - similar to those described here - will continue to build a momentum toward the deeper expression of this mindset. Ultimately, future discussions engaging 'post-human' design processes will gain traction, though they remain highly-speculative and beyond the scope of this article.

4. Conclusion

This paper aimed to articulate the emergence of a novel data-centric mindset embodied in the Silicon Architect and provide an understanding of its transformative impact on the architectural design process. Research indicates that the inevitable digitalization of the architectural design process will increase the demand for data-centric competency to effectively extract architectural value from an "opulence" of data (Carpo, 2017, p. 9) now available to the architect. This context will drive a shift in the architectural mindset, pushing architects to see beyond the validity of their previous mental models adhered to in the design and delivery of architecture.

In partnership with technology, the data-centric mindset taking-shape here is changing what architects are able to achieve technically, but more fundamentally it is altering their own view of themselves. The emerging mindset of the Silicon Architect - taken furthest by Andrasek in her ‘composite cognition’ with machine learning - is expected to greatly impact both the future architectural design process and the architect. It is envisioned as devolving the architect’s own (highly-prized) agency, in favour of a human-machine intersection, able to surpass the imaginative limits of architects constrained by a prevailing mindset. Andrasek’s design process potentially offers architects access to new disciplinary hypotheses and conceptual territory by facilitating higher-order imaginative prospection (Murphy, 2022). Through it, architects are pointed beyond habitual blind spots in their existing mindsets towards newer versions. Seen in this way, it is possible to grasp how technological influence may have contributed to earlier transformative shifts in mindset between Master Builder, Beaux-Art, Modern, Parametric and Silicon Architect.

Most recently, the architectural profession has been impacted by new AI technologies (particularly Large Language Models and Image Generators). Whilst acknowledging their value, Geaghan and Andrasek (2023) highlight that automated output from current AI software like Delve, Dall-e, Midjourney etc. is unquestionably beneficial and appealing, but derives from already known images (taken from existing visual databases). These automated responses are derived from training data that have already been “deemed detrimental to cities and the environment” (para.6). Instead, Andrasek’s unit of construction is the 3D voxel, not a pre-existing semiotic unit (of column, wall, roof) recognised in the assembly and sub-assemblies emerging from image generation. Andrasek clearly invokes generative methods that originate from ‘first principles,’ and reach for new instances of design, thus driving her work toward previously “unseen” and “unknown states” (Geaghan & Andrasek, 2023, para. 5).

Over time, Andrasek’s data-centric design approach - and the mindset it is now giving rise to - will itself become systematised and institutionalized. At that point, the path to re-encountering novelty will resume through subversion of the prevailing design process and an accompanying mindset. This cyclical condition aptly corresponds with the depiction of avant-garde vs mainstream architectural design in Schumacher (2011, p. 110) where the author describes ‘cumulative’ periods of design innovation (with their stages of stability), interrupted by ‘revolutionary’ periods.

Ultimately, in an exercising of this new mindset, the emerging Silicon Architect is set to re-direct the architectural design process in ways that may help their discipline escape the limits of its own paradigmatic imagination, doing so in ways that operate beyond human cognitive capabilities. Such data-centric engagement will push architectural ambition toward unchartered imaginative territory. Through on-going exposure to these technologies, the architect’s mindset is transformed, as is the architectural imaginary.

Acknowledgements

I would like to express my sincere thanks to my professor (co-author of this article) for his constructive feedback, and insights, which have greatly enhanced both the depth and quality of this work. I further acknowledge the SoA+D Lab-based Scholarship for its financial support, which enabled the research underlying this study. I am especially grateful to the Redek team for their invaluable assistance with editing, late-night feedback sessions, and consistent moral support. Finally, I thank the editors of this journal for their thoughtful consideration and assistance in refining this article, ensuring both its quality and subsequent dissemination within the academic community.

Author Contributions

Conceptualization, W.K.; Methodology, W.K. and C.T.; Formal Analysis, W.K.; Investigation, W.K.; Original draft, W.K.; Review & Editing, W.K. and C.T.; Visualization, W.K.; Supervision, W.K. and C.T.; Project Administration, W.K. All authors have read and agree to the published version of the manuscript. This research received no funding.

References

Abrams, J. (2008). *Companies we keep: Employee ownership and the business of community and place* (2nd ed.). Chelsea Green.

Ahmed, V., Tezel, A., Aziz, Z., & Sibley, M. (2017). The future of big data in facilities management: Opportunities and challenges. *Facilities, 35* (13/14), 725-745. https://doi.org/10.1108/F-06-2016-0064

Alambeigi, P., Chen, C., Burry, J., & Cheng, E. (2017). Shape the design with sound performance prediction: A case study for exploring the impact of early sound performance prediction on architectural design. In G. Çağdaş, M. Özkar, L. F. Gül & E. Gürer (Eds.), *Future trajectories of computation in design: 17th international conference, CAAD futures 2017, Istanbul 12-14 July, Proceeding* (pp. 115-127). Cenkler Matbaa. https://sites.google.com/unicamp.br/caadfutures/proceedings

Al-Azzawi, T., & Al-Majidi, Z. (2021). Parametric architecture: The second international style. *IOP Conference Series: Materials Science and Engineering, 1067*, 012019. https://doi.org/10.1088/1757-899X/1067/1/012019

Almusaed, A., & Yitmen, I. (2023). Architectural reply for smart building design concepts based on artificial intelligence simulation models and digital twins. *Sustainability, 15*(6), 4955. https://doi.org/10.3390/su15064955

Andrasek, A. (2018). *High resolution fabric of architecture* [Doctoral thesis, Royal Melbourne Institute of Technology]. RMIT University. https://researchrepository.rmit.edu.au/esploro/outputs/doctoral/High-resolution-fabric-of-architecture/9921861856401341

Andrasek, A. (2019). In search of the unseen: Towards superhuman intuition. *Architectural Design, 89*(5), 112-119. https://doi.org/10.1002/ad.2487

Arantes, P. F. (2019). *The rent of form: Architecture and labor in the digital Age*. University of Minnesota Press.

Bacharidis, K., Sarri, F., & Ragia, L. (2020). 3D building façade reconstruction using deep learning. *ISPRS International Journal of Geo-Information, 9*(5), 322. https://doi.org/10.3390/ijgi9050322

Beard, J. L., Wundram, E. C., & Loulakis, M. C. (2001). *Design-build: Planning through development.* McGraw-Hill.

Behzadan, A. H., Menassa, C. C., & Pradhan, A. R. (2015). Enabling real time simulation of architecture, engineering, construction, and facility management (AEC/FM) systems: A review of formalism, model architecture, and data representation. *Journal of Information Technology in Construction, 20*, 1-23. http://www.itcon.org/2015/1

Blake, P. (1976). *The master builders: Le corbusier, Mies van der Rohe, Frank Lloyd wright*. Norton.

Burr, K. L., & Jones, C. B. (2010). The role of the architect: Changes of the past, practices of the present, and indications of the future. *International Journal of Construction Education and Research, 6*(2), 122-138. https://doi.org/10.1080/15578771.2010.482878

Burry, M. (2011). *Scripting cultures: Architectural design and programming*. Chichester. Wiley.

Carpo, M. (2009). Revolutions: Some new technologies in search of an author. *Log, 15*, 49–54. http://www.jstor.org/stable/41765259

Carpo, M. (Ed.). (2013). *The digital turn in architecture 1992-2012.* Wiley.

Carpo, M. (2017). *The second digital turn: Design beyond intelligence*. The MIT Press.

Carpo, M. (2019). D*igitally intelligent architecture has little to do with computers* (and even less with their intelligence). UCL Discovery. https://discovery.ucl.ac.uk/id/eprint/10074434/

Christev, D. (2017, February 15). *Grasshopper - kangaroo 1 vs. kangaroo 2* [Video]. Youtube. https://www.youtube.com/watch?v=R_Bfmm8y-Ms

Cobley, E. (2009). *Modernism and the culture of efficiency: Ideology and fiction*. University of Toronto Press. https://doi.org/10.3138/9781442697430

Cudzik, J., & Radziszewski, K. (2018). Artificial intelligence aided architectural design. In *A. Kepczynska-Walczak & S. Bialkowski (Eds.), Computing for a better tomorrow-Proceedings of the 36th international conference on education and research in computer aided architectural design in Europe, Łódź, Poland, 19th-21st September 2018* (Vol.1, pp. 77-84). eCAADe. https://ecaade.org/downloads/eCAADe-2018-Volume1.pdf Carlson, C.Fu, T. (2023, June 29). Tim Fu uses "midjourney for architecture" to transform crumpled paper into starchitect buildings. Dezeen. https://www.dezeen.com/2023/06/29/tim-fuai-crumpled-paper-starchitect-building-designs/ Center for Augmented Computational Design in AEC. (2020, December 20). Talk 3: Alisa Andrasek - complex city [Video]. YouTube. https://www.youtube.com/watch?v=rq2IwYNcmAw

Chaiyakul, Y. (2020). Simple lumen method calculations for louver luminaire. *Journal of Architectural/Planning Research and Studies, 18*(1), 83-98. https://doi.org/10.56261/jars.v18i1.241087

Darko, A., Chan, A. P. C., Adabre, M. A., Edwards, D. J., Hosseini, M. R., & Ameyaw, E. E. (2020). Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities. *Automation in Construction, 112*, 103081. https://doi.org/10.1016/j.autcon.2020.103081

del Campo, M. (2022). Deep house-datasets, estrangement, and the problem of the new. *Architectural Intelligence, 1*(12), 1-14. https://doi.org/10.1007/s44223-022-00013-w

del Campo, M., Manninger, S., & Wang, L. J. (2019). Sensibilities of artificial intelligence an examination of architecture in a posthuman design ecology. In C. Gengnagel, O. Baverel, J. Burry, M. R. Thomsen & S. Weinzierl (Eds.), *Impact: Design with all senses : Proceedings of the Design Modelling Symposium, Berlin 2019* (pp. 529-538). Springer. https://www.academia.edu/40484480/Sensibilities_of_artificial_intelligence_an_examination_of_architecture_in_a_posthuman_design_ecology

Deutsch, R. (2015). *Data-driven design and construction: 25 strategies for capturing, analyzing and applying building data.* John Wiley & Sons.

Dimcic, M. (2017). Artificial intelligence in architecture. In G. Celani & O. Kanoun (Eds.), *Frontiers of science and technology: Automation, sustainability, digital fabrication - selected extended papers of the 7th Brazilian-German conference, Campinas 2016 Brazil* (pp. 199-208). DeGruyter. https://doi.org/10.1515/9783110537680-014

Dinmohammadi, F., & Wilson, D. (2021). Understanding the end-users and technical requirements for real-time streaming data analytics and visualisation. In C. Yang (Ed.), *2021 26th International conference on automation and computing: System intelligence through automation & computing: University of Portsmouth, Portsmouth, UK, 2nd-4th September 2021* (pp. 1-6). IEEE. https://ieeexplore.ieee.org/document/9594257

Doyle, S., & Senske, N. (2018). Digital provenance and material metadata: Attribution and co-authorship in the age of artificial intelligence. *International Journal of Architectural Computing, 16*(4), 271–280. https://doi.org/10.1177/1478077118800887

Eiris, R., & Gheisari, M. (2017). Research trends of virtual human applications in architecture, engineering and construction*. Journal of Information Technology in Construction (ITcon), 22*, 168-184. https://www.itcon.org/paper/2017/9

Euchner, J. (2023). Democratizing innovation. *Research-Technology Management, 66*(4), 9-10. https://doi.org/10.1080/08956308.2023.2212584

Friederich, P., Krenn, M., Tamblyn, I., & Aspuru-Guzik, A. (2021). Scientific intuition inspired by machine learning-generated hypotheses. *Machine Learning: Science and Technology, 2*(2), 025027. https://doi.org/10.1088/2632-2153/abda08

Garric, J.-P. (2016). The French beaux-arts. In M. Bressni & C. Contandriopoulos (eds.), *The companion to the history of architecture: Nineteenth-century architecture* (Vol. 3, pp. 45-59). John Wiley & Sons. https://www.academia.edu/35147076/_THE_FRENCH_BEAUX_ARTS_in_The_Companion_to_the_History_of_Architecture_Volume_III_Edited_by_Martin_Bressani_and_Christina_Contandriopoulos_John_Wiley_and_Sons_Inc_Published_2016

Gaudillière-Jami, N. (2023). The house that looked like it should collapse, natural language processing for architectural design. In M. Turrin, C. Andriotis & A. Rafiee (Eds.), *Computer-aided architectural design: Interconnections: co-computing beyond boundaries: 20th International Conference, CAAD Futures 2023, Delft, The Netherlands, July 5–7, 2023, Selected Papers* (pp. 97-111). Springer.

Geaghan, J., & Andrasek, A. (2023, August 7). *Harnessing the power of AI in architecture: Alisa Andrasek. ARCHITECTURE, AU*. https://architectureau.com/articles/harnessing-the-power-of-ai-in-architecture/

Gournay, I. (2019). The legacy of the ecole des beaux-arts in the formation of North American deco: Academic and social tenets and their interpretations. In B. Elliott & M. Windover (Eds.), *The Routledge companion to art deco* (pp. 13-36). Routledge.

Gournay, I., & Leconte, M.-L. C. (2013). American architecture students in belle epoque Paris: Scholastic strategies and achievements at the ecole des beaux-arts. *The Journal of the Gilded Age and Progressive Era, 12*(2), 154-198. https://doi.org/10.1017/S1537781413000054

Harrouk, C. (2021, January 12). *The Creative process of the four pioneers of modern architecture* [Photograph]. ArchDaily. https://www.archdaily.com/925464/the-creative-process-of-the-four-pioneers-of-modern-architecture?ad_medium=gallery

He, W., Shong, J. Y. L., & Wang, C. (2022). AI-driven BIM on the cloud. In I. As, P. Basu & P. Talwar (Eds.), *Artificial intelligence in urban planning and design: Technologies, implementation, and impacts* (pp. 101-117). Elsevier. https://doi.org/10.1016/B978-0-12-823941-4.00009-3

Herrera, F., Bailenson, J., Weisz, E., Ogle, E., & Zaki, J. (2018). Building long-term empathy: A large-scale comparison of traditional and virtual reality perspective-taking. *Plos One, 13*(10), e0204494. https://doi.org/10.1371/journal.pone.0204494

Holm, L., & Schaufelberger, J. (2019). *Construction superintendents: Essential skills for the next generation*. Routledge. https://doi.org/10.1201/9780429400575

Holzwarth, V., Schneider, J., Kunz, A., & vom Brocke, J. (2019). Data driven value creation in AEC along the building lifecycle. *Journal of Physics: Conference Series, 1343*, 012046. https://doi.org/10.1088/1742-6596/1343/1/012046

Institute for Ethics in AI Oxford. (2022, July 13). *Using AI to accelerate scientific discovery* [Video]. YouTube. https://www.youtube.com/watch?v=jocWJiztxYA

Jordy, W. H. (1969). The aftermath of the Bauhaus in America: Gropius, Mies, and Breuer. In D. Fleming & B. Bailyn (Eds.), *The intellectual migration: Europe and America, 1930-1960* (pp. 485-543). Belknap (Harvard University Press).

Jupp, J., & Awad, R. (2017). BIM-FM and information requirements management: missing links in the AEC and FM interface. In J. Ríos, A. Bernard, A. Bouras & S. Foufou (Eds.), P*roduct lifecycle management and the industry of the future: 14th IFIP WG 5.1 International Conference, PLM 2017, Seville, Spain, July 10-12, 2017, revised selected papers* (pp. 311-323). Springer. https://doi.org/10.1007/978-3-319-72905-3_28

Kaltenbrun, J. A. (1924). The Ecole Nationale des Beaux--Arts. *Ohio State Engineer, 7*(4), 17-18. http://hdl.handle.net/1811/33640

Ke, S., Xiang, F., Zhang, Z., & Zuo, Y. (2019). An enhanced interaction framework based on VR, AR and MR in digital twin. *Procedia Cirp, 83,* 753-758. https://doi.org/10.1016/j.procir.2019.04.103

Kimball, B. A. (1992). *The professional ideal in America: A history*. Blackwell.

Knippers, J., Kropp, C., Menges, A., Sawodny, O., & Weiskopf, D. (2021). Integrative computational design and construction: Rethinking architecture digitally. *Civil Engineering Design, 3*(4), 123-135. https://doi.org/10.1002/cend.202100027

Kocaturk, T. (2017). Towards an intelligent digital ecosystem-sustainable data-driven design futures. In P. S. Brandon, P. Lombardi & G. Q. Shen (Eds.), *Future challenges in evaluating and managing sustainable development in the built environment* (pp. 164-178). Wiley-Blackwell.

Kohs, G. (Director). (2014). *AlphaGo*. https://www.alphagomovie.com/

Kolarevic, B. (2008). Post-digital architecture: Towards integrative design. In K. Terzidis (Ed.), *What matters (s): First international conference on critical digital: 18-19 April 2008 Harvard University Graduate School of Design* (pp. 149-156). Harvard University, Graduate School of Design. https://papers.cumincad.org/data/works/att/cdc2008_149.content.pdf

Kostof, S. (Ed.) (2000). *The Architect: Chapters in the history of the profession*. University of California Press.

Kramer, R. (2016). From skillset to mindset: A new paradigm for leader development. *Research and Educational Journal, 5*, 26-45. https://doi.org/10.17323/1999-5431-2016-0-5-26-45

Leen, N. (2020, April 7). *Le Corbusier: Complexity and contradiction* [Photograph]. WordPress. https://www.federicamorgillo.it/le-corbusier-complessita-e-contraddizione/

Levitskaya, M. (2021). *Using machine learning (ML) for facade material recognition* [Diploma thesis, Vienna University of Technology]. TU Wien. https://repositum.tuwien.at/handle/20.500.12708/17821

Limchutrakul, P., & Srisutapan, A. (2021). Design guidelines for enhancing daylight performance in office building by using electrochromic glass. *Journal of Architectural/Planning Research and Studies, 18*(2), 87-100. https://doi.org/10.56261/jars.v18i2.236246

Mađanovic, M. (2018). Persisting Beaux-Arts practices in architectural education: History and theory teaching at the Auckland school of architecture, 1927–1969. *Interstices Journal of Architecture and Related Arts, 18(Special Issue)*, 9-24. https://www.interstices.ac.nz/index.php/Interstices/article/view/515

Manzoor, B., Othman, I., & Pomares, J. C. (2021). Digital technologies in the architecture, engineering and construction (AEC) industry-A bibliometric-qualitative literature review of research activities. *International Journal of Environmental Research and Public Health,* (18)11, 6135. https://doi.org/10.3390/ijerph18116135

Marcos, C. L. (2020). From physical analogy to digital codification, digital turns, complexity and disruption. In A. Arena, M. Arena, R. J. Brandolino, D. Colistra, G. Ginex, D. Mediati, S. Nucifora & P. Raffa (eds.), *Connect connecting a design for knotting and weaving drawing for weaving relationships: 42th International Conference of Representation Disciplines Teachers Congress of Italian union for drawing proceedings 2020* (pp. 599-607). FrancoAngeli. http://hdl.handle.net/10045/109432

Martinho, H., Pereira, I., Feist, S., & Leitão, A. (2020). Integrated algorithmic design in practice: A renovation case study. In L. C. Werner & D. Koering (Eds.), *Anthropologic: architecture and fabrication in the cognitive age-Proceedings of the 38th international online conference on education and research in computer aided architectural design in Europe, Berlin, Germany, 16th-17th September 2020* (Vol. 1, pp. 429-438). eCAADe. https://papers.cumincad.org/cgi-bin/works/paper/ecaade2020_016

Mindrup, M. (2014). Translations of material to technology in Bauhaus architecture. *Wolkenkuckucksheim Internationale Zeitschrift zur Theorie der Architektur, 19*(33), 161-172. https://cloud-cuckoo.net/fileadmin/hefte_de/heft_33/artikel_mindrup.pdf

Mrosla, L., Koch, V., & von Both, P. (2019). Quo vadis AI in architecture? survey of the current possibilities of AI in the architectural practice. In J. P. Sousa, G. C. Henriques & J. P. Xavier (Eds.), *37th Education and Research in Computer Aided Architectural Design in Europe and XXIII Iberoamerican Society of Digital Graphics, Joint Conference* (Vol. 2, pp. 45-54). eCAADe. https://pdf.blucher.com.br/designproceedings/ecaadesigradi2019/ecaadesigradi2019_302.pdf

Murphy, A. (2022). *Imagination in science. Philosophy Compass, 17*(6), e12836. https://doi.org/10.1111/phc3.12836

Mallgrave, H. F., & Goodman, D. (2011). *An introduction to architectural theory: 1968 to the present*. Wiley-Blackwell.

Malaeb, J., & Wenjun, M. (2019). *AIA Artificial intelligence in architecture: General understanding and prospective studies. Artificial intelligence in architecture*. https://www.academia.edu/40398871/AIA_Artificial_Intelligence_in_Architecture_GENERAL_UNDERSTANDING_AND_PROSPECTIVE_STUDIES?auto=citations&from=cover_page

Nia, H. A., & Rahbarianyazd, R. (2020). Aesthetics of modern architecture: A semiological survey on the aesthetic contribution of modern architecture. *Civil Engineering and Architecture, 8*(2), 66-76. https://www.hrpub.org/download/20200229/CEA4-14814597.pdf

Ochiai, H., Ishiyama, M., Momose, T., Fujiwara, N., Ito, K., Inagaki, H., Nakagawa, A., & Esaki, H. (2011). FIAP: Facility information access protocol for data-centric building automation systems. In *2011 IEEE conference on computer communications workshops (INFOCOM WKSHPS)* (pp. 229-234). IEEE. https://ieeexplore.ieee.org/document/5928814

Paes, D., Arantes, E., & Irizarry, J. (2017). Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. *Automation in Construction, 84*, 292-303. https://doi.org/10.1016/j.autcon.2017.09.016

Peri, S. (2020, April 1). *Move 37 and what humans can do in the "age of AI".* LinkedIn. https://www.linkedin.com/pulse/move-37-what-humans-can-do-age-ai-suraj-peri

Ploennigs, J., & Berger, M. (2023). AI art in architecture. *AI in Civil Engineering, 2*(8), 1-11. https://doi.org/10.1007/s43503-023-00018-y

Poole, M., & Shvartzberg, M. (Eds.). (2015). *The politics of parametricism: Digital technologies in architecture*. Bloomsbury Academic.

Pratama, L. A., & Dossick, C. S. (2019). Workflow in virtual reality tool development for AEC industry. In I. Mutis & T. Hartmann (Eds.), *Advances in informatics and computing in civil and construction engineering* (pp. 297-306). Springer. https://doi.org/10.1007/978-3-030-00220-6_36

Prime Weber Shandwick. (2015, October 7). *Hemnet-The house of clicks* [Video]. Vimeo. https://vimeo.com/141663270

Qabshoqa, M., Kocaturk, T., & Kiviniemi, A. (2017). A value-driven perspective to understand data-driven futures in architecture. In A. Fioravanti, S. Cursi, S. Elahmar, S. Gargaro, G. Loffreda, G. Novembri & A. Trento (Eds.), *eCAADe 2017 ShoCK! - Sharing Computational Knowledge! - Proceedings of the 35th international conference on education and research in computer aided architectural design in Europe (*Vol. 2, pp. 407-416). eCAADe. https://ecaade.org/downloads/ecaade2017_volume2_screen.pdf

Rocker, I. M. (2008). Versioning: Architecture as series?. In K. Terzidis (Ed.), *What matters (s): First international conference on critical digital: 18-19 April 2008 Harvard University Graduate School of Design* (pp. 157-170). Harvard University, Graduate School of Design. http://papers.cumincad.org/data/works/att/cdc2008_157.content.pdf

Royal Academy of Arts. (2018, October 10). *AI and creativity, the Rothschild Foundation lecture* [Video]. YouTube. https://www.youtube.com/watch?v=d-bvsJWmqlc

Schumacher, P. (2011). *The Autopoiesis of architecture: A new framework for architecture* (Vol. 1). Wiley.

Seyedzadeh, S., Rahimian, F. P., Glesk, I., & Roper, M. (2018). Machine learning for estimation of building energy consumption and performance: A review. *Visualisation in Engineering, 6*(1), 5. https://doi.org/10.1186/s40327-018-0064-7

Simon, M. (1996). The Beaux-arts atelier in America. In J. Kinnard & K. Schwartz (Eds.), Proceedings: 84th ACSA annual meeting & technology conference. (pp. 319-325). https://www.acsa-arch.org/proceedings/Annual%20Meeting%20Proceedings/ACSA.AM.84/ACSA.AM.84.76.pdf

Sun, H., Fan, M., & Sharma, A. (2021). Design and implementation of construction prediction and management platform based on building information modelling and three-dimensional simulation technology in industry 4.0. *IET collaborative intelligent manufacturing, 3*(3), 224-232. https://doi.org/10.1049/cim2.12019

Tamke, M., Nicholas, P., & Zwierzycki, M. (2018). Machine learning for architectural design: Practices and infrastructure. *International Journal of Architectural Computing, 16*(2), 123-143. https://doi.org/10.1177/1478077118778580

Tao, Y. X., Zhu, Y., & Passe, U. (2020). Modeling and data infrastructure for human-centric design and operation of sustainable, healthy buildings through a case study. *Building and Environment, 170,* 106518. https://doi.org/10.1016/j.buildenv.2019.106518

Tönissen, R. (2013). *The death of the architect: Conceptualizations of authorship and the emergence of open source in architecture discourses* [Master's thesis, Wageningen University]. WUR Library. https://edepot.wur.nl/276511

Tsigkari, M., Tarabishy, S., & Kosicki, M. (2021, March 29). *Towards artificial intelligence in architecture: How machine learning can change the way we approach design*. Foster + Partners. https://www.fosterandpartners.com/insights/plus-journal/towards-artificial-intelligence-in-architecture-how-machine-learning-can-change-the-way-we-approach-design

Tsimer, A. (2018). *How did panel houses appear?* [Photograph]. culture.pl. https://culture.pl/ru/article/kak-poyavilis-panelnye-doma

Vu, A., & Iso, N. (2022). *Construction 3D printing is gaining new heights in Texas, as printing begins on the first multistory printed structure in the United States* [Photograph]. Hannah. https://www.hannah-office.org/work/cores

Wainwright, O. (2023, August 7). *'It's already way beyond what humans can do': Will AI wipe out architects?*. The Guardian. https://www.theguardian.com/artanddesign/2023/aug/07/ai-architects-revolutionising-corbusier-architecture

Weber Shandwick. (2018). *One house, two million architects, a whole new market*. https://www.webershandwickindia.com/work/hemnet-house-of-clicks/

Wonderlab. (2023, March 15). *MorphoCyte* [Photograph]. https://www.alisaandrasek.com/projects/morphocyte

World Economic Forum (WEF). (2021, April 21). *A framework for the future of real estate.* Insight report. https://www3.weforum.org/docs/WEF_A_Framework_for_the_Future_of_Real_Estate_2021.pdf

Wikipedia. (2021). *AlphaGo (film)* [Photograph]. https://en.wikipedia.org/wiki/AlphaGo_(film)

Wikimedia Commons. (2018). *Lee Sedol (W) vs AlphaGo (B) - Game 2* [Photograph]. https://commons.wikimedia.org/wiki/File:Lee_Sedol_(W)_vs_AlphaGo_(B)_-_Game_2-_BW.jpg

Wilson, K. B., Bhakoo, V., & Samson, D. (2018). Crowdsourcing: A contemporary form of project management with linkages to open innovation and novel operations. *International Journal of Operations and Production Management, 38*(6), 1467-1494. https://doi.org/10.1108/IJOPM-12-2016-0753

Xiao, D., Heaney, C. E., Mottet, L., Fang, F., Lin, W., Navon, I. M., Guo, Y., Matar, O. K., Robins, A. G., & Pain, C. C. (2019). A reduced order model for turbulent flows in the urban environment using machine learning. *Building and Environment, 148*, 323-337. https://doi.org/10.1016/j.buildenv.2018.10.035

Yildrim, E. (2022). Text-to-image generation A.I. in architecture. In K. H. Kozlu (Ed.), A*rt and architecture: Theory, practice and experience* (pp. 97-119).Livre de Lyon. https://www.academia.edu/93724464/Text_to_Image_Generation_A_I_in_Architecture

Zarkadakis, G. (2016, November 26). *Move 37 or how AI can change the world.* Huffpost. https://www.huffpost.com/entry/move-37-or-how-ai-can-change-the-world_b_58399703e4b0a79f7433b675#:~:text=In%20Game%20Two%20of%20AlphaGo,the%20boundaries%20of%20human%20intuition

Zhu, G., & McArthur, J. J. (2020). Automatic generation of architectural layouts using genetic algorithms in BIM. In *Proceeding 37th CIB W78 Information Technology for Construction Conference (CIB W78), São Paulo, Brazil* (pp. 17-26). http://dx.doi.org/10.46421/2706-6568.37.2020.paper002

1stDIBS. (2015, November 28). P*air of large ca. 1845 Beaux Arts Drawings - Paris opera house* [Photograph]. https://www.1stdibs.com/art/drawings-watercolor-paintings/paul-jacot-pair-of-large-ca-1845-beaux-arts-drawings-paris-opera-house/id-a_695252/#zoomModalOpen