Quo vadis AI in Architecture?

Survey of the current possibilities of AI in the architectural practice

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The permeation of various fields by the applications of artificial intelligence (AI) has arrived in the collective consciousness and is increasingly present in the physical world. Current results of AI research in the field of architecture illustrate that already today within every step of the architectural conception and fabrication approaches towards their automation are being made. Even the very human features of motivation and creativity aren't left untouched anymore. This paper discusses, on the basis of different concepts and examples, up to what extent the contemporary possible implementations of AI and their underlying algorithms are able to conquer the architectural profession. Furthermore, it presents a summary of an automation-concept for the whole profession.

Keywords: *Artificial Neural Networks, Artificial Intelligence, Creativity, Architecture, Automatisation*

INTRODUCTION

The permeation of various professional fields by the application of Artificial Intelligence (AI) has arrived in the collective consciousness and is increasingly present in the physical world. The AI research in architecture as in other domains is ongoing and split into various branches and subbranches. This is partly the reason why the inquiry up to which degree the architectural profession in its entireness could be adopted by some combination of Artificial Neural Networks (ANN), is difficult to decode and not intensively discussed within the profession. Another reason for the underestimation of its importance is the interest in their self-preservation which is inherent to all professions, therefore also to architects. This auto-centric interest can cause a general ignorance of one's own substitutability by machines. Creatives,

as well as highly qualified professionals, consider primarily their professionalism, their know-how, and expertise as irrevocable and by machines inimitable values. In particular, empathy and intelligence along with creativity, which is inherent to humankind, seem to be the main aspects why experts of different domains sympathize with the idea of being irreplaceable.

TODAYS AI

Today, as in the past, under the code name of artificial intelligence (AI), attempts are being made to imitate human decision-making structures by computation in order to, for example, create computer programs that work independently on tasks and solve problems. In order to achieve this, ANNs are being researched in various disciplines. Some of the core AI

research topics are directly connected to and make use of mathematics. Thereof topics such as stochastics, which includes probabilities and statistics, are applied and inferences are made to treat problems that have no analytical solution. The collective term AI encompasses various sub-areas. These sub-areas include beneath others robotics, pattern analysis, pattern recognition, prediction, and knowledge-based systems. These sub-categories can already be relevant in diverse phases of architectural conception and subsequent production. For example, in its simulation or fabrication. Research in robotics aims to facilitate and adopt tasks which are up to now executed by humans or yet not at all. The first tasks to be adopted by AI-driven robots are summarized under the 4 Ds. Those 4 Ds represent tasks which are dangerous, dull, dirty or dumb (Bekey et al. 2008). AI has clearly become a stimulus term. New breakthroughs are being celebrated at ever shorter intervals. One can experience it actively on one's mobile phone or indirectly via propositions at for example online markets. Nevertheless, particularly technology critics are not convinced by the technical progress which is propagated through different media. By regarding the past, this opinion becomes partly intelligible. As for example, since the end of the 1950s research has been carried out on self-driving cars. The concrete realisation and implementation of this, partially still very unexplored terrain is, however, sluggish or not at all fulfilled.

André Loesekrug-Pietri, spokesman for the Joint European Disruptive Initiative (JEDI), alerts to not underestimate the future development of AI in the USA and China: "Europe not only underestimates the dimension of the development of artificial intelligence. Above all, we underestimate its speed."

BEGINNING OF ARTIFICIAL NEURAL NETWORKS IN ARCHITECTURE

The question of the possible substitutability of human professions, in our specific case architects, by ANNs is by no means new. This research topic emerged in architecture already around the 1960s by pioneers like Nicholas Negroponte, Cedric Price, Christopher Alexander, Richard Saul and others (Steenson 2017). Nicholas Negroponte in cooperation with computer specialists from MIT worked on an *Architecture Machine*. This machine was not merely planned and designed to support architects, but was intended to take over the entire profession (Vrachliotis 2019). Though the upcoming AI euphoria did not last for long and so shortly thereafter, in the 1980s, the first hype cycle of AI research came to an end. The AI industry, which was at that time already worth billions of dollars, collapsed for various interacting reasons. Nonetheless, research and interest in the topic never completely run dry (Kaplan 2016). This has led to the fact, that today, AI research and its implications in our everyday life are more obviously recognized than ever before. Therefore, due to the current technological achievements, an examination of questions around ANNs is again of the highest topicality.

CONTEMPORARY AI & ARCHITECTURAL PRACTICE

Contemporary AI research in architecture is based on the development and the implementation of different algorithms erecting so-called Artificial Intelligences. AIs are in the plural, as by now there is no *Artificial General Intelligence* (AGI) and the AIs which are being developed until today are mainly performing independent one from another, without being interconnected to form an Architectural Artificial Intelligence (AAI). Different algorithms are written and trained for the performance adoption of specific procedures and requirements in every step of the building process. From the project initiation, across the numerous and varied creative steps leading to the ultimately built environment.

In the following, a selection of already possible AI implementations in the field of architecture will be discussed, strung together and evaluated in the context. To structure the architectural conception, oriented on the German *Honorarordnung für Architekten und Ingenieure* (Germany 2010) - Fee Structure for Ar-

chitects and Engineers - the architect's profession can be concentrated in the following four steps:

1. Establishment of the Project Basis
2. Preliminary Design
3. Final Design, Approval Planning, Execution Planning, Preparation of the Awarding of Contracts, Participation in the Awarding of Contracts
4. Construction and Site Supervision

1. Establishment of the Project Basis

At the very beginning of every project persists the need of establishing the basis for it. Independent of the case, whether for a competition, a design assignment or a free design project, *sine qua non* the architect or the computational agent has to have an intrinsic motivation to locate and solve problems or a given situation to change it. For humans and higher mammals, such intrinsic motivated behaviour can be "curiosity, interest in novel stimuli or surprising events, and interest in learning new behaviours" (Baldassarre & Mirolli 2013). In computation, the intrinsic behaviour can be generated through a virtual reward which is programmed in the algorithm (Baldassarre & Mirolli 2013). The current state of the art in urban studies have allowed to describe multilayer characteristics of the urban environment as dynamic systems within a Remorph Framework. Within this framework data of spatial parameters are collected, analysed and visualised (Nematollahi, Shahbazi & Nabian 2019). Depending on this analysis and other statistical data containing, for example, information about the population, are allowing pattern recognition algorithms, which would be a part of an AAI, to detect underlying patterns. Furthermore, to analyse and to deduce those patterns in order to subsequently articulate already existing issues or predict future trends in the population or built environment which urge to be given attention to.

Deep Learning (DL) is a branch of Machine Learning (ML) which is developing since the 1960s. One of its components are Deep Neural Networks (DNN), which are Artificial Neural Networks, that are trained with fed data and have been developing since the 1960s. Those ANNs are inspired by the human brain. Nonetheless, they don't represent it, as the functioning of the human brain isn't completely understood by and also the ANNs work out in congruent ways. In ANNs data is processed on one or more hierarchical levels which hereby allows a *learning* of the machine. By analysing and processing data itself, the AAI agent is able to learn about any kind of subject and no longer depends on manual or explicit instructions from a programmer. DNNs surpass the human brain in the speed they process information, in the way they pass on information to a connected network in real time and in the amount of lossless information storage. The human brain is therein limited. Furthermore, it is possible to auto-update the database with novel induced data at any time or, to connect it to the internet, where it is able to acquire new data on its own. Another aspect of Deep Learning algorithms is their generative designs. This represents the algorithm's capability to adopt the natural process of evolution. Therefore, the programmed system is able to explore through potential -not predetermined - permutations, possibilities to adjust and ameliorate itself. This approach differs fundamentally from Shape Grammar approach applied in earlier times. Shape Grammar is rule-based and therefore offers only a limited and predetermined variety of output (Carpo 2017).

Within the above-explained issue-detecting part of the AAI agent, a topic on which to operate can be determined and therefore an architectural project can be initiated. This initiation already includes the accumulation, selection, and analysis of all linked and relevant information. This analysis is fundamental for the following design project. Hence, the key elements can be distilled and hierarchised, the given constraints indicated and the ambitions defined.

2 Preliminary Design

Subsequent and based on, the outlined establishment of a design inquiry and its included analysis,

key elements, constraints and ambitions, a preliminary design can be generated.

Already today, AI is a powerful tool when it comes to execute repetitive tasks, in the processing of huge amounts of data simultaneously or when the settings are clearly structured, following precise mathematically defined rules (Carpo, 2017). But one of the components which is still lacking for the creation of a *General Artificial Intelligence* is the fusion of the different single components and its elaboration in versatile and flexible domains where one encounters creative tasks. To a certain extent, architects are creatives who, at best, realize their ideals and visions for the future in an original way. To achieve this, one is said to need creativity.

Creativity. The exact meaning of the word is controversial and to this day, there is no unified definition of it in specialist circles (Parkhurst 1999). Summarizing the paraphrases of M.A. Runco & G.J. Jaeger and M. Csikszentmihalyi, one could describe creativity as the ability to imagine and sometimes furthermore to create something original, unparalleled and useful or beneficial - including, for example, the expression of one's own emotions in art or music. A well-known example of creativity is solving a problem in a novel and original way (Runco & Jaeger 2012) (Csikszentmihalyi 2014).

For Immanuel Kant "The proper field for a genius is the imagination, because imagination is creative, and just because it is less subject to the coercion of rules than other faculties, it is more capable of Originality." (Kant 1978). Today, creativity, related to imagination, has lost some of its aura as it became more researched. According to biologist and brain researcher Gerhard Roth, 1995, creativity is related to mechanisms in the brain. There, chemical processes link the contents of the long-term memory in a new and productive way that produces new ideas for the consciousness.

AI in Art. What is art? As commonly known: everything and nothing can be art, it depends on who judges. In order to facilitate the discussion, the assumption everything can be art is applicated here.

One part of current AI research in the domain of art is based on machines solving strong nonlinear problems and form abstractions of large amounts of data. ANNs techniques are therefore predestined to form the core of it. Generative Artificial Networks (GAN) are being developed since 2014, by researchers around Ian Goodfellow (Goodfellow et al. 2014). Here one ANN - the generator - generates possible candidates, which subsequently are proved for authenticity by a second ANN -the discriminator. GAN assesses its own creation and is thus by definition a form of reflection. Recurrent Neural Networks (RNN) can use its intuition, which in this case is calculated by mathematical error minimalization, to make good decisions in unpredictable situations. In further research it is to be explored, if the anthropomorphic terms which are being used here have to be redefined, or new terms have to be implemented to distinguish clearly between human und machine abilities.

The output of artificial neural networks is always based on the data the algorithms are trained on. Therefore, an eclecticism, a revival of certain building styles which are not current at the moment are possible. As well as the generation of something entirely new, as the fed and mutated data can be connected to one another in ways humans have never thought of by now. At this point, nonetheless it should not be forgotten, that the core of *creative*, as well as other predictive and assimilating products of AI, is at the same time still a big issue. As AIs are calculating with the fed information, discrimination of not in the datasets represented subjects are not to be excluded and forgotten. In other cases, this negligence could lead to miscalculations and disastrous consequences.

Artificial neural networks imitate human brain processes in many cases. Thus, if computer generated art is accused of not being creative, but the computer merely analyses previously known styles, images, compositions, etc., identifies quantifiable (statistical) correlations and creates something new through modification and variation - then AI creativity is in many cases no other approach than creativ-

ity in the human brain. The human brain leaves linear thought patterns and connects - often subconsciously - existing knowledge until a new connection makes sense. In this context, the following sentence is quite fitting: The secret of creativity is knowing how to hide your sources.

At the end of 2018, a painting (Edmond de Belamy, 2018) generated by an algorithm achieved a record in a world-wide auction. This event has revived the discussion of whether and how AI is able to be creative, similar or even better than humans. But even before, information technology-based methods for analysing and producing art were used: for example, Swiss artist Ursus Wehrli's approach to the analysis of paintings is shown in his action "tyding up art" (Wehrli, 2002). The works of the artist shown therein illustrate how well-known works of art can be viewed and arranged through pattern recognition and classifications. The method developed as an art project has then also be carried out by the algorithm Wehrli 2.0 (Ufer et al., 2012). Even earlier, other artists, such as Harold Cohen and Simon Colton, used software applications to create acclaimed art projects (AARON, 1974), (The Painting Fool, 2001). The capability of computers creating art has already been inquired about on different aspects as authorship and genius in different art domains. (Hertzmann 2018).

More recently, in 2015 the Chinese artist Wang Yuyang has presented his software suite WANG YUYANG# (WYY#) which is conceiving artworks on its own and has brought the automation of art conception to the next level. The artist and its software suite form an interoperable unit. In this cooperation WYY# is operating with a raw database, connected to the internet, containing numerous references, as well as a collection of algorithms. The database in combination with the algorithms form the reasoning power of the unit. Based on WYY# raw database, it is conceiving preliminary ideations, which are furthermore processed to form a Process Database. Therefrom WYY# generates concepts which will be translated into ASCII Code, that is again connected to the Raw database to select visual forms to make sense of the concepts. Some more steps are following to guarantee the quality of the material properties, compositions, textures, tonal properties, brush strokes and others so that the final object or painting is fitting to WYY# initial description of the work. Continuously, the single components are joined. WYY# establishes a title for the artwork which is at the final step physically fabricated by Wang Yuyang (Hock 2017). This example is showing impressively how the computer-human interaction can turn around, as the reflecting and concepting core is adopted by a machine.

The above-mentioned examples are just a few of many existing. They suggest that the creation of a piece of art can in principle also be done by a machine. However, the question of how a creative performance of a machine can be recognized and evaluated, and how it relates to human performance, is also important. Although the value of art relies partly on the artist's talent and ingenuity but also on the public's reaction to it and is, therefore, a complex subject.

One example to evaluate AI created artworks in question has been launched by Dan Rockmore, director of Dartmouth College's Neukom Institute for Computational Science in 2017. He proposes the Turing Test in Creative Arts (TTCA). The original Turing Test is about determining during a conversation if it is possible to distinguish whether the interlocutor is a human or a machine (Copeland 2003). Analogous to the original Turing Test, the TTCA deals with the question of whether people can distinguish between human and algorithmically produced art - in this case, creative works in the form of literature and music. Rockmore's defined goal is explicitly not to replace human creativity, but to assess if current computer technologies can produce creative results that are indistinguishable from man-made ones (Neukom Institute Turing Tests in the Creative Arts', 2018).

Whether machine creativity and its resulting products can be distinguished from human creativity certainly still depends on the input data, the discriminator and the written code which creates it. A certified general rating system to distinguish or com-

pare *human art* and *AI art* does not exist, yet. But one must confess: The distinguishability between AI and human coalesces.

Another inquiry that will probably occupy not only creatives but all the people working with AI is the question of its authorship. When the algorithms, generating the AI, create something - who can be named as the author, the AI itself or the Algorithm?

The case of the Belamy painting has raised questions about the authorship. Algorithms who have created "Edmond de Belamy", alike many other algorithms are open source ones and therewith accessible to everyone. Hence, one could argue, the authorship behind the final result is at least partly to everyone engaged in the creation of every used algorithm. Everything else would be contumelious towards the programmers who have made efforts and contributed with their work.

As Art is liberated from boundaries and the exigent need to have a determined higher purpose, it can pioneer science, cultural changes, universal concepts and also the application of novel technologies. This is why it is important to observe it's ongoing subjects, as they might be a precursor of the future.

Creativity in Architecture. Architecture is a unique blend of engineering and art. As an art form, it must not only be measured in terms of design, but must also fulfill functional, economic and ecological requirements. Therefore, in contrast to a painting, a building is not solely an art object but also a functional constructive object with high demands on its practical use.

Research in automation solutions for the building industry, especially in architecture, is based on the endeavour to create spaces. Those spaces are aimed to be best tailored to the users and, at the same time, to meet cultural, legal, structural, budgetary and temporal requirements. The increasing complexity of these variables is becoming progressively difficult for one person alone to manage. However, today computer programs can be trained on given data to solve complex non-linear problems which are also occurring in the architectural

design. Furthermore, computational architects can be equipped with sufficient memory and computing capacity to find an equation and several optimal solutions for the emerging variables. The design of Architecture is taking into account various requirements. Some of those are easily translatable into mathematical variables, like environmental and structural constraints such as demands on climate resistance and stability, but also administrative regulations as laws e.g. distance spaces or maximum and minimum heights. Such underlying constraints are influencing the possible emerging designs and provide a certain framework in which AI can develop concepts for further buildings. The successful generation of floorplans through, for example, alternative graph-based machine learning algorithms represent a part of the ongoing research in the conceptual generation of architecture. This approach exploits Deep Learning, GAN and the associated Creative Adversarial Networks (CAN) to generate conceptual design à la form follows function (As, Pal & Basu 2018). In another GAN-using approach by Stanislas Chaillou, AI is also used to create floor plans. He defined the footprint shape, orientation, and wall thickness as well as its texture as the metrics for capturing the basis of a style and the program, connectivity, and circulation for its organisation. Starting from there, the ANN was trained with already existing floorplans to finally generate new and already furnished ones adapting to the above-mentioned parameters. Chaillou's approach offers the architects to intervene, by defining the buildings' footprint, entries or windows at any state of the process in order to influence the architectural outcome (Chaillou 2019).

As those examples offer by now merely a 2D plan for architecture, it needs to be extruded in a convenient way. Therefore, multidisciplinary design optimisations simulations can be used to provide a design adapting loop, where AI is testing reams of variants to determine the best fitting one. Today computers are able to create a performance feedback loop out of the following main steps 1) generate/adapt design alternatives 2) Simulate and test the

design upon predefined parameters 3) Evaluate the results and take a decision 4) Execute the decision: back to step 1) or proceed to the next stage (Gerber & Lin 2014). This multidisciplinary design optimisation can be run over n - generations. Here lies one of the crucial points why AI is predetermined to inherit an important role in the future of architectural design. For such a heuristic approach, as an n-generation feedback loop, engineers would need a lifetime, whereas computers calculate the solutions in a comparatively short amount of time (Carpo 2017). Through this saving of time and therefore money, mass customisation at no namable higher cost can be done. For every person, situation or condition a perfectly adapted building could be conceived. This yields the hope for the future to be able to say: Bye, bye, serial housing!

Although, the current state of the art clarifies: not all the aspects which are important for the architectural conception, such as the subjective criteria of the user, ideology and culture can be formalised by now. With a regard to e.g. the information social media is collecting and processing to feed one with tailored advertising, it is not provoking to imagine a comparable use of personal data for a perfectly personalised home or adapted built environment.

With the implementation of AI, the architect's role seems to evolve: "The role of the architect here, I think, is not so much to design a building or city as to catalyse them: to act that they may evolve." - Gordon Pask (Frazer 1995).

Prospect of possibilities. Theoreticians argue, as the limits of the possibilities offered by AI are far from being reached, it is impossible to determine or even imagine what the creations of AI-generated architecture could be like. The concept of artificial intelligence includes the *artificiality* of the whole intelligence, what implies that the AI is "artificial in every sense of the word" and therefore abandons the Anthromorphism, Biomimicry or other human defined concepts, which are still inherent to contemporary AIs (Morel 2019). The mathematician Richard Wesley Hamming interpreted the possible effects which

computation can have on our overall conception of the world as the following:

"Just as there are odors that dogs can smell and we cannot, as well as sounds that dogs can hear and we cannot, so too there are wavelengths of light we cannot see and flavors we cannot taste. Why then, given our brains wired the way they are, does the remark "Perhaps there are thoughts we cannot think," surprise you? Evolution, so far, may possibly have blocked us from being able to think in some directions; there could be unthinkable thoughts."(Hamming 1980)

3 Final Design, Approval, Execution Planning, Preparation of the Awarding of Contracts, Participation in the Awarding of Contracts

The final design is a derivation of the preliminary design, where the final construction plans are being conducted. Furthermore, official demands and announcements have to be automatically concluded and supervised in order to receive the city authority's construction permit. As future architecture might be designed and planned in cooperation with special construction companies, new and not yet certified construction methods and materials need to get approved. If the erection method has not been particularly designed for the relevant project the AAI agent automatically prepares the awarding of contracts and selects furthermore the candidates.

The analysis and the preliminary design have already taken into account the legal or physical constraints which could occur at this point and impede the intended construction permit. Nonetheless, the rigorousness of the initial framework, needs to be discussed, as *thinking outside the box* or small variations of the regulative framework could in some cases lead to far better results. In the future, this step seems to be a formality and needs to be updated by city authorities in order to facilitate the admission of novel building materials and methods.

4 Construction and Site Supervision

The large-scale construction industry is facing a recession of human labour force. These manual shortages are caused by multiple reasons like the aging population and a decline of trained workforce, as more attractive, less dangerous or higher education options are increasingly preferred. In order to prevent the emerging work-force gap, various options of robotic technologies are developed to pre-fabricate and construct on site.

Successively to the selection of the construction companies in the earlier step and the preparation of the site, the on-site construction begins. Here, the *file to factory* principle can perfectly be adopted. It is evident, that at this point of the architectural procedure, the way the building will be erected is already defined. But to stay in the chronological structure, the implementation of AI into construction has not been discussed until now.

The connection of the construction steps, as well as the communication between the different companies on site are crucial for the success of the process. This connection and communication can be achieved through the direct communication of all operators via Internet of Things.

For the purpose of becoming independent of human workforce at prefabrication and on-site constructions, large-scale assembly robots such as the Humanoid Robotics Platform (HRP) series from Japan's Advanced Industrial Science and Technology Institute are being developed since 2000. Their latest version is the HRP-5P which is a prototype for humanoid robots (Kaneko et al. 2019).

The problem-solving approach by researchers investigating humanoid robots that are imitating humans is one way to trigger the ongoing change on site. Nonetheless, the maybe more intriguing part of robotised construction are the novel, upcoming possibilities which are not inspired by the human example. Flight assembled architecture, where quadrotor helicopters have assembled for example bricks without human intervention, has become known through the researches of Gramazio and Kohler in coopera-

tion with the robotic system by Raffaello D'Andrea. (Gramazio & Kohler 2014). Other promising examples focus on large- scale 3D printing or a plant-like growing of the built environment.

The questions one is also facing at this step of the process is, what will be the results when AI will be creative in order to generate or combine new forms and ways to assemble, construct, erect and influence the future built environment. By combining different research areas such as biology or geology with construction, new materials and ways of construction could occur. Here again, it can't definitely be determined what will occur when algorithms start adopting this domain.

The building monitoring is a construction phase, which is - when well prepared - a phase following the plans. Nevertheless, on every construction site are appearing earlier or later unforeseeable problems, which humans have to solve creatively and quickly, in order not to hinder the following construction steps. To conquer those by now not predictable issues is to train an AAI to determine upcoming problems by itself and find solutions for them, analogous to the preliminary design, where it generates solutions for the whole problem.

CONCLUSION AND OUTLOOK

Architecture and new technologies have a promiscuous relationship. The influences of current and future AI are fundamental and affect many areas of society. The inquiry of the possible adoption of creative services by machines is therefore inevitable. In architecture, the interpenetration of creativity and art with questions of technology, functionality, and construction is particularly clear and socially relevant. As the represented ideas are partly mere theory and the already existing achievements are not connected one to another, yet, the rise of an AAGI is not to be expected in the near future. At this moment of time, we are experiencing exceeding possibilities to enhance the architectural design process and its construction. Nonetheless, the aim to connect the research fields and scientists to create coherent results to take ad-

vantage of the existing possibilities remains to be reached.

The advent of AI-generated architecture humans haven't thought of yet, has already been announced. But the today existing examples of an AI generated built environment still needs more years of research and collaboration between the different fields to achieve the announced quality.

For future comparisons of AI-generated architectural topics, a Turing Test in Architecture could be a promising way to evaluate and compare ongoing research achievements.

This article is not composed with the aim to pursue the abolishment of human architects, but instead to create awareness of the actual research and application situation within the profession. As the contemporary possibilities and changes affect the discipline, a critical debate should take place. This interlocution should have the same importance as the debates about ecological, social and other subjects that influence people and their built environment. The role human architects will inherit in the future is depending on their positioning today within the emerging technologies. Taken the expounded points into account, two future scenarios seem feasible. The two main scenarios where AI is furthermore employed into the architectural practice, can be described as the following:

1. AI is adopting the architect's profession, as the human profession doesn't define clear standards for AI (, yet).
2. Human architects will regulate the role AI will adopt.

In fact, it is possible, that today we shape the technologies and afterwards, those technologies shape our built environment and therefore in some manner us.

Hence, it is essential not only to become familiar with the technical possibilities, to update the architectural education system and the administrative regulative components but also to deal ethically with the advantages and consequences.

REFERENCES

As, I, Pal, S and Basu, P 2018, 'Artificial intelligence in architecture: Generating conceptual design via deep learning', *International Journal of Architectural Computing*, 16(4), pp. 306-327

Baldassarre, G and Mirolli, M (eds) 2013, *Intrinsically Motivated Learning in Natural and Artificial Systems*, Springer Berlin Heidelberg, Berlin, Heidelberg

Bekey, G, Ambrose, R, Kumar, V, Lavery, D, Sanderson, A, Wilcox, B, Yuh, J and Zheng, Y 2008, *Robotics: State of the Art and Future Challenges*, PUBLISHED BY IMPERIAL COLLEGE PRESS AND DISTRIBUTED BY WORLD SCIENTIFIC PUBLISHING CO.

Carpo, M 2017, *The second digital turn: design beyond intelligence*, The MIT Press, Cambridge, Massachusetts

Copeland, BJ 2003, *The Turing Test The Elusive Standard of Artificial Intelligence*, Springer Netherlands, Dordrecht

Csikszentmihalyi, M 2014, *The Systems Model of Creativity*, Springer Netherlands, Dordrecht

Frazer, JH 1995, *A natural model for architecture : the nature of the evolutionary model*, Architectural Association, London

Gerber, DJ and Lin, SHE 2014, 'Designing in complexity: Simulation, integration, and multidisciplinary design optimization for architecture', *SIMULATION*, 90(8), pp. 936-959

Germany, initials missing (eds) 2010, *VOB: Vergabe- und Vertragsordnung für Bauleistungen: Teil A und B: HOAI: Verordnung über Honorare für Leistungen der Architekten und der Ingenieure: Textausgabe mit Sachverzeichnis*, Deutsch. Taschenbuch-Verl. ; Beck, München : [München]

Goodfellow, IJ, Pouget-Abadie, J, Mirza, M, Xu, B, Warde-Farley, D, Ozair, S, Courville, A and Bengio, Y 2014, 'Generative Adversarial Networks', *arXiv:1406.2661 [cs, stat]*

Gramazio, F and Kohler, M (eds) 2014, *Made by robots: challenging architecture at a larger scale*, Wiley, London

Hamming, RW 1980, 'The Unreasonable Effectiveness of Mathematics', *The American Mathematical Monthly*, 87(2), pp. 81-90

Hock, R 2017, 'Datumsoria: The Return of the Real', *no title given*

Kaneko, K, Kaminaga, H, Sakaguchi, T, Kajita, S, Morisawa, M, Kumagai, I and Kanehiro, F 2019, 'Humanoid Robot HRP-5P: An Electrically Actuated Humanoid Robot With High-Power and Wide-Range Joints', *IEEE Robotics and Automation Letters*, 4(2), pp.

1431-1438

Kant, I 1978, *Anthropology from a pragmatic point of view*, Southern Illinois University Press, London

Kaplan, J 2016, *Artificial intelligence: what everyone needs to know*, Oxford University Press, New York, NY, United States of America

Kühnberger, KU, Rudolph, S, Wang, P and GI, initials missing (eds) 2013, *Artificial general intelligence: 6th international conference, AGI 2013, Beijing, China, July 31-August 3, 2013 ; proceedings*, Springer, Berlin

Morel, P 2019, 'The Origins of Discretism: Thinking Unthinkable Architecture', *Architectural Design*, 89(2), pp. 14-21

Nematollahi, MA, Shahbazi, S and Nabian, N 2019, 'Application of AI in Urban Design', in surname missing, initials missing (eds) 2019, *Computer Vision and Audition in Urban Analysis Using the Remorph Framework*, Springer Singapore, Singapore, pp. 1-12

Parkhurst, HB 1999, 'Confusion, Lack of Consensus, and the Definition of Creativity as a Construct', *The Journal of Creative Behavior*, 33(1), pp. 1-21

Runco, MA and Jaeger, GJ 2012, 'The Standard Definition of Creativity', *Creativity Research Journal*, 24(1), pp. 92-96

Steenson, MW 2017, *Architectural intelligence: how designers, and archtiects created the digital landscape*, The MIT Press, Cambridge, MA

Steunebrink, BR, Koutník, J, Thórisson, KR, Nivel, E and Schmidhuber, J 2013, 'Resource-Bounded Machines are Motivated to be Effective, Efficient, and Curious', in Kühnberger, KU, Rudolph, S, Wang, P and GI, initials missing (eds) 2013, *Artificial general intelligence: 6th international conference, AGI 2013, Beijing, China, July 31- August 3, 2013 ; proceedings*, Springer, Berlin

Testa, P, O'Reilly, UM, Weiser, D and Ross, I 2001, 'Emergent Design: A Crosscutting Research Program and Design Curriculum Integrating Architecture and Artificial Intelligence', *Environment and Planning B: Planning and Design*, 28(4), pp. 481-498

Vrachliotis, G 2019, 'Architekturmaschine - Individualisierungssysteme', *Arch+*, Datatopia(234), p. 216

[1] http://bregman.dartmouth.edu/turingtests/

[2] http://stanislaschaillou.com/