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Cover images
Front: Aggregation of drones for building temporary pavilions as adaptive systems.
Back: Projected window: simulation based on the work of Renè Magritte and the local landscape by Alex Nogueira.

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Towards an Architecture Operating as a Bio-Cyber-physical System

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Abstract

Today's physical-digital continuum challenges designers and architects to envision architecture as a Bio-Cyber-physical System that is operating as part of a larger ecosystem while addressing societal challenges with a broader understanding of sustainability in mind. This paper identifies current conditions, challenges and opportunities, while proposing an intercultural dialog toward achieving a better future. The purpose is to enlighten and explore the threshold where the physical interlaces the domain of immaterial flows of information as well as identify some of the digital and material design aspects shaping the multiple facets of bio-cyber-physical-systems in order to propose some possible solutions for current design challenges.

Keywords

architecture, Bio-Cyber-physical System

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The physical-digital continuum

This paper aims at rising a multidisciplinary debate around the evolution of design and architecture in the era of digitalization. It has been written in remote collaboration between three design researchers, who work at academic institutions in three European cities, Milan, Delft and Leuven, while the pandemic associated with the COVID-19 virus has been confining everybody within domestic walls. The lockdown did not prevent collaboration as for some time collaboration in academia has been exercised even without meeting in physical space using various tools that facilitate remote interaction. They build a virtual academic network, with a potentially unlimited number of classes and laboratories, libraries and meeting rooms, which can be accessed without leaving individual homes. This virtual network has been through the pandemic activated more than ever with meetings, classes, symposia taking place exclusively online.

Virtual social interaction, work, and collaboration is not only for university campuses, it is for all contexts: libraries, offices, banks, shops, museums, recreational spaces and more. These spaces, once designated buildings dedicated to specific functions, increasingly facilitate forms of social aggregation that take place in cyberspace. The digital intertwines the physical creating a digital-physical continuum.

In this context, the relevant question is how architecture and design knowledge, education and practice can and should exploit the potential of this physical-digital continuum in order to address contemporary challenges?

Architects have been designing physical environments for thousands of years, providing shelters and buildings that facilitate human activities: market-places for trading and schools for education; hospices for care-giving; temples and churches for praying; libraries for archiving knowledge. *Praescriptum et lineamentum*, which translates from Latin to project and drawing, are architecture's means for achieving *res ædificatoria*, which translates as art of building (Samsa, 2004; Samsa, 2012). These address the need to foresee and resolve the requirements of architecture's legitimacy, feasibility, efficiency, aesthetic impact and duration over time, from Alberti (1485) to recent times.

By shaping physical spaces, architects have embodied the paradigms of social organization associated with the buildings, and they provided the means for defining the constraints and freedoms related to their physical organization and arrangement. From the '90s of last century, the spread of the Internet, the development of the Internet of Things (IoT), the construction of the technical infrastructures for broadband data transfer, and the evolution of digital facilities, provided the means for the construction of a cyberspace that interlinks with the physical space (inter al. Rowland, 2015; Bolton, 2018).

Today, almost every institution or entity has a double identity and embodiment: a physical one – associated to the physically materialised building and the physical interaction between people – and a virtual one -relying on digital interactions, software applications, and Artificial Intelligence (AI).

During the lockdown, several institutions switched within a few days to remote activities. Universities turned into online education environments and online commerce grew to unprecedented levels. Museums and art institutions started experimenting with new online formats to keep the engagement with their audiences alive. While some activities may return to their physical manifestation after the pandemic, most may have been irreversibly transformed. The architecture-purpose relationship rendering architecture as means of access to goods and services opened up during the pandemic towards involving a blend of physical and digital resources to address needs and solve problems. It requested an understanding of architecture operating as a bio-cyber-physical system, shifting the focus to a contemporary *res ædificatoria* operating as part of a larger ecosystem where sustainability is approached in a broader sense, as framed by the United

Nations in the 2030 Agenda. The emerging question is thus how bio-cyber-physical architecture may address issues related to climate change, rapid urban densification, etc.

If at first, the cyber space was a parallel universe, defined as an alternative to the physical space, progressively, the physical- and cyber- spaces converged demanding further investigation of the merging realms, where the two meet, hybridize, and become fertile in various ways.

This paper aims at rising a multidisciplinary debate around the evolution of design and architecture in the era of digitalization. The purpose is to enlighten and explore the threshold where the physical project interlaces the immaterial flows of information, in order to identify some of the digital and material design issues shaping the multiple facets of bio-cyber-physical-systems and propose some possible solutions for current design challenges.

The cyber-physical

If the term 'digital' refers to a format for encoding information, the prefix 'cyber-' in the formation of compound words such as cyber-physical, points at the interactive context created by the embodiment of ubiquitous computing. Each materialisation and construction technique bring new and specific expressive opportunities, enabling new functional solutions and new design languages. The digital as building matter does not make exception: the architectures of the Information Technologies (IT) give shape to new social compositions, while interactive multimedia provide the means to create forms of sensorial engagement and sense making.

The impacts of the digital on human society was apparent since its very beginning: Maldonado (1997) discussed its potentials and criticalities focusing on three dimensions: (1) the political organization of societies (with the cyberspace as a potential democratic space), (2) the urban context (including the transformation of the large urban agglomerations; the work and education at a distance, etc.), and (3) the evolution of the individual experiences, perception and self-perception, in the blended realities produced by the mix of physical and virtual realms.

Eastman (1972), Negroponte (1969, 1975, 1995), Maldonado (1994, 2005) and others, pointed out even before the spread of the Internet, the deep transformation of the human capabilities related to the adoption of the digital technologies, and the potential impacts on architecture, individuals and organizations. After five decades, the deep interpenetration of the physical and virtual dimensions of reality is obvious, and it is time to claim the priority to develop new approaches for the design of bio-cyber-physical systems by integrating and evolving the contributions provided by the different disciplines concurring to their creation, and by engaging in a critical conversation about the future while in progress of already building it.

Affected by the worldwide pandemic with still unpredictable consequences, present times create a sense of urgency in the search for new approaches in design practice and education and ask for a better capability to bring into focus the political issues and societal challenges of these times. Digitalization poses issues going beyond contingency (Floridi, 2014; Tegmark, 2017), and asks for new approaches in the design practice and education.

The bio- and the cyber-physical

Considering the bio-cyber-physical as means of *res ædificatoria* focusing on the creative opportunities offered by ubiquitous computing and Artificial Intelligence (AI) together with all the technologies required for building physical environments, the qualities of these environments need redefinition. This involves integrating the attributes of material buildings – in terms of form, function, etc. – with those of the digital solutions, including usability, acceptability and accessibility.

The construction of material buildings is based on the laws of physics regulating the static and dynamic behavior of architectural structures, and on the characteristics of the materials and construction techniques, which define the adequacy with respect to the functional use, operation in time and aging. The topologies of architectural spaces and their interior design enable and constrain the actions of human beings who inhabit them, while their forms and materials produce sensorial effects. Cyber-spaces follow other laws, creating engagement based on interaction with human beings. The space of the Internet appears as potentially infinite, and the association of the cyber and the physical dimensions opens up unexplored scenarios such as automatic construction processes, dynamic and robotic architectures involving hybrid experiences. To profit from technologies, it is necessary to develop the sense of criticism with respect to meaningfulness of possible solutions, since not all the imaginable functionalities provide real value to the end-users.

The merging of the physical and the digital is one of the phenomena manifesting the evolution of the design disciplines, and it is in some and complex ways related to the switch from the aesthetic of the objects to the aesthetic of the actions, namely, of the act of use (Findeli, 2005).

It is imperative to better understand and explore how the concepts of experience and value, used in Interaction and Service Design, can be deployed in bio-cyber-physical systems, and how the physical features of buildings and artefacts fit the requirements of the human body and mind: the rationales, satisfactions and utilities related to the interactions proposed through the interfaces and to the action-reaction mechanisms embodied in the systems.

Bio-cyber-physical phenomenology

In the 70s (inter al. Eastman 1972; Negroponte 1975) speculation on opportunities entailed by the Information Age established an early discourse on intelligent environments in architecture. Since then, various applications have been developed for Ambient Intelligence (AmI) (Zelkha et al. 1998), Interactive Architecture (inter al. Fox & Kemp 2009), Adaptive Environments (Bier, 2018), etc.

In the same line of thought and experimentation, an extended AmI enabled by a Cyber-physical System (CPS) built on a Wireless Sensor and Actuator Network (WSAN) has been developed at Technical University Delft (TUD) (inter al. Liu Cheng et al., 2017; Bier, 2018). Amongst others, it involves Human Activity Recognition (HAR), in order to continuously regulate dynamic changes like illumination for e.g. (Fig. 1).

It has been integrated in a stage with an adaptive LED-based illumination system that responds to three scenarios: (1) Initiation, (2) Lecture, and (3) Break. In the first scenario, as soon as the system is powered, the lights start to pulsate indicating that the stage comes to 'life'. In the second scenario, the lights react to the movements of the speaker, which change colour for a certain period of time. In the third scenario, the lights respond to the audience and their movement during the break. The system is also equipped with

Machine Learning (ML) algorithms in order to identify which combinations of light colour and intensity contribute to improving the 'well-being' of the speaker, by identifying if the light is too bright or too dimmed. In this context, the system continuously seeks to improve the state of the speaker by regulating the light via ML mechanisms using HAR (Liu Cheng et al., 2017).

FIGURE 1 Interactive stage at the *Game Set Match symposium*, TU Delft (2016).

That ML employs data collected from users to learn how to respond to users' needs by establishing a bio-cyber-physical feedback. The design of such feedbacks requires Design-to-Robotic-Production and -Operation (D2RP&O) methods (Bier, 2018) that not only anticipate but also learn from users and the environment. This learning process takes place in both the D2RP as well as in the D2RO processes as they increasingly converge. While D2RP focuses on linking the design to the production process of buildings, D2RO links the design to the operation of buildings. Together, they establish a comprehensive framework for the AI supported building of buildings that are imbued with AI. Both, AI embedded in building processes (based on D2RP) and AI embedded in buildings (based on D2RO) involve on some level Human Robot Interaction (HRI): If in D2RP, humans work safely together with semi-autonomous production robots, in D2RO humans interact safely, healthily, and pleasurably with the built environment. In both cases the new meaning of building production and operation is not created by the one or the other, but by the interaction between the two.

An AI system that intertwines with the physical environment can be distributed and replicated in many diverse ones. An example is the project *Connected Lighting for a Caring City*, developed in collaboration with the MIT Design Lab and the company Signify (Pavlovic et al., 2019a; Pavlovic et al., 2019b). The project was developed in 2018 and focused on the development of a design vision for an artificial lighting system that would have the effect of making urban dwellers feel cared for, within the context of growing megacities. The design concept envisioned a personal assistant that would accompany the users during their daily activities within diverse indoor and outdoor urban settings. The interface with this assistant involved gesture-based modalities that support seamless user interactions for controlling light sources, complementing common daily activities.

In this project, human experience within usual daily inhabited spaces has been enhanced via communication with an AI system that, in this particular case, dynamically adapts the lighting sources. The concept envisions an experience with an AI system that in time learns about the users' activities and preferences and adapts the diverse ambient accordingly.

An example is having the lighting AI system remind an elderly user when it is time to take the medicine by adapting the lighting in his/her home environment (Fig. 2); other examples are having the AI 'coach' provide guidance and illuminating signs through available infrastructure to an user on his/her daily jogging activity within the urban outdoor environment, or support the jet lagged frequent business traveller by adapting the lights in his/her environment after the flight. In this project the emphasis was on creating adaptive environments powered by AI algorithms, which are sensitive towards the city inhabitants and their activities. Even though it is strongly embodied and visible within the physical environment, the design concept of a 'caring' AI system was born from an approach of designing for meaningful experiences for city inhabitants, thus underlining the strengths of designing with bio-cyber-physical systems in mind.

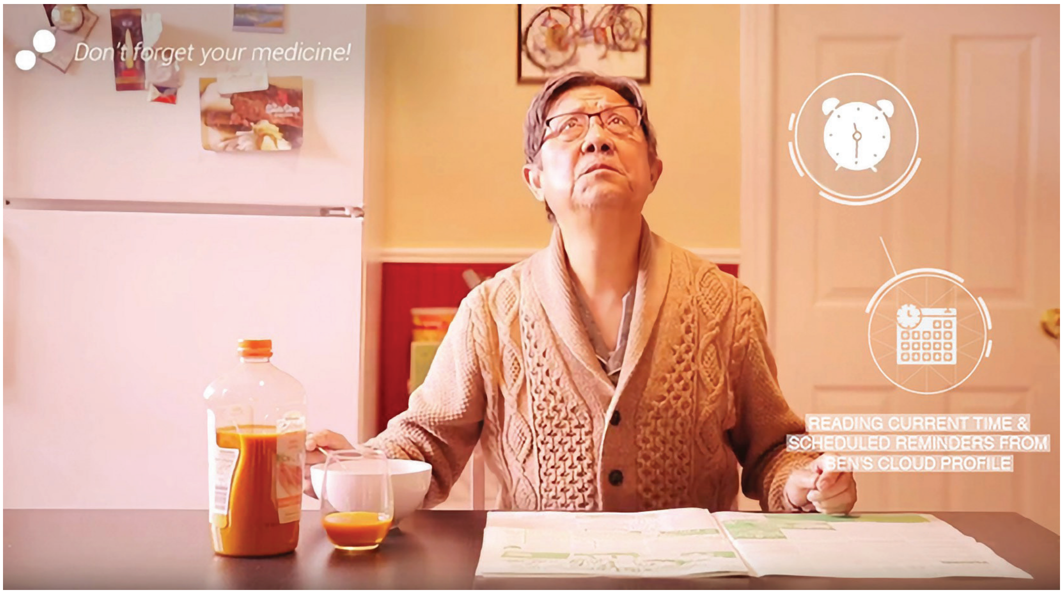

FIGURE 2 AI system reminding an elderly user when it is time to take the medicine by adapting the lighting in his/her home environment, *Connected Lighting for a Caring City project*, MIT Design Lab (2018).

Connected Lighting for a Caring City is an example in which the embodiment of AI is ambient related, and to a certain extent non-anthropomorphic. This is to note that designing an interactive environment powered by AI in the back-end is quite a challenge, which can however take inspiration on bits and pieces from diverse fields of practices. Therefore, such challenge surely requires a convergence of diverse fields of interaction in order to provide a holistic User Experience (UX) design approach and thus it requires reasoning on bio-cyber-physical considerations.

Even though the technical development and implementation of complex systems of diverse sensors and actuators (within an environment) could be challenging, it is still not the main challenge that bio-cyber-physical systems impose. The main design quest within these systems is designing for meaningful and desirable interactions and experiences, which implies also giving a certain new character and interaction language to the environments. Designing such systems, therefore, implies designing an embodiment of the AmI, considering its own interaction language and behaviour.

During the 2019 Milan Design Week, Sony Design presented a series of concepts of interactive environments named *Affinity in Autonomy*. The environments were sensitive to human presence, movements and behaviour, and were responsive. Visitors of this exhibition could interact with many diverse objects by getting to know their well-thought pre-designed behaviour. In one room, a visitor would try to call for the 'attention' of an object (with a very unconventional physical shape) by moving his/her hands close to the area of the object. While the object would show non-immediate reaction, almost demonstrating initial fear from the human through slight shivering, it would further apparently develop confidence, so the more time passes the relation between the two is being built (Fig. 3, image left). In another room, a visitor would find him/herself surrounded by many spheres, where each of them has its own AI, and each one reacts and interacts with the human in its own manner: some spheres were more 'curious' or more 'sceptical' than others, while some are just more 'playful' (Fig. 3, image right).

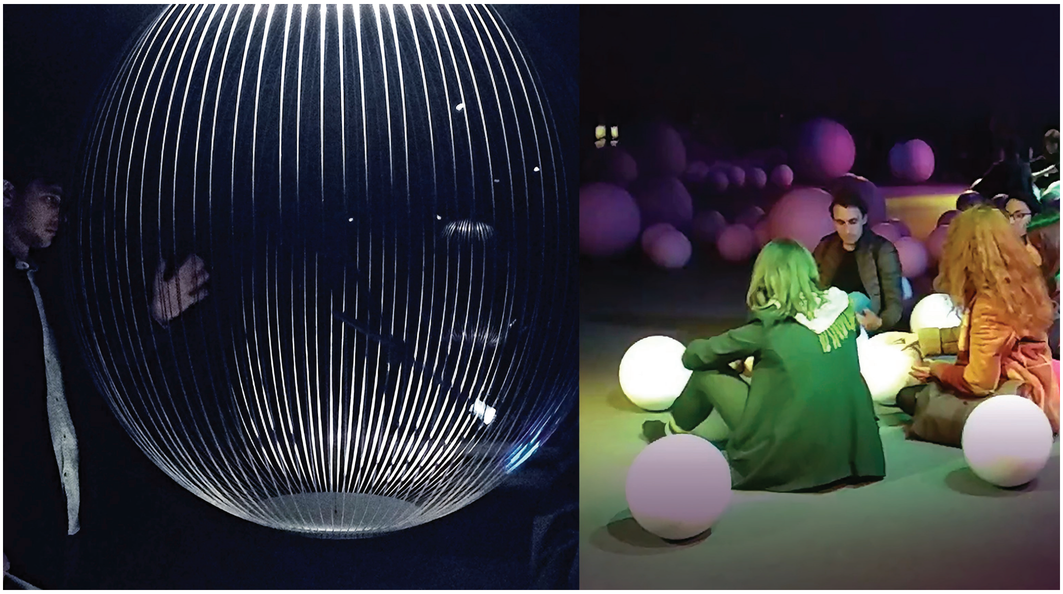

FIGURE 3 *Affinity in Autonomy* interactive environments exhibited at the Milan Design Week, Sony Design (2019).

The project *Affinity in Autonomy* demonstrated in a very concrete and tangible manner the importance of designing behaviours and characters of interactive environments, which do not possess a human physical appearance, yet they manage to build unique relations.

Adaptive architecture is applicable to many diverse environments from smart homes and domotics, to smart retail and service shops, offices, hospitals, urban public spaces, and art installations. All of these environments require a novel approach to their design, an approach that is ever more complex, systemic and responsible, and goes beyond the traditional practices of architecture.

Discussion

The emergence of bio-cyber-physical systems corresponds to the requirement of addressing today's challenges while taking people, contexts, local and global environments into account. As shown in the presented case studies, the convergence of sciences and design related disciplines provides conceptual and practical tools to approach design challenges involving users and social subjects in the interpretation of needs and in the definition of the project goals and values. AI produces more convenient models of the physical world and supports decision processes (Tegmark, 2017). The capabilities of data collection and processing feeds creativity and provides knowledge supporting design approaches based on unprecedented accuracy and capability to collect insights on the impacts of projects.

In the realm of the experimental adoption of new technologies in design and architecture, the goals of social and environmental sustainability are a priority. The modelling of the performances and characteristics of the physical environments can inform the project toward a more suitable use of resources, and toward the optimization of performances with respect to the variable behaviours of the end users. Digital and robotic applications expand the techniques that can be used in construction and multiply the contexts in which construction can take place. Furthermore, the integration of digital and robotic applications into the built environment enhances and expands human experience, offering opportunities for increased wellbeing and the creation of new interactions and meanings.

The well-known statement of Churchill (1943) 'We shape our buildings, and afterwards, our buildings shape us' and its variants, has probably never been so true: the ubiquitous presence of digital information is clearly producing deep impacts on individuals and the society as a whole, and the changes are far from being predictable. The question of tools available for developing awareness about the potential impacts of the designed artefacts and constructs requires further specification (Varisco et al., 2019) as it requires intercultural and interdisciplinary dialogue. Humanistic studies have always provided the cultural and critical framework to support the reasoning about the aims and purpose of the design project. Today, the interlacing between humanities, design and mathematical data processing has produced new techniques. These techniques and methods of UX Design are available to the market and are seen as tools to optimize the use of digital solutions at a global level, but they can also provide the tools to better understand the changes and impacts that technological innovation brings (Pillan & Colombo, 2017; Pavlovic, 2020). In addition, the methods and techniques of co-design provide the tools for stakeholder involvement (including the end-users) from the earliest design stages (Mandolfo, 2020). The comparison and, perhaps, the hybridization of disciplines such as architecture, interaction design, sociology, psychology, biology, and computer sciences appears as a necessity, which must overcome the limits and constraints of the disciplinary territories.

While the digital-physical continuum enables the creation of services for education, healthcare, participation to the social and political management, and distributed industries and work, the tensions and conceptual issues need to be considered. The transformation of the design approaches is far from being a linear process and this paper outlines some issues as a matter of reflection and discussion.

The first issue involves the time scale. In the time when the Renaissance architects debated about the ideal urban layout and features, they were assuming that structures should be created for eternal or at least long-lasting duration. The construction times were very long, as were the decision-making and design processes. The extended time scale of creation created pastiches reflecting the evolution of tastes, needs and political contexts, and generated imperishable cultural heritage. The cost and energy requirements of the material construction have constrained the building construction for centuries, which has been a limit. The efforts required by the material building limited the amount of created artifacts and forced the implementation to balance perspective goals and expected duration. The issue of duration (duration itself, and duration as related to the cost/benefits ratios) is a complex topic that should always be part of the design reasoning, also considering the sustainability aspects.

The time scale of the digital creation is instead impressively short and the obsolescence of the components and solutions (such as processors, sensors, interfaces and infrastructures for data transfers) is counted in years if not months. In an overpopulated world, with a cogent need of reducing the consumption of energy and natural resources, the design of buildings as bio-cyber-physical systems should take place with a strong awareness of the advantages and impacts of the project choices in the short and long term. Furthermore, the fragility and obsolescence of the electronic components should be managed as to obtain the suitable resiliency required to maintain the main functions in time and in case of changes of the overall context.

Until now, cyber-physically enhanced architecture has shown potential to contribute to the reduction of energy consumption by AI supported operation of environmental control. It can also increase efficiency of spatial use by physical reconfiguration (inter al. Bier et al., 2018).

A second challenge, although not secondary, concerns the definition of needs-priorities-goals to which the to be designed solutions should respond. The cyber-physically enhanced buildings should be congenial to the biology of humans, since robotics and automation are aimed at unbinding humans from the slavery of repetitive and heavy works, empowering them beyond the limits of their embodiment. The bio-cyber-physical-systems introduce a new typology of artefacts and buildings, where the dynamic behaviors and agency of machines designed to be smart and proactive merge with the static solidity of architectural structures. This calls for experimentation and discussion about what is perceived to be convenient, suitable, useful and meaningful. Automation of functions has potentially a high impact on lifestyles, offering solutions capable to reduce the efforts of management and control on spaces and machines; automation can affect accessibility but it imposes constraints on human control, and rises issues about the use of personal data and on decision making. Automation can provide optimal solutions with respect to resources, but it can also affect individual freedom and it requires definition of suitable prioritization criteria.

The third challenge addresses democracy in the design of bio-cyber-physical systems. These systems are dynamic structures based on sophisticated technologies, often employing implicit data collection and processing related to user behaviors. Such personal data enable the implementation of effective services, creating value through new functionalities as well as control of performances. The optimization of performances and design of AI systems is an issue of democracy, since it involves the search for a compromise between the individual wellbeing and the collective advantage. Furthermore, the centralization of the controls should be counter-balanced by the individual rights on decision making or, at least, by the knowledge about principles governing the control algorithms.

The creative exploitation of the physical-digital continuum involves tensions between the individual and collective advantage, and between the present and the next generations of humans and non-humans who will inhabit the planet. The challenge of designing architecture as a bio-cyber-physical system is a challenge of defining new paradigms of development, progress, wellbeing, capable to orient the design in present times characterized by very rapid changes and new formal languages.

The fourth issue is the social impact from expected labor skill shift due to increased automation and the challenge to respond to the demand of developing new skills. The human remains in the loop as only about 50% of tasks can be automated and about 5% of tasks remain in complete human control. The rest of the tasks remains to be defined as bio-cyber-physical in nature and the challenge is to choreograph the interaction between bio- and cyber-physical systems.

Findeli (in verbal communication) used to define design and architecture as forms of anthropology: by creating and using new artefacts and reflecting on own experiences, humans can explore and learn about the environments, the possible social contexts that are compatible with the human nature, but also the meaning of being human.

The evolution of technologies involving design to production and operation methods imbued now increasingly with AI, opens the way to a new *res ædificatoria*. This new 'art of building' engages with technological developments of the 3rd and 4th industrial revolutions. Similar to the way Modernist architects understood that the 2nd industrial revolution and new materials fundamentally changed architecture, today's architecture is transformed through the 3rd and 4th industrial revolutions with their robotic, AI, IoT applications, which impact not only its design and production but also its operation. While this paper identifies some of the opportunities and challenges of this transformation, the proposed intercultural dialog requires further expansion and deepening.

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