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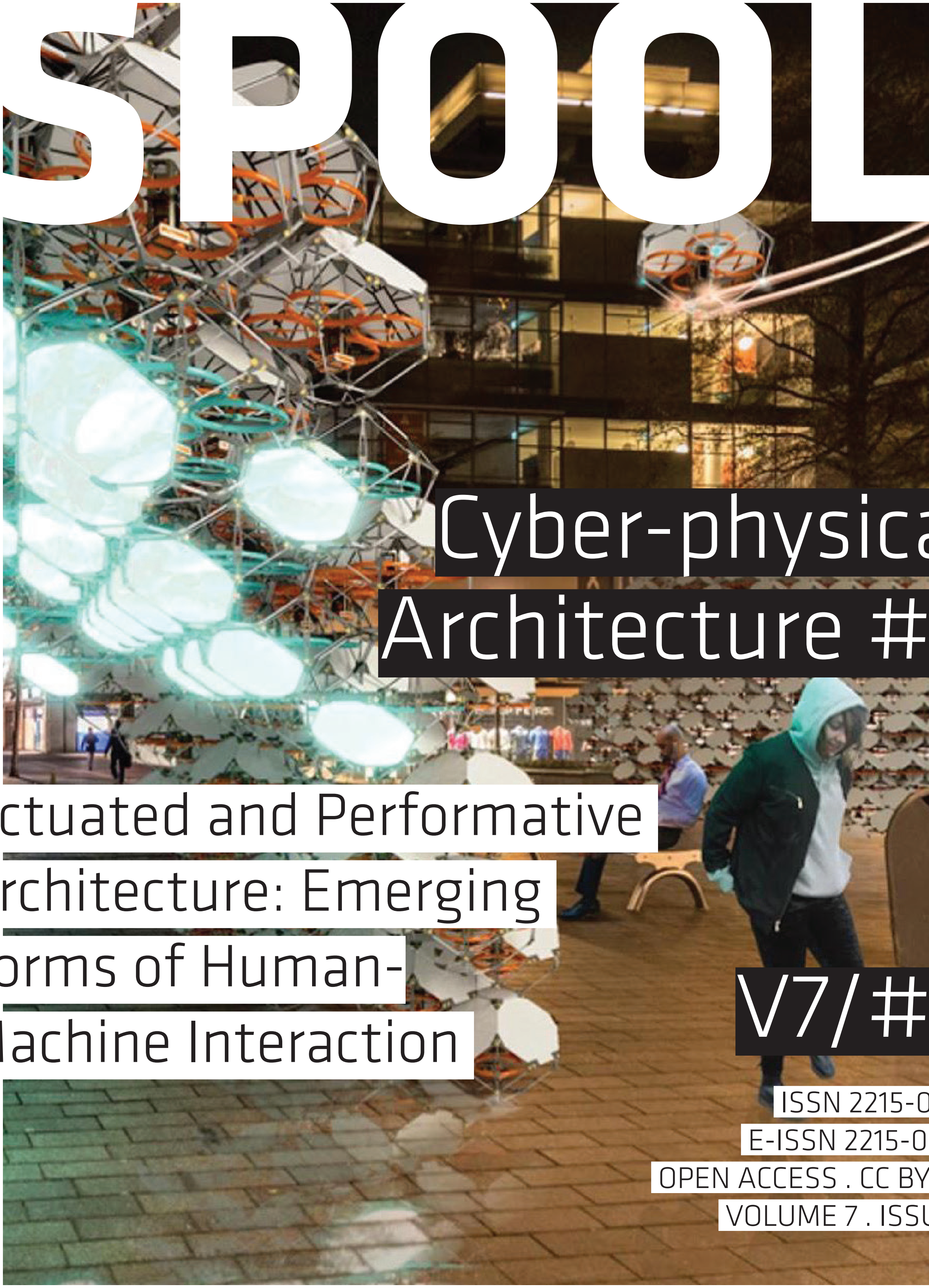

Cyber-physical Architecture #3

Actuated and Performative Architecture: Emerging Forms of Human-Machine Interaction

V7/#3

ISSN 2215-0897
E-ISSN 2215-0900
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VOLUME 7 . ISSUE 3

SPOOL

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Editorial

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SPOOL - Journal of Architecture and the Built Environment

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ISBN
978-94-6366-358-8

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.

Publisher
TU Delft Open

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ISSN 2215-0897
E-ISSN 2215-0900
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EDITORIAL

Actuated and Performative Architecture: Emerging Forms of Human-Machine Interaction

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Human-Machine Interaction is expanding its reach beyond displays and objects to its next frontier: the built environment. This involves not only known visions of ubiquitous computing and adaptive environments but sensor-actuator networks, large-scale interfaces, and the Internet of Things. More than and including these systems, Actuated and Performative Architecture renders the built environment as a cyber-physical system aiming to address challenges of everyday life. Embedding computation, including robotics, into the physical fabric of buildings fosters a potentially more intimate relationship between the built environment and people. Mixing the physical and the digital redefines the borders between types of spaces, the affordances and meanings of environments, and the sense of presence. Unlike a conventional space that has a limited range of responses to dynamic, changing conditions, Actuated and Performative Architecture is intimately interconnected with users and local conditions.

This Spool [CpA] #3 issue poses and attempts to answer questions on the nature of this intimate human-machine bond, encouraging the discussion of its potentials also in terms of individual and social resilience. This issue of Spool, moreover, attempts to explore the design of bio-cyber-physical systems, which requires integration of natural, physical, and virtual architectures with digital systems and social organizations.
In designing interactions between the (augmented) human and cyber-physical environments, the collection and use of personal data, the management of a multi-layered design approach, and the ethics of such design activity require attention from experts in architectural design, interaction and UX design, civil and architectural engineering, mechanical and electrical engineering, computer and information science, sociology, psychology, education, ethics, philosophy, media arts, and science and technology studies.

The papers in this issue address some of the opportunities and challenges of Actuated and Performative Architecture by exploring concepts such as time-based and experience-based design paradigms, narratives as frameworks for enhancing human–machine social relations, immediate systems, augmented realities, and cyber-physically enhanced environments.

If Barbara's paper explores the directions taken by time-based design in order to identify new paradigms for contemporary spaces and their design, Nogueira et al. explore the digital reinterpretation of the architectural element window by means of image capture and future interactive projection aiming at expanding experience in indoor environments. Pavlovic et al. outline the importance of mapping user experiences for cyber-physically enhanced environments by discussing design practices that can support this activity, while Friedrich proposes immediate systems in architectural research and praxis. Architecture as a Bio-Cyber-physical System that is operating as part of a larger ecosystem aiming to address societal challenges with a broader understanding of sustainability in mind, is discussed by Pillan et al. In addition to these papers, the Dialogues on Architecture initiated in the first CpA issue are continued in this issue with a dialogue addressing the impact of computation and cyber-physical systems on architecture initiated by Nicolosi.

The attempt to answer questions related to the nature of the human-machine bond in architecture reveals some of the current achievements and even more future challenges. Cyber-physical architecture requires a multi-layered transdisciplinary approach that integrates humans and robots from design and production to operation of buildings.

DOI

https://doi.org/10.7480/spool.2020.3.5487

Temporal Dimensions in the Mediation between Machines, Humans and Spaces

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Abstract

This paper questions the need to introduce into the design methodologies and education, the temporal dimension in architectural design. It questions the need, to introduce methodologies and protocols to be able to define, design, and measure the variables involved in the actuation of spaces.

While in the history of design, spatial qualities have been central in the search for techniques and tools, temporal qualities have entered, with the advent of the digital revolution, as qualities capable of deforming, compressing, reconfiguring spaces and supporting new ways of living. The paper investigates various time-based approaches developed by scholars and designers from different disciplines, and the consequent proposals that have been developed so far.

The directions that time-based design has explored concern:

A Spaces: Digital technologies of algorithmic design/production have made spaces and components adaptable in order to guarantee kinetic or sensorial performance over time through integration with robotic actuators.
B Experience: Interactive technologies have made possible a continuous adaptability of spaces to human needs, through a continuous dialogue between humans and spaces via machines and computer systems that are able to formulate proposals for the customization of spaces.
C Behaviours: Communication technologies, which have changed people's behaviours and their interaction with spaces. The spaces have been imbued with distributed digital media hosting the temporalities of real life. The times of 'online' life have introduced new configurations of experiential space.
The paper explores the directions taken by design that can be considered time-based, to identify the cardinal points and the new paradigms for contemporary spaces.

Keywords

time-based design, adaptive spaces, liquid architecture, mobile media, robots

DOI

https://doi.org/10.7480/spool.2020.3.5488

Context

The research on the potential, that the digital revolution brought to architecture, began in the early nineties of the last century and the explorations, both in design, theory and construction, have been visionary and promising of spatial experiences. In contrast, there is a sense of inadequacy today related to the real estate market and the actual spaces where we live in. Built spaces static, insensitive to the new forms of living that the revolution of digital technologies introduced (Carpo, 2013).

During the extraordinary experimentations in the last 30 years, little has entered into the design of daily interior spaces, often leaving the task of meeting the need for flexibility, adaptation, mobility that the various forms of time involve only to the furnishings.

Today, we live in a multitemporal connection in a continuous and 'liquid' flow. When Zygmund Bauman (2007) introduced the concept of 'liquid modernity', he launched a deep reflection on the spatial-temporal morphology of places, on relationships and technologies, which is still ongoing.

From that moment, interior design could no longer be the same as before, because the fluidity of time would have reshaped the space as well. The spaces weren't the frame, the reference set, of human actions but instead became one of the possible media able to allow adaptability and flexibility, in a continuous flow of changes characterized by an endemic uncertainty.

The concept of liquid space was adopted by many scholars, architects and designers who adapted it to different contexts. Among these Marcos Novak, who claimed "*A liquid architecture is an architecture whose form is contingent on the interests of the beholder; it is an architecture that opens to welcome you and closes to defend you; it is an architecture without doors and hallways, where the next room is always where it needs to be and what it needs to be. It is an architecture that dances or pulsates, becomes tranquil or agitated. Liquid architecture makes liquid cities, cities that change at the shift of a value, where visitors with different backgrounds see different landmarks, where neighbourhoods vary with ideas held in common, and evolve as the ideas mature or dissolve.*"

Novak introduced the concept of 'liquid architecture' as an expression of the 'fourth dimension', incorporating the time alongside space among its primary elements. Novak's liquid architecture bended, rotated, and mutated in interaction with the person who inhabited it (Panahi, 2017).

Novak used the concept of liquidity to formulate what was called the *Transarchitecture*, where he began to explore the links between virtual spaces with materials, robotization, interactivity and communication through multimedia technologies and computer modelling.

A few years later, David Nelson Rose and the Future Arts Initiative expanded this definition to include the use of multi-sensory multimedia technologies. The reason was to increase brain function, as an act of the designer, to create a cohesive dialogue between the observer and the model. Liquidity was the cause, but also the effect, of a way of life that tried to thin the boundaries, mixing real life and digital presence; virtual proximity and physical distance, etc. but above all, that warped the spaces through media technologies and different forms of time.

Time-Based design

The definition of *time-based* design comes from a book, edited by Leupen, Heijine and van Zwol (2005), in which they began to investigate how the design of spaces should involve in time. Leupen acknowledged that *"the speed of modernization and the unpredictability inherent in the process makes it very difficult to establish reality for such a slow-moving medium as buildings".*

The term, borrowed from the videos, tried to describe the difficulty, for spatial designers, to establish a living relationship with the places, while the transformation was in progress.

The question had a genealogy in the thirties of the 20th Century, when Johannes van den Broek and Mart Stam began to experiment with forms of time-based architecture, in the attempt to make the most of the spaces, questioning the flexibility of the rooms during the hours of the day. The solutions were highly flexible and visionary, so much so that they became a reference, many decades later, when the masterplan and the project of the International Passenger Terminal (2002) in Yokohama was designed by FOA (Carpo, 2013).

While Leupen explored the temporal dimension of projects in lack of space, van Zwol dealt with the changed relationship between work and living, the potential mixtures and functional overlaps, considering the possibility of *"room for building with no specific ends".*

Their research was directed towards scenarios different from those of Novak, but they started from the same question: how could the temporal dimension be included in the genesis of architectural spaces?

It could be argued that the topic of time-based design was initially addressed by two sides: on the one hand, all those who explored the digital revolution as the possibility to modify spaces in time as did masters such as Eisenman, Lynn, Oosterhuis, and Novak, up to the temporal aspects of parametrically-driven architecture. On the other, all those who rooted the transformations within physical space, as a bottom-up need.
The design of behaviours becomes the basis for the sharing economy applied to spaces.

Both approaches started from an assessment of the inadequacy of existing spaces, and sought through a time-based approach to:

- transform monofunctionality, by introducing the need to design spaces versatile in form and time;
- introduce customization of spaces;
- rethink the performance of components (walls, floors, ceilings, etc.);
- introduce new rhythms in the spaces (difference between day and night; variation between days, months, years; connections between different time zones);
- change the size/form of each space according to the changing needs;
- change the sense of privacy;
- etc.

These paradigm shifts in architecture produced entire strands of research and experimentation.

Some were rooted in the utopian strands of radical architecture, that considered that the temporal dimension would transform buildings into living machines, building scale vehicles, adaptable to inhabitants and contexts in a dynamic relationship with people and places (i.e. Walking City by Archigram, Generator Project by Cedric Price and John Frazer).

Others tried to make humans, and their spaces, interact through computers and robots able to accommodate the time they spent in the spaces.

The dynamic transformation of analogic spaces, following temporal instances, concerns structures, volumes and sub-systems as for instance:

- Sliding elements as showcased in the Domestic Transformer by Gary Chang' in Hong Kong, in which walls and furnishings move to accommodate various functions. The unused space is crushed and compressed to make room for the parts in use.
- From folding walls and doors such as Origami, designed by Michael Janzen to the Embryologic House by Greg Lynn that envisages a system of 9 steel frames and 72 aluminium struts, to support 2048 digitally fabricated panels facilitating changes in every individual component that can be transmitted throughout every other element in the system.
- Rolling volumes as for Transformer, the temporary pavilion designed by OMA in Seoul, which is rotated on its sides in order to become a theatre, a fashion show location or an exhibition hall;
- Pneumatic structures that can be inflated and easily transported, but also made possible by the use of new materials such as ETFE's film used for Allianz Arena by Herzog & De Meuron.

The dynamic dimension in buildings has been already explored William Zuk and Roger H. Clark, in Kinetic Architecture (1970). In time kinetics have been intertwined with robotics, to support interaction with the inhabitants. *"This ability to act may imply physical such as geometrical, material, or sensorial transformation and reconfiguration. Robotic building components (such as doors, walls, floors, etc.) may support daily life activities offering solutions for dealing with rapid increase of population and urban densification as well as contemporary inefficient use (25%) of built space"* (Bier, 2014).

The underlying consideration, of part of these projects, is that a person cannot live multiple real spaces simultaneously, so those empty spaces could be compressed until they are used again. With a compliant mechanism system a prototype was built to meet the needs of the inhabitants by reconfiguring 24/7. (Hyperbody, Pop-up Apartment, 2013).

Such architecture uses time to design components through actuated spaces (i.e. Aegis Hyposurfaces by dECOI), interactive spaces (i.e. Muscle Projects by Hyperbody); adaptive spaces (i.e. ADA, Intelligent Spaces by SPECS-lab).

Another original and experimental, less studied yet valuable contribution, was the one proposed by Physiological Architecture by Philip Rahm, who tried to explore the interaction of time with circadian and environmental qualities to modify physiological effects on the body. In Split Time Café he defined an intimate relationship between space and frequency of light, transforming space into an authentic natural clock, that induced those present in a state of sleep or wakefulness, depending on the excitement and inhibition of the visitor's endocrine system.

The revolution introduced by the smart technologies has led to a further possible scenario in the time-based design, related to the mediation, between humans and spaces, that these devices perform in acceleration, compression, time overlap. They are able to accommodate temporal and functional instances in continuous mutation within real spaces (Hassanein, 2017).

The smart technologies reshape spaces, interiors, architecture, buildings, infrastructures according to the needs, desires, environmental conditions, as well as customize experience (Carpo, 2017).

Temporal dimensions in the mediation between machines, humans and space

The implications on the design of spaces involves a reversal of the traditional paradigms of living spaces. It pays a greater attention to phenomena, that are in part already underway, such as space-sharing, adaptive architecture, etc.

A time-based design affects: the function itself; the change in the sense of privacy; the dimensions; time and its rhythms; the boundaries between offline and *'online'* spaces in a globalized room, etc. (Floridi, 2009).

The impact of digital technologies on time-based design affects not only the production and construction of spaces and their performance, but also the possibility that the space *"can be controlled, actuated, and animated by digital means"* (Bier, 2010).

The inadequacy of the spaces we inhabit, is accentuated by the most significant technologies today, which are those involving:

- mobility that is distorting the perception of space and time;
- communication, which is redefining the interaction between chronemics and proxemics;
- sharing, which is encouraging the flexibility, transformability and availability of spaces.

Mobility and coordination media

The mobility of high-speed transports, in territories and cities, produces some paradox: the closest spatially is not necessarily the nearest in actuality. This warps and bends spatial configurations.

Mobility, which is not necessarily movement, produces perceptual deformations, which configure space possibilities still unexplored (Barbara, 2012). In the field of mobility, telecommunications often play an average role of coordination between individuals located in distant areas (Castells, 1989).

To plan meetings and travels is a continuous action that users carry out, in their urban movements. It is a form of tele-cocoon that allows people to stay in constant touch with theirs contacts, solving micro-coordination problems. Mobile telecommunication cannibalizes 'dead times' and allows the in-between time to be manned. Paradoxically, the time of the displacement - which is different from the time of the journey- typical of the commuter, becomes an ideal time-space to leave as a phenomenology and to connect elsewhere (Barbara, 2012).

Through this *'connected presence'*, all the places, where we pass through, are pervaded by a sense of intimacy, but also of separation from context and absence (Perry, 2001).

Communication media have become indispensable tools to create a sense of proximity in distance, or absence, helped by a simultaneous, and not delayed, interaction. The asynchronous media have a lower degree of involvement than those of sharing, of the experience embedded in the space of places (Castells, 2001).

Simultaneous communication, compared to the asynchronic one, has completely changed the ways of establishing communities or simply supporting them. It has allowed the sharing of the daily experiences, by the emigrants with their families and their countries of origin, of the visiting or exchange students, revealing the emotional nuances of relationships and not only the essential information.

These media have developed 'trans-national' families, whose multi-territorial lives are hosted in the country where they stay but live virtually in the continuous connection with the countries of origin. Their daily communications go beyond the boundaries of states and cultural limits, drastically reducing the sense of homesickness, of distance and the incidence of repatriation (Ling, 2008).

Communication and media for location and presence

The studies about chronemics -often combined with the proxemics ones- which analyse the relationships with time in its various manifestations, show that the temporal dimension is extremely personal, social and cultural and the failure of synchronicity, causes dystonia, misunderstandings, inconvenience (Zucchermaglio, 2013).

Cell phones and media have changed our relationship with physical space and with people. They change the forms of time by encouraging multi-temporality, simultaneity, etc. but above all, they manipulate the distances between things and people, they redefine the organization of time in the spaces, in the relationships and in the processes.

Depending on the involvement, the experience can be:

- immersive, if it involves only the user but excludes those present;
- pervasive, if it pushes those present in the background;
- conjunctive, if it involves all those present.

Even today, smart devices are mainly used:

- to protect and to build a cocoon, around yourself, to be able to exclude the context and to ensure a portable reality consistent with your emotional state, with your needs of the moment;
- to connect to a network of digital belongings, occupying temporarily the spaces, camping, setting up and using smart infrastructure able to rebuild anywhere our digital, productive, existential habitat;
- to share information and traces of our movements and lives, leaving a footprint, able to increase our visibility, orientation, but also, from the point of view of the network, to control our lives and those of others (Ling & Campbell, 2010).

Cocooning media are used to build protection against the intrusion of other people or circumstances. One of the primary functions of these technologies is to provide a personalized space, connected to a person and not to a physical place, to protect themselves from the involvement of places or the co-presence of others.

These technologies create a private territory within the boundaries of an urban space. Cocoons are micro-places, built by private, controlled infrastructure, which temporarily occupy public spaces for personal use.

Often it is related to audio media, because through headphones, people try to establish a personal boundary between own soundscape and the environment around them. These technologies are often used by commuters.

Camping media are used to settle in public spaces in order to build their own digital camp. As in some cafés, parks or co-working. Compared to the cocooning effect typical of commuters, who make a simple crossing from place to place, camping involves a staying, albeit temporary. Rather than *'killing time'* in passing places, camping *'spends time'* and *'schedules'* time in locations outside the home and office. A digital camping site usually is a highly social environment.

Footprint technologies are those that require to leave a trace. These media are portable objects used to make purchases, to navigate, to interface with urban environments. They include objects such as smart phones, tablets, loyalty cards, credit cards, digital wallet, membership cards (Ling, 2008).

Media for time-based spaces

The time-based space, configured by the new media, replaces or adds new possibilities, but above all, it intensifies the social presence. Mobile media have increased space-time flexibility in social interactions. Time and space have amplified the degrees of freedom requiring more flexibility, negotiation and reconstruction of roles and rules, both in the private and in the public areas.

Communication makes many activities shareable. When we are connected, we experience a co-presence because, in Heideggerian terms, the physical space in which we are, is juxtaposed with the phenomenological one.

It is a negotiation based on a subjective sense of space and time that, to ensure the process of interaction, requires maximum involvement and identification. The greater the inclusion and involvement, the better the interaction. The context, the space in which the body is physically present, becomes the background and not the stage of the action (Light, 2006).

However, media communication does not make us free from spaces, places and practices, but makes them available for other networkers.

This not only gives us extra space, but also makes us open, in real time, to monitor, control and, above all, to be available. The high responsiveness to stimuli, that communication media requires, is an important stress factor, because the mobile communication society always and everywhere makes a representation of the self, become seamless between private and public.

The flexibility of mobile communication can make some relationships more informal, but sharing times increases the feeling of control and acceleration. The time of mobile networks is unforeseen, volatile, chaotic, allowing intimate connections in every moment of social life and making us ubiquitous. Places and times of disconnection are more and more rare: everything you can do online is open 24/7 (Barbara, 2012).

So private space and public space blend into each other. Private space seems to become more open and global as the public becomes more intimate and local (Augé, 2009).

The space-time changes as a result of the adoption and use of wireless technologies, which had ensured *'space flows'* and *'timeless time'* based on a shift, in the social and economic order characterized by decentralized and flexible nodes, based on the sharing of interests, the need for information, as well as shared places (Castells, 2007).

The expansion of space and time allows different forms of social practices at work, in education and in relationships. Many of these practices are hybrid, merging together recognizable structures within liquid forms.

A revolution in spaces based on mobile workplace and virtual teams, which even during the recent lockdown, has guaranteed work, teaching, communication and adaptation of living and working spaces *"instead of thinking of places as areas with boundaries around, they can be imagined as moments articulated in a network of established social relations"* (Massey, 1994).

Conclusions

The liquidity that Bauman was writing about, adopted by Novak and the designers inspired by the digital revolution, is therefore mixed with the temporal revolution introduced by the media of communication in our daily lives. These are all the elements for starting a time-based design of the spaces in which we live.

It is therefore necessary, for the design disciplines, to adopt the new paradigms, make a synthesis of existing approaches and define criteria for the measurability of the results achieved.

Above all that they graft the know-how and the results of these experiments into the profession, even the most ordinary design, and into the spaces of our everyday life.

It is necessary to build analysis and representation tools (chronotopes) to understand the new relationships between real and virtual times and spaces; introduce in architecture and architectural education methodologies and software able to model through time spaces (Grasshopper, etc.). With regard to the production and construction of dynamic forms of space, robotics would continue to intervene in the customization of shapes, dimensions, possible interactions as it has already been doing for decades. Finally, for the design of the experience, an interactive dimension would be able to manage spaces in an adaptive way according to the demands of an increasingly diversified society.

These conclusions are not the destination, they are the result of exercises carried out in the laboratory of spatial design that I hold at the Politecnico di Milano. They are the beginning of a process of systematization of what exists, which has as a mandatory goal to train designers able to include the temporal qualities in future projects and spaces.

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Towards a Digital Window

Interpenetrations, Challenges and Potential of Augmented Reality in Architecture

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Abstract

The present work has as its starting point and inspiration in the observation of the habit of staying at the window, mostly performed by older adults, in Lisbon, Portugal. Beginning from this habit, we seek to substantiate, develop, and record speculative and artistic visual experiments that propose a digital reinterpretation of the architectural element window. Such experiments deal with the intertwining of diverse concepts as hybrid architecture, material, digital, virtual, and augmented reality (AR). The experiment, entitled *Projected Windows*, consists of three different installations where we visually simulate, through image capture and projection, various possibilities of visual reinterpretations of the window in the context of the interior of dwellings. The experiment is based on digital imaging. The first two parts of the experiment are non-interactive AR experience, while the third one is a visual interactive AR experience. The project is in the initial phases of development, indicating the potential of correlating concepts, which allow to fundament experiences and visual narratives that can instigate greater advances in terms of interactivity as the work progresses.

Keywords

hybrid architecture, materiality, prosthesis, digital, augmented reality

DOI

https://doi.org/10.7480/spool.2020.3.5492

Introduction

Adopting the window's theme is a way of discussing architecture based on the analysis of its parts, and through this, aiming, to some degree, to make generalizations about the whole. In this same ambition, we pay attention to the domestic habit of staying at the window, or "*janelar*", observing, and eventually interacting with the landscape and its agents. "*Janelar*" was how the Portuguese writer Eça de Queirós (1845-1900) referred to the act of staying at the window in his novel *O Primo Basílio* (2013), originally published in 1878. This habit, still frequently observed in the city of Lisbon/Portugal (among others), also tells us about dwelling and issues inherent to population ageing, addressed here as general subsidies for us to investigate, speculate, and explore visual interpretations of the window.

Gonçalo Furtado & Inês Moreira (2001) justify the house as the ideal space for investigating architecture in view of the transformations arising from information technology, both for being it a predominant theme in architectural production and because it is the environment where people spend most of their time. In this regard, Patrícia Matias (2016) details the issue, stating that it is precisely the most aged portion of the population that spends the most time in the domestic interior. Perhaps, this fact justifies the occurrence of the habit of staying at the window, as recorded in Figure 1.

FIGURE 1 Lady at the window, Alcântara, Lisbon (author, 2019)

This work is still justified in the perception that architecture and architectural practice have great potential for being explored in association with the digital field, in areas as augmented reality (AR), for example. The project opens up to behaviour analysis and the interface in interactive and intelligent environments (Krueger, 2006). Therefore, it becomes possible to glimpse, as Neil Spiller (2006) suggests, the house as an interface, and to conjecture about a range of design possibilities that can come about from this prism. Antoine Picon (2003, p. 109) points out that cinema has sought to illustrate the possibilities of this approach: "the changes in the perception of ordinary space that should be brought by the development of sophisticated interfaces between the ordinary space and the digital one."

In this context, our general hypothesis is that the visual simulation of digital windows, as an augmented reality (AR) experience, is capable of providing new possibilities for domestic visual interaction. Thus, the article's main goals are to substantiate, develop, and record small speculative experiments that propose a digital reinterpretation of the architectural element window.

Such reinterpretations aspire to simulate and present possibilities of visual interaction with space, in a conceptual way. These experiments are carried out with the intention of instigating future developments, which may constitute alternatives that contribute to the human-machine interaction in the daily domestic experience. These preliminary contributions seek to be beneficial to all, in general; but, especially in the case of older adults, it could, in the future, enable easy and uncomplicated operational interfaces, which would allow greater digital inclusion, for example.

The methodology is structured in two main stages. The first stage consists of a brief literature review (A), where concepts developed and explored previously by Anne Friedberg (2006), Antoine Picon (2003), Beatriz Colomina (1994), Georges Teyssot (2005), Mark Wigley (1991), and Ronald Azuma (1997) are highlighted. In the second stage, we develop and present the visual experiment (B) *Projected Windows*, divided into three parts: *window.jpg*; *window.gif*; and *window.avi*.

Significant experimental works, with a similar theme, have already been carried out, with their own goals and methods, which show great references for possible future evolutions of the work developed herein. In this sense, it is worth mentioning, Mark van Doorn et al. (2008), Peter Dalsgaard & Kim Halskov (2009), and Xiao-Nan Liu & Min-Zhi Shao (2020), related to the public spaces (a sort of Media Façade, which is a subdivision of urban computing). In Mark van Doorn et al. (2008), we have a narrative (retail context) structure translated into a programming script that generates an interactive display system. Peter Dalsgaard & Kim Halskov (2009) show us the development of an interactive mechanism that allows only the directly observed part of the window shop to become transparent, while the rest remains translucent. Recently, Xiao-Nan Liu & Min-Zhi Shao (2020) created a scene with four different interaction devices and assessed which one arouses the most public attention and interaction. And as a reference for a future evaluation phase, we cite the work of Ferreira et al. (2016), which presents methods and criteria for evaluating the bodily reaction in different simulations in the domestic space.

With the relationship of these apparently diverse subjects, we hope to present a coherent narrative capable of tracing a logical path that supports a particular sort of visual-spatial human-machine interaction. Even though we are aware of the brevity of this text, we believe that its approach, and the way it is structured, can open paths for future phases of work, which can be developed with greater depth.

Towards a conceptual window (a)

In Latin, *Fenestra* points to an opening that promotes lighting and ventilation (Friedberg, 2006, p. 103), while in Portuguese the consolidated word is *Janela* (from the vulgar Latin *Januella*), being the diminutive of the term *Janua*, which designates door (Wikcionário, 2017). In English, the word “window” (originating in the Old Norse), etymologically, leads to the junction of “wind” and “eye”, reinforcing the meaning of an opening that allows ventilation of the eyes (Friedberg, 2006, p. 103).

In the book *The Virtual Window: From Alberti to Microsoft*, Anne Friedberg (2006, p. 103) gives us an overview of the first records and early evolutions of the window: “The window began as an opening slit for light and ventilation (a *clostra*) and developed in Roman times as glazing was introduced. Representations of windows appear in wall paintings in Egypt and in reliefs from Assyria.”

The evolution of the window occurs due to the most varied reasons, from the improvement of glass production techniques to behavioural changes of social and economic nature. Since before Leon Battista Alberti (1404-1472) compared painting to an open window (in 1435), many analogies have been made about the window; however, Friedberg (2006) does not believe that Alberti refers properly to the capture of the image of what was seen through the window by painting, but rather to the framing power of the window. The author is guided by metaphors that are attributed to the window as the guiding thread of her narrative;

in this universe, it highlights the window as a possible visual metaphor for photography, cinema, television, computer screen, etc. Each with its particularities and limits.

For Friedberg (2006) the visual metaphor resides in the immateriality of language, even when it refers to the material world. In this sense, the virtual window is the element capable of providing a simulacrum understood by virtuality:

> The screens of cinema, television, and computers open "virtual windows" that ventilate the static materialities and temporalities of their viewers. A "windowed" multiplicity of perspectives implies new laws of "presence" – not only here and there, but also *then* and *now* – a multiple view – sometimes enhanced, sometimes diminished – out the window. (Friedberg, 2006, pp. 4-5)

To avoid terminological confusion, we must differentiate the terms "digital" and "virtual" in the context of this work. By "digital" we mean the information processed and based on the binary logic, proper to the computer. The concept of virtuality, on the other hand, precedes the development of computers and is linked to the power of representation, which refers to the appearance of something real, potentially real, or believable – a simulacrum –, as do painting, photography, cinema, television and even the computer screen (Friedberg, 2006).

As much as this concept about the virtual is basal for this work, it is also important to bear in mind the digital bias of our approach, where all the information worked in the experimental stage, has its information mediated by digital, since the image capture, post-production, and exhibition. Such visual speculations would not be possible, in the same way, without the participation of computing (although we recognize a very restricted and practically embryonic use of it here). Therefore, when we talk about *Projected Windows*, we are also referring to a virtual window (as proposed by Friedberg, 2006), but conceived and mediated by a digital apparatus (*digital window*).

To understand that the screen (of cinema, television, computer, smartphone, etc.) can be considered an architectural window (Friedberg, 2006) is a key point in our discussion. This metaphor (as presented in *Things to come*, 1936, among others movies, for example) allows us to discuss the issue of materiality since the materiality of the traditional window is different from the materiality of the virtual and digital window.

In a more hurried glance, we could imagine that *Projected Windows* are marked by immateriality; however, as Antoine Picon (2003) maintains, materiality is not an exclusive result of physical matter. Under this perspective, our relations with the physical elements are changed (and mediated) by digital elements, in a hybrid environment, where our experiences are affected, thus generating a new type of materiality:

> The notion of enhanced or increased reality does convey the idea of a different materiality made possible by the hybridization of the physical and the digital. This hybridization is not yet fully there, but some features of the displacement of materiality can be already observed. (Picon, 2003, p. 109)

In a way comparable to that exposed by Picon (2003), and considering the underlying particularities of each scope, Friedberg (2006, p. 11) states that "Virtual images have a materiality and a reality but of a different kind, a second-order materiality, minimally immaterial."

From the blurring between material and immaterial, different types of materiality emerge, as stated by Picon (2003) and Friedberg (2006). Extending the question a little further, Georges Teyssot (2005), in his article *Hybrid Architecture: An environment for the prosthetic body*, points to this blurring of limits previously considered to be clear, where dualities such as interior/exterior, public/private, organ/function, etc., become extremely slippery and blurred in contemporary times. Such blurring is also perceived when we focus on real/virtual duality, once augmented reality (AR), virtual reality (VR), and mixed reality (MR) are rapidly expanding concepts, for example.

Le Corbusier, quoted by Beatriz Colomina (1994, p. 332), states that it was first the invention of the locomotive that was responsible for the "interpenetration" of the countryside into the city, and the city into the countryside. Afterward, the architect highlight that new devices deepened this flow, like the telegraph, the telephone, airplanes and finally, television (then a novelty). We understand that the approach pointed out by Le Corbusier, and called as interpenetration, is related to the blurring verified by Teyssot (2005) and Picon (2003), where everyone is deeply affected by the advances in information technology. It is important to establish these relationships, as they impact the emergence or reframing of concepts such as hybrid architecture, AR, and prosthesis.

Faced with the most varied challenges imposed by contemporary society and the unfolding of the digital age, Teyssot (2005) defends the concept of hybrid architecture as a coherent alternative, where digital technologies can allow a new (hybrid) manner of relating space and body, the body and the machine, the body and its materiality.

A hybrid architecture becomes important, not only for being it the sum of different parts, but mainly because it is the potential result of the intertwining (interpenetrations) of different parts (and often antagonistic, such as body/machine, to speak in Teyssot's terms). We understand that this is precisely the type of argument that justifies this work, as stated by Teyssot:

> The urgent task architecture ought to assume, therefore, is that of defining and imagining an environment not just for "natural" bodies, but for bodies projected outside themselves, absent and ecstatic, by means of their technologically extended senses. Far from assimilating the tool with the body according to the mechanistic tradition of Cartesian dualism, we must conceive tools and instruments like a second sort of body, incorporated into and extending our corporal powers. (Teyssot, 2005, p. 81)

When Teyssot (2005) states that we must design tools and instruments that incorporate and expand the body's capabilities, he clearly refers to prostheses. In a very brief form, we can say that the concept of prosthesis is naturally architectural, evidenced by the etymology of the word, since "Prosthesis" derives from "Thesis", which, in its Greek origin (*thesis*), had its meaning related to the idea of structure, proposition, position, and something that stands firm against adversity (Wigley, 1991).

Through a more general approach, Le Corbusier understood the house as a prosthesis responsible for shelter and protection against the elements (a complement to the skin), since the windows were comparable to the eyes that, in certain contexts, have gained so much importance in the architect's work, to the point of being

affirmed by Colomina (1994, p. 7): "The house is a device to see the world, a mechanism of viewing."; and, in the words of the architect himself: "All my architecture is conditional upon the windows." (Le Corbusier, as cited in Reichlin, 1988, p. 61). In turn, Marshall McLuhan (1964) points to computer memory as a device (prosthesis) for the expansion and enhancement of human memory.
Teyssot (2005) points out that, according to Marshall McLuhan, like the media, architecture is also an extension of the human body, that is, a prosthesis. Such an argument is still defended by Mark Wigley (1991): "Of course, the mechanical eyes, ears, and skin provided by modern systems of construction/representation have given way to technologies that relocate architecture within an electronic space […]". Certainly, our speculative experiment *Projected Windows* meets this approach, aiming to point a possible repositioning for architecture (based on inhabiting) within a hybrid space, where digital elements can enhance the domestic experience.

According to Ronald Azuma (1997), while virtual reality (VR) is considered a fully immersive experience, the augmented reality (AR) is a variation of it, where we can see the real world, but merged with virtual fragments. Thus, what our visual experiments are offering are some sort of AR experiences which, conceptually, can also be understood as a hybrid space. There is still the concept of mixed reality (MR), which is not explored in this work (as well as VR). MR can be considered a variation of AR, where exists a deeper spatial real-time interaction between digital and physical contents (Milgram & Kishino, 1994).
The concepts and references listed here, even if presented in a summarised form, seek to establish an investigative line capable of supporting and justifying the proposed experiments, understanding them as AR experiences into domestic space.

Projected windows (b)

The experimental proposal has a visual speculative character, intending to provoke reflections about the human-machine interaction through architectonic spatiality, mediated by the digital reinterpretation of the window. For its realisation, we use digital image capture devices, image post-production software, and a projection device (SVGA projector).

Even though our starting point is the habit of staying at the window (commonly practiced by the elderly portion of the population, as said before), in our experiments we do not use this group at this moment of development, once we are in the preliminary stages. However, in the future steps this is an important aspect to be faced. And it is worth noting, as of now, that our experiments, even in initial way they may be, are premised on providing easily accessible AR experiences, without the need to use head-mounted displays (HMDs), AR glasses, or similar, that are often uncomfortable, especially for older adults.

The three *Projected Windows* are based on elements from digital culture, namely: the image (in .jpg format); the animated image (in .gif format); and the video (in .avi format). We try to take advantage of the specific features that each digital format has in order to create unique AR installations.

In support of this article, all experiences are presented as figures (inanimate images), though, on the *digital window* website (Nogueira, 2020) it is possible to have a more diversified and realistic view of the experiments, as well as to better understand their insertion in the domestic interior.
Finally, it is worth mentioning that all the images were made based on an existing window, in a housing context, in the city of Lisbon, in 2020. And starting from this real window, its replication and digital manipulation provides us with possibilities that try to replace and metaphorically rethink the window in the house.

FIGURE 2 Scheme and simulation based on the work of Renè Magritte and the local landscape (author, 2020)

window.jpg

The first projected window, the installation *window.jpg*, is based on a static image, in .jpg format (or .jpeg, *Joint Photographic Experts Group*), obtained through the use of a digital camera that (like any digital camera) "contains sensors capable of capture the light emitted or reflected from the objects, and decomposes it into its fundamental components: red (R), green (G) and blue (B)" (Contribuidores da Wikipédia, 2020), that is, the camera transforms into digital binary information, the variations of light and colour found in a given temporality and spatiality.

In this simulation, we take as base a large set of paintings by René Magritte (1898-1967), where the artist turns to the window theme. The artist challenges the framing of the window and seeks to expose permanent friction between the exterior and the interior, merging them, a sort of "augmented virtuality". These premises, in general, justify taking part in this artist's work as a compositional reference.
In *window.jpg* (see Figure 2) we try to continue the external landscape, visually "breaking" the wall and evidencing (in a simulated way) a new possibility of framing the window, questioning its limits and changing its perception, with a non-interactive AR experience.

The digital file, projected on the wall, pursues to break the continuity of the surface, shuffling the outside and the inside, in a similar way with Magritte's paintings. Image capture emulates an appropriate framework, capable of maintaining an articulate perspective. Geometric coherence and scale were taken into account during the projection. Nevertheless, the difficulty of calibrating the projection brightness, due to the abundant source of natural light offered by the window, remains a challenge.

It should be noted that, in *window.jpg*, the proposed visual narrative can be viewed/assembled at any time. However, its narrative coherence restricts it to the daytime period (as a visualization that intends to merge the interior and the exterior, to a certain degree of continuity), just when its image projection quality (light on masonry and white painted wood) is more critical. At night the projection reaches its best aspect, but the external context is transformed and prevents the idea of visual continuity.

window.gif

In this second experiment, we explored the .gif (*Graphics Interchange Format*) format, which allows us, in the same image file (bitmap), to explore up to 8 bits per pixel (Contribuidores da Wikipédia, 2020). In this way, it is as if an image could be transformed continuously through changes in its own colour palette. This type of file can behave similarly to an animation, with the succession of different layers of colours, within a certain time interval. However, its parameters are more limited (and lighter) than those aimed at animations in files of video.

FIGURE 3 Scheme and the temporal dimension, in the time of a .gif (author, 2020)

In this sense, Friedberg (2006) points out the chemical process that managed to fix the image of the camera obscura, as the one responsible for introducing time as a dimensional element in visual culture. According to the author, while one photography records a fraction of time, a sequence of photographs can simulate the time passing.

In this simulation, the installation *window.gif* (see Figure 3), we seek to take advantage of the potential provided by the .gif format, to represent a sequence of images, representing a passage of time. Therefore, we capture the same frame 96 times, over the 16 hours of sunshine of the same day in late spring (shots were taken every 10 minutes), to record the transformation of external light, reflected in the colour changes on the images.

Subsequently, these images were grouped next to a window frame and converted into a .gif file, that is, they were transformed into a single image, where the 16 hours were compressed into a .gif lasting 20 seconds that are repeated continuously (the result in .gif can be seen on the project website , but as a way to visualise what is proposed and discussed, we set up the panel contained in Figure 3).

This non-interactive AR experience also proposes a temporal and spatial complement, as it projects a daytime view originally not available on an inner wall without a window, at night. These simple manipulations can show how elementary experiments (like the present one) have the power to alter, to some degree, the space-time perception and the internal environment ambiance.

window.avi

The third and last projected window, *window.avi* installation (see Figure 4), we intend to reproduce the existing window in real-time, and for that purpose, two cameras are required. The first one behaves like an eye prosthesis (together with the projector, via wireless connection), left in an active mode, the device simultaneously reproduces what it "sees". The second digital camera takes on the prosthetic function of memory, as it is in charge of registering the experiment, where we can even observe both the existing and the reproduced window, simultaneously (such visual speculation finds precedents, to some extent, in video installations by Nam June Paik, Bruce Nauman, among others mentioned by Friedberg, 2006).

In this approach, at the moment of simultaneity, the temporal relationship breaks with the cinematic logic of the montage; though, it generates other unusual spatial possibilities, such as creating a sort of perpendicular reflex "mirror", or the possibility of seeing the body interact with the projected image itself, and, in some positions, with its shadow (as can be seen in our short film *window.avi*, also available on the aforementioned website).

In this visual interaction, the challenge was to reproduce the window to duplicate its visuality, which starts from the indoors towards the outdoors; however, potentially, other "windows" could be developed, with other interiors, or other exteriors, or still, with other intentions and goals.

This visual interactive AR experience, more emphatically than the previous ones, illustrates part of the possibilities of interaction that can be established inside the dwelling. For Friedberg (2006, p. 150) "The screen functions as an architectonic element, opening the materiality of built space to virtual apertures in an 'architecture of spectatorship'".

This sort of interaction can reach greater complexity than visuality (explored here), and potentially involve other dimensions of information that can be read as digital information (sounds, gestures, etc.). In this context, an interface system capable of adequately relating to the domestic interior and allowing interactions between the body, space, and cyberspace can be envisioned (and projected).

FIGURE 4 Scheme and the digital allowing new domestic visual experiences (author, 2020)

Conclusions

In this article we, briefly, articulate diverse subjects, proposing a conceptual background for a digital reinterpretation of the architectural element window. Assuming a specific domestic habit of the most aged part of the population as inspiration to try explore borders between real and virtual, having as object the window, as a historical, metaphorical, physical and digital agent. The goals of supporting, developing, and recording speculative visual experiments that pursue to propose a digital reinterpretation of the window were achieved with the development of augmented reality (AR) installations. The methodology applied proved to be adequate, and in the continuity of the research, it will explore other frameworks, in order to go further through programming toward achieving a more interactive approach, specially creating and testing more inclusive solutions, especially for older adults. Nevertheless, works with this scope, more conceptual, artistic and experimental, are important to help us visualize and conjecture about new creative possibilities, identify critical points, and develop a thematic affinity.

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Ambient UX for Cyber-physical Spaces

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Abstract

Ambient User Experience (Ambient UX) is a conceptual framework providing a strategy for design processes that target cyber-physical spaces. Such design processes interface Wireless Sensor-Actuator Networks (WSAN), Artificial Intelligence (AI), and physically built environments. For managing the complexity of such design processes and ensuring the development of a design facilitating users' satisfaction, design approaches focused on experience and user activities linked to bio-cyber-physical feedback loops are needed. This paper points out how Ambient UX supports decision-making in a design process. It outlines the importance of mapping user experiences for cyber-physically enhanced environments by discussing design practices that can support this activity and presenting a representative case study implemented with students at TU Delft.

Keywords

Ambient UX, user journey, Wireless Sensor-Actuator Networks, Artificial Intelligence, Cyber-physical Systems and Spaces, design methods

DOI

https://doi.org/10.7480/spool.2020.3.5490

Introduction

Current digital design and media architecture practice demonstrate the rich potential of interactive media for the built environment; however, the meaningful integration of interactive media in architecture remains challenging. Dalton et al. (2016) discuss Ubiquitous Computing (UC) embedded into the built environment as a way of creating environments that meet the dynamic challenges of future habitation. The integration of UC in the built environment requires envisioning the built environment as a Cyber-physical System (CPS) consisting of mutually informing computational and physical mechanisms that communicate and operate cooperatively (inter al. Rajkumar et al. 2010) through a Wireless Sensor and Actuator Network (WSAN) (inter al. Yang, 2014). These environments are sensitive and responsive to people; they integrate a variety of devices operating in concert to support human activities in an unobtrusive way, using intelligence that is hidden in the network connecting them. Such cyber-physically enhanced environments (Bier et al., 2018), build up on systems and approaches known as Ambient Intelligence (AmI) (Zelkha et al., 1998) and Interactive or Digitally-Driven Architecture, (inter al. Fox and Kemp, 2009; Bier and Knight, 2010; Bier et al. 2017). They involve Artificial Intelligence (AI) (inter al. Ferber & Weiss, 1999) and rely on the Internet of Things (IoT) (inter al. Atzori, Iera & Morabito, 2010), and UC (inter al. Lyytinen & Yoo, 2002).

Various interactive systems enhance today experiences and activities as, for instance, Google Home , a voice-activated virtual helper that is connected to the Internet and performs basic tasks like searching the web for travel options, or identifying the schedule of the day. It can be trained to recognize voices and customize its responses. Amazon Go makes shopping more efficient in physical stores, while HealWell improves moods of users, such as hospital patients, and dynamically adapts according to ongoing activities. The Concept-I vehicle automates driving activities and anticipates users' needs. Such systems respond to the contemporary shift from material-based activities to information-based actions; they impact cognitive walk-paths and mind-body ergonomic principles. In this context, architecture becomes cyber-physical in nature and is increasingly aware of users and their changing needs.

Designing for Experiences

The design of systems that are cyber-physical in nature requires the understanding of the complex tangle of physical and mental processes associated to human activities, including motivations, cognitive and emotional ways of involvement, etc. Designing for users' experiences (UX), implies to approach the design in a holistic manner, considering the diverse levels of influence the design solution might have on individual and societal level, together with their impacts on individual and collective lifestyles and freedom of action. Designing for interactive and therefore cyber-physically enhanced spaces imposes rethinking and reshaping design approaches from practices currently employed in the field, towards more hybrid approaches that lie at the intersection of diverse fields. This paper discusses a framework for a holistic UX approach, which appears to be missing in current UX practices as a structured design process. The framework is based on the merging of Architecture knowledge with those of UX Design and Interaction Design, and on the adaptation of conceptual models and of pragmatic tools typical of these disciplines for the project of such systems.

Ambient UX

The Ambient User Experience (Ambient UX) approach provides a strategy for structured design processes that target the integration of Cyber-physical Systems (CPSs) in architecture (Pavlovic, 2020). The Ambient UX framework consists of Design Domains (DD) defining what is to be designed and User Values (UV), identifying why what is to be designed is designed. Ambient UX design in architecture implies consideration of various intersecting and sometimes overlapping DDs such as interaction design (focused on services, journeys of users, social organizations, interfaces and interactions between people and facilities) and architectural design (focused on the built environment) with the aim to achieve a continuous and cohesive user experience across devices, time, and space (Pavlovic, 2020). In projects focused on user experience, the overall design integrates the design of interactions – including macro and micro scale analysis and optimization of the activities of the users - with the design of physical environments.

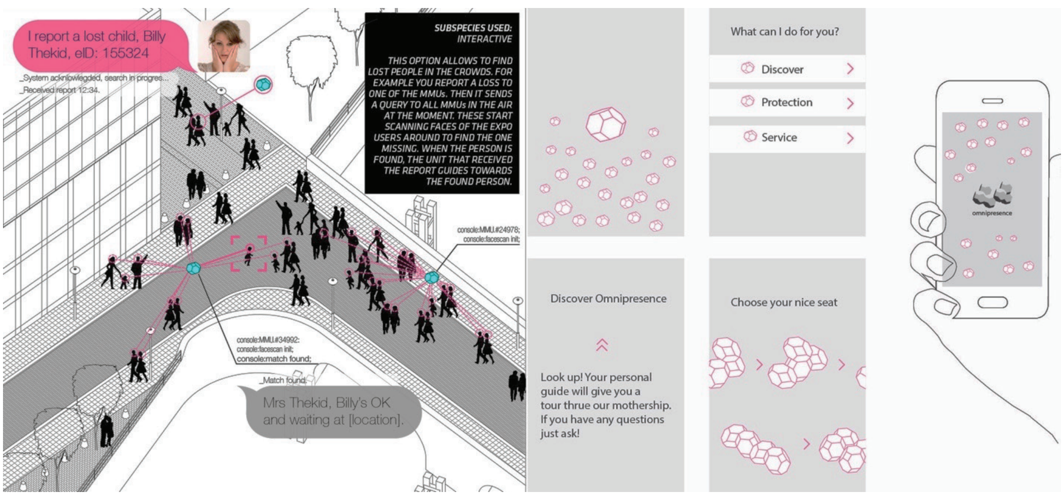

FIGURE 1 Mapping potential activities and interactions.

Mapping Experiences

In order to manage the complexity of CPS solutions for the built environment and to orient design towards the optimal satisfaction of users, the project process includes both the physical facilities to be designed and the description of the non-tangible and non-material sources of value related to the CPSs to be designed, by mapping techniques focused on experience and user activities (inter al. Dalton et al., 2016; Kalbach, 2016) are explored through case scenarios.

The material features of the designed solutions imply natural constraints i.e. physical constraints that limit what can be done to the affordances, which convey possible uses, actions, and functions (Norman, 2013); the analysis of the interaction between users and solutions leads to the identification of a palette of constraints and enablers. These constraining/enabling points of activities together with the understanding of their impact on activities are starting points for designing user experiences. In a design approach fully focused on experience, the jobs and journeys of users in the context are fully investigated, together with the implicit and explicit motivations and meanings, while their envisioning make possible the political discussion on the convenience and desirability of the possibilities of actions by the subjects involved in the implementation and management of the CPS.

While the project and implementation of such systems requires the contribution of different disciplines – from Computer Sciences to Architecture, from Service Design to Robotics and more – the framework aims at an effective and efficient management of the project process.

The framework identifies three networks of interactions describing the independent dimensions experienced by the users in a CPS, which correspond to three diverse types of architectures to be implemented and made coherent in the project: spatial (interaction related to the physical environment and facilities), information (interaction related to manifest and hidden information flows), and relational (interaction related to human/social relations and forms of social organization). The recognition of these different axes along which the project develops, but which require the capacity of holistic integration is the core of Ambient UX, and the conceptual reference for managing the complexity of CPSs.

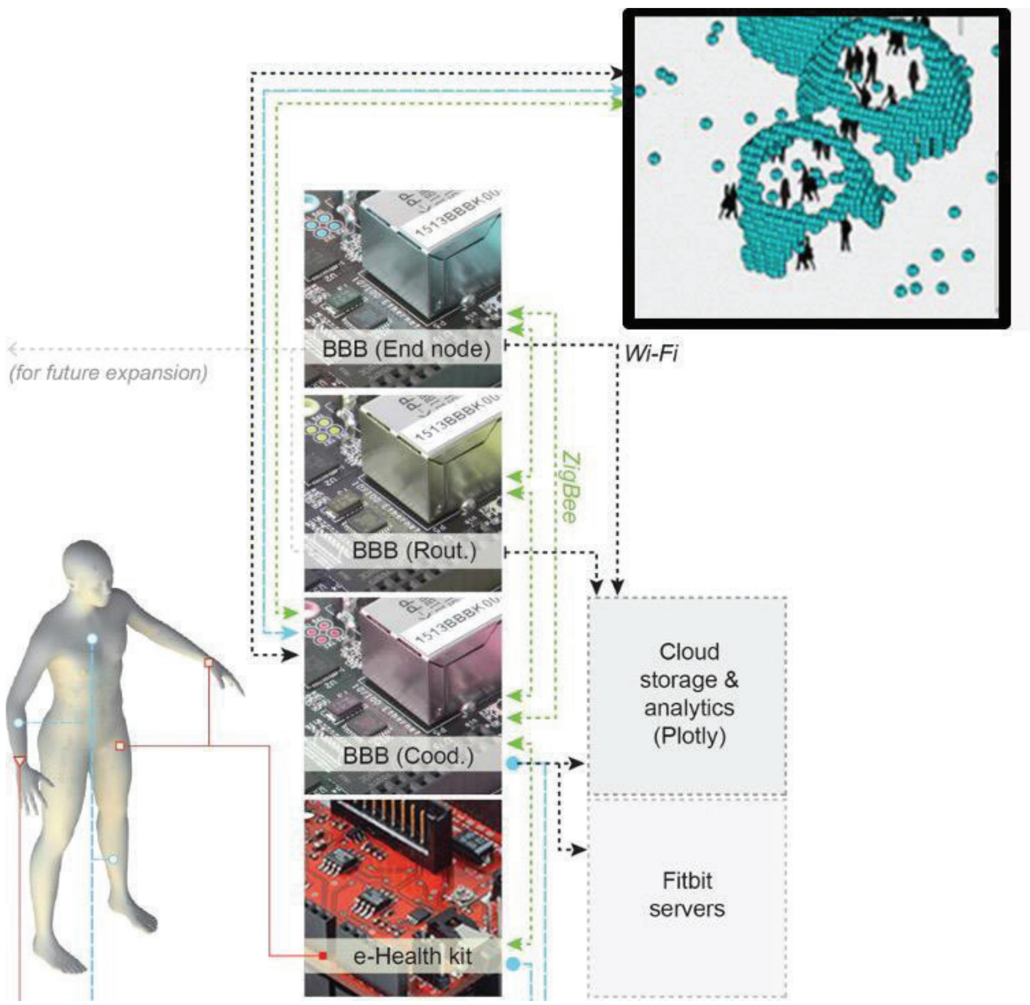

FIGURE 2 Bio-cyber-physical feedback loop established via AI supported WSAN is detecting human needs and is actuating the swarm of drones accordingly.

Such spatial, informational, and relational aspects were considered in the Omnipresence project developed at TU Delft, wherein swarms of drones were introduced as means to guide visitors through a fictional world exhibit in Rotterdam (Fig. 1) as well as means to create temporary pavilions (Fig. 2 and 3) by anticipating potential activities and developing possible scenarios. The swarm of drones was then designed to respond to such scenarios by integrating cyber-physical features that would allow the swarm to operate semi-autonomously.

Cyber-physically Enhanced Spaces

Designing interactive spaces where the built environment is enhanced cyber-physically implies thinking about architectural design in a different manner. Rather than designing for a range of functionalities the focus is on designing for human activities. This entails anticipating possible activities (the what, how and why for them) and designing dynamic responses accordingly. In this context, the development of multiple scenarios supports decision-making. The mapping of activities that might take place helps identifying most desirable scenarios the design should enable, as well as the possible problematic non-desirable scenarios the design should avoid.

Such cyber-physically enhanced spaces imply designing on the interface between Artificial Intelligence (AI), Wireless Sensor-Actuator Networks (WSAN) and architecture (Bier et al. 2018). The design calls upon definitions of AI that support computational as well as physical operation of the system.

FIGURE 3 Aggregation of drones for building temporary pavilions as adaptive systems.

AI for CPSs

Even though AI has been developed for decades now (McCorduck et al., 1977), only in the recent years it has started to emerge as a significant new technology promising to have a large impact in diverse application fields in the industry, where the questions is not anymore if it will be implemented across industries but rather how it should be adopted efficiently (Brown, 2019; Ghosh et al., 2019). AI is embodied in many diverse forms, with capabilities that mimic cognitive functions such as learning and problem solving (Russell & Norvig, 2016). The design of the embodiment of AI has been explored in user experience (UX) and user interaction (UI) design, where the hardware of the system is tackled through product and spatial design, while the system values and performances are addressed through service and speculative design. In this context, various forms of AI may be combined. For instance, Swarm Intelligence (SI) targeted in the Omnipresence project for the autonomous flying of drones may improve in time through Machine Learning (ML), as a form of AI that improves automatically through experience and learning in time. Such AI forms are the backbone for user interaction flows within AmI and adaptive systems in architecture (Fig. 3). They rely on WSAN embedded into the physical environment.

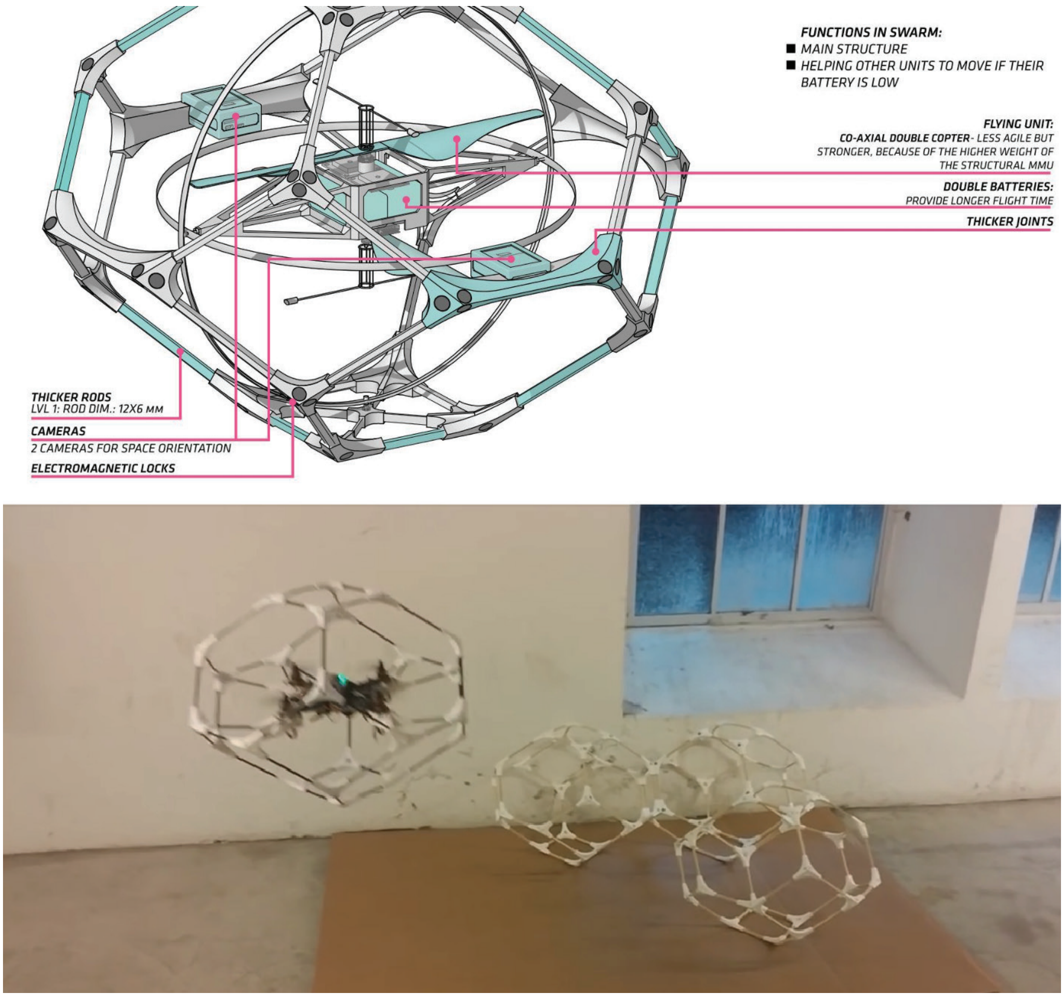

FIGURE 4 Drones design and testing of drones' aggregation of the Omnipresence project developed at TU Delft

WSAN

WSAN are spatially dispersed and wirelessly networked sensors (for monitoring the physical environment) and actuators (such as servo motors for implementing various tasks) controlled by computer-based algorithms, which in this case are AI algorithms. The WSAN is embedded into the built environment, which facilitates tangible interactions and activity flows. In the Omnipresence project the WSAN is distributed in the drones (Fig. 2 and 3) and together with AI is detecting human needs for guidance or shelter and is actuating the swarm of drones accordingly. When designing such WSANs, the main challenge is to anticipate human activities, and plan for the responses of the interactive system.

An implicit Ambient UX approach for the design of cyber-physically enhanced built environments was employed in the development of the reconfigurable pavilions (Fig. 1-3). The temporary structures were emerging as aggregations of drones (Fig. 3) and demonstrated the potential of this technology for architectural purposes while responding to needs of dynamic reconfiguration. The drones act as a coordinated swarm communicating with each other and aware of the environment thus avoiding collisions and forming domes that shelter temporarily visitors of a fictive world expo in Rotterdam (Fig. 3).

After various activities were considered and several configurations were simulated, the aggregation of four drones was tested by building 1:1 prototypes (Fig. 4). The coordinated flight and aggregation behaviour was intended to rely on swarm intelligence (SI), which is the collective behaviour of (natural or) artificial self-organized systems and is a form of AI. SI systems consist typically of a population of simple agents, in this case drones, interacting with one another and with their environment. The agents interact locally following simple rules such as separation, alignment, and cohesion (Corne et al., 2012) leading to the emergence of intelligent global behaviour, which in this case manifests itself as domes. Specific flocking rules allow them to aggregate into domes by following structural requirements: As soon as a first row is in place, the second row and the next ones follow until the aggregation is complete. The SI relies on WSAN involving spatially dispersed and dedicated sensors for monitoring the physical conditions of the environment and the people. The goal is that on request or self-initiated drone swarms create temporary shelters protecting people from sun or rain. This is implemented by SI allowing the drones to flock, on top of which ML is introduced to facilitate learning in time from the environment and users. While all these principles were considered, simulation, prototyping and testing has remained at proof of concept level.

Conclusion

The presented paper highlights the challenges and opportunities of cyber-physically enhanced architecture. It discusses the design of such architecture involving inter al. consideration of DD, UX and UI, AI, and WSAN requirements, which not only involve anticipation (by mapping activities) but also learning. If SI works with data collected within a short period of time, ML employs data collected from users and environment over a longer period of time in order to learn to respond to users' needs by establishing a bio-cyber-physical feedback. Such feedback involves AI ranging from basic intelligence level operating with if-then-else constructs to high levels of 'emotional intelligence', supported by learning processes that are tailoring actuation according to users' needs. While such feedback links the human with the cyber-physical space, the question of how to design an embodiment of intelligence that is human-like or if it should be human-like in the first place requires further definition.
While the case studies presented in the paper illustrate the potentials and the challenges of CPSs, Ambient UX and the framework proposed in the paper offer a conceptual reference for the definition of design methodologies for their design.

Acknowledgements

This paper has profited from the input of TUD students and researchers involved in the described projects.

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Immediate Systems in Architectural Research and Praxis

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Abstract

Immediate Systems are defined as systems that overcome the limitations of remote design by embedding design and implementation in situations of use. This paper extends the theoretical framing of IS and traces three approaches towards IS in architecture: as adhocist mode of action, as acceleration of design transfer and as human-architecture symbiosis. These three approaches consider the same phenomenon from different perspectives respectively, that of the lived experience of the user-designer, that of the designer's methodology and technology, and that of ecology.

Keywords

immediacy, immediate systems, design by use, design environments, design methods

DOI

https://doi.org/10.7480/spool.2020.3.5491

Introduction

The aim of architecture is to adapt the environment according to human wants and needs. In praxis however, architectural processes are detached and slow to respond to actual needs. Design usually takes place in environments which are spatially and temporally separated from construction, and both design and construction are separated from actual use. To the degree of this remoteness architecture must rely on hypothesis. In the words of architectural historian and critic Mario Carpo, this is the essence of design "*as it has been known since the Renaissance: design is a predictive tool, it models something before it happens.*" (Carpo, 2017)

Digitally-driven mass customization, performance optimization and building information modeling and management are well-discussed and employed praxes in architecture which emerged in the wake of the digital revolution (Kolarevic, 2003) (Kalay, 2004) (Carpo, 2017). They are foreboding what has been called the fourth industrial revolution, aimed not primarily at increased production capabilities but instead at unprecedented levels of flexibility, adaptability and integration. Products and services are increasingly linked with one another and their environment, driven by the ability to cater directly to customer wishes, affecting the value creation chain and effectively inverting the relationship between industry and its customers (Sendler, 2013, 2018). Whereas the first three industrial revolutions provided increasingly economic answers to the question 'how' to produce, the fourth industrial revolution increasingly links design and production to situations of end-use, offering value by answering the 'what' and 'why' questions in exhaustive detail.

Immediate Systems

Immediate Systems (IS), as defined by the author (Friedrich, 2020), can be conceptualized as a special form of Human-in-The-Loop Cyber-physical Systems (HiLCPS) (Schirner, Erdogmus, Chowdhury, & Padir, 2013). They are comprised of interacting digital, analog, physical, and human components, forming systems where people and environments are bound in a tight loop between human intention and immediate adaptation. They embed design and implementation in situations of use, overcoming the limitations of remote design.

Recapitulating prior framing of IS (Friedrich, 2020), IS offer interaction in the style of direct manipulation (Hutchins, Hollan, & Norman, 1985; Shneiderman, 1983), and leverage the psychology of the Immediacy Effect and Flow Experience (Keren, 1995; Nakamura & Csikszentmihalyi, 2009).

As conditions were named that IS are meta-systems binding user and environment, provide a tight feedback loop between intention and adaptation, establish and maintain a state of continuously available adaptivity and can include any combination of multiple modalities, e.g. temporal, spatial, tactile, embedded, intentional or procedural.

Framed as habitat (May & Kristensen, 2004) or environmental niche, and related to Gibson's original Theory of Affordances (Gibson, 1986), IS offer the affordances to shift boundaries between self and environment, afford creative immediacy and afford furnishing the environment with new affordances.

Awareness, guidance, intimacy, embeddedness, mastery and re-framing are additional affordances or characteristics, that were discussed and derived from examples (Graham, 1993; Keinonen, 2009; Martino, 2006; Roberts, 2014; Shneiderman, 1983; Weschler, 2009).

Immediate or Mediated?

The term immediate here is used to incite multiple connotations:

- as indicating a quality of human experience,
- as a quantitative difference in speed relative to conventional approaches,
- indicating a discrete qualitative difference obtained through methodical or technological improvements that cut middleware,
- as continuous integrated end-to-end process, in which intention and action may not be limited to one locus but be distributed across the entire system and
- as the state of being of an emergent system, which constitutes itself in the relationships of all its parts all at once.

While these connotations may each be legitimate, one should be aware that the notion of immediacy is often perceived as semantic construct with no relation to the real world. *Immediacy* eludes our grasp in its paradoxical nature. Any immediacy in space and time can itself be recognized only through the mediate knowledge of physiology; any immediate experience is inseparable from sub-conscious inference and interpretation; and if immediate ideas exist, they cannot be differentiated from prior knowledge. Understood as absolute absence of mediation, the notion of *immediacy* falls prey to scientific realism (Wallraff, 1961).

Applying this phenomenological critique to a discussion on media technology, the argument can be made that an attempt to achieve immediacy by means of technological mediation is paradoxically a hyper-mediacy. For example, attempts to create intuitive user interfaces that make themselves invisible ('transparent immediacy'), are in turn embedded in human's conscious efforts to manipulate a high-tech apparatus (Bolter & Grusin, 1999).

Martin Heidegger's famous example of using a hammer (Heidegger, 1967, pp. 68-70) shows how technology mediates an immediate experience of the world. A person that puts a nail in the wall works on the nail, while the hammer, being ready-at-hand, withdraws itself from attention. It is only in malfunction that is no longer ready-to-hand. As a hammer is bent it becomes conspicuous and asks for our attention again. According to Heidegger, this readiness-to-hand is the mode being of equipment, which is revealed only in use. The ancient Greek term for things matches this understanding of the world, it is *prágmata*, that which one encounters in praxis. Heidegger's texts are ontological, the matter of his philosophy is not the properties or relations of things that exist in the world but their very existence. Putting down the hammer allows for other modes of reflection and perception, but equipment reveals its being only and immediately through its use. In this sense, inversing the skepticism of Wallraff, the mediate is primarily immediate, only to be recognized in malfunction. This recognition of the primarily immediate as mediate is not reserved for equipment: a hammer may break, but so may a hand.

The equipment ready-to hand never is on its own, but always situated in an equipment totality. The hammer is bound to the nail by its adequacy for putting it into a wall, and similarly is bound into the equipment totality by references in-order-to. In the context of previous framing of IS it is tentative to draw a brisk parallel to Gibson's Theory of Affordances. Affordances too are situated neither in the user's perception nor an object's independent reality, they only exist and are to be revealed in a relationship of use. Yet affordances are not limited to the being of tools or equipment; everything and substance could afford something.

Approaches to IS in Architecture

In order to situate IS within architectural history and theory, three possible readings of the effects of IS in architecture will be discussed:

1. New adhocism, a mode of action where the environment is adapted ad-hoc using any means available, possibly utilizing but not dependent on any pre-existing technology or framework.
2. Accelerated design transfer, as consequence of evolving information and communication technologies, which lead to increasing interaction density between humans and their environment in combination with an expansion of their environment due to increasing interactions between the systems of which it is constituted.
3. Human-architecture symbiosis, which arises as consequence of cyber-physical systems which include both humans and the built environment.

These three readings offer different angles on approaching IS, with adhocism being situated in the context of the user, design transfer in the context of the designer and human-architecture symbiosis as perspective on technological mediation in the built environment, not as artifact but systemic. They have in common that they all originate in the 60s and 70s and were deemed newly relevant a generation later. The different perspectives are offered to indicate that IS touches on the subjects of design participation and user empowerment, on design methodology and design technologies, on habitats and human-technology relations. The reader may be familiar with one or several of these subjects, which can be considered as stepping stones towards a better understanding of different facets of the main theme of IS.

New Adhocism

In the early 70s, Charles Jencks proposed architectural *adhocism* as strategy to overcome the disjunct between the needs of the individual and generic design solutions; the ideal of adhocism thus is the immediate fulfillment of purposes. Jencks argued that by taking initiative and combining parts ad hoc, the individual could overcome the distance and estrangement caused by specialization, bureaucracy, and hierarchy. In doing so, the individual would not only answer their immediate needs but create, sustain and transcend themselves (Jencks & Silver, 1972, p. 15).
Adhocism preached the power of improvisation where technological means and social conventions failed to support the fulfilment of human purpose. As manifesto it walked the line between parody and political agitation for a more participatory architectural praxis, a more democratic style, through the application of readily available technological means.

In 2008, Matthew Fuller and Usman Haque (Fuller & Haque, 2008) proposed a *new adhocism* on the urban scale: the production of cities *beginning immediately with building and construction*. Any form of design or planning, sketching, modeling, or brainstorm session should be discarded. Their place should be taken by activities performed on actual building materials and thought processes expressed at full scale, immediately on the artifact inhabited. Fuller and Haque took the ideas of the 60s and 70s, including the adhocism of Jencks and the concept of underspecified architecture of Pask, who proposed to design buildings as evolutionary systems (Pask, 1969; Haque, 2007). They combined them with contemporary technology and best praxess that emerged in open source software development, embracing modularity and granularity to simplify re-use and re-development.

The New Adhocism approach is no longer fully dependent on make-shift solutions, as systems and components can passively, actively and pro-actively adapt and be adapted to custom causes.

Accelerated Design Transfer

Architect and researcher Richard Foqué introduced the concept of *design transfer* (Foqué, 1975, 2010) in analogy to the concept of *technology transfer*. Design transfer indicates *how a new design affects its environment and spreads out in time*. Foqué related design transfer to the concepts of *densification of human space* (Skolimowski, 1969) and *expanding environments* (Hall, 1962). *Human space* is described by the interactions between a human being and their environment; its density is measured by the number of patterns in which one is required to participate. The concept of *expanding environments* entails that constituents of natural and man-made systems interact in increasing numbers, affecting each other's behavior fundamentally.

According to Foqué, the evolution of information and communication technologies cause the expansion of interaction environments and the densification of human interaction space to augment one another, leading to an increasingly complex design situation. Foqué calls this an *explosion of the design situation* which coincides with the *implosion of design transfer time* caused by the radical *acceleration of design transfer*. Both developments contribute to a situation of design impotence which necessitates a new conceptualization of design activity and its methods.

In the new situation, leveraged by the Building Information Modeling (BIM), the traditionally consecutive phases of briefing, design, construction and operation are linked to one another. They enter a continuum where they can overlap and increasingly merge, resulting in an interactive designing-building process, in which previously consecutive activities are integrated and executed concurrently.

The account of Foqué bears similarities to Kalay's (Kalay, 2004) descriptions of the design process becoming a *network of design* which includes manufacturing, marketing and distribution organizations, and also a *distributed design process* which spans across professions, organizations and geographic locations. Both developments challenge the traditional hierarchy of the design process. Furthermore, embedded and networked computing devices in building components and machines for production and assembly can respond to occupant's needs as they arise, resulting in reduced waste and more efficient building and use.

The acceleration of design transfer, which coincides with the replacement of linear processes with networked concurrent processes, includes material fabrication and construction. According to Achim Menges (Menges, 2015), construction is becoming not only *computerized*, i.e. automated for the sake of improved precision and efficiency, but increasingly *computational*, i.e. an indeterminate process of materialization which extends the design process and is driven by cyber-physical feedback. As Menges states, predictive modelling may eventually be replaced by continual (re)construction, as design and materialization merge. "This potential fusion of the processes of design and making provides a considerable challenge to both established design thinking and current design techniques."

Menges's account of cyber-physical making however does not mention the users who interact with these systems, for example the architect, the builder, the inhabitant. Ultimately, it is them who pose a need for building, who set up and maintain the systems, who are bound into the ongoing process. As phenomenon of the fourth industrial revolution (Sendler, 2018), cyber-physical making ultimately would not stop at merging design and materialization but be driven by the far end of the value chain.

Accelerated Design Transfer shifts architectural praxis from a linear, sequential process towards processes executed in parallel, as a network of simultaneous activities, in which humans and things together compute, connect, sense, actuate and communicate.

Human-Architecture Symbiosis

In his 1960 article *Man-Computer Symbiosis* (Licklider, 1990, pp. 3-4), Licklider predicted the development of computer-human symbiosis, a kind of man-machine system positioned between mechanically extended man and autonomous artificial intelligence. The first aim of this development is to make machines that help *formulate technical problems*, for example machines that help identify the questions to the answers they provide or machines which cooperate in intuitively guided trial-and error procedures. The second aim, which Licklider considered closely related, is to develop machines that can participate in real-time processes in order to achieve *immediate man-machine communication*.

The cybernetic architecture movement of the 60s and 70s explored the architectural potential of the emerging computation revolution. The 1969 article *Cybermation* (Rabeneck, 1969), for example, considered the limited capabilities of then already existing automated mass-customized production in the building industry to answer changing demands. *"Imagine we can improve the built environment through developments in performance design and industrialized building, but that people's need of change accelerates faster than our ability to satisfy it. Our predictive ability remains inadequate. [...] Buildings ought to allow any degree of change over time [...] given the constraints of our current technology"* (Rabeneck, 1969, p. 497).

By applying computational systems to the design, construction and use of architecture, the notion of *human-architecture symbiosis* can be posited between modernist architecture, whose development was driven by the mechanically extended capability of industrialized production, and futuristic visions of artificially intelligent built environments which are autonomous and self-reliant. The Architecture Machine Group of Nicholas Negroponte was one of the pioneers in exploring cybernetic architecture. On the most extreme end existed the idea of architecture being artificially *intelligent, self-producing* and *autogenic* (Negroponte, 1975, pp. 144-145). The more conservative concept of a *designer-machine symbiosis* (Negroponte, 1969) maintains the remoteness of the designer, and therefore requires a machine that is able to work with missing information (Negroponte, 1970). An approach that encompasses user, technology and designer directly is the agenda of *making the built environment responsive to me and you* (Negroponte, 1975), which in context could be understood as *human-architecture symbiosis*.

Architects and architectural researchers aim to make the built environment increasingly adaptive (Eastman, 1972; Yiannoudes, 2016) and interactive (Fox & Kemp, 2009; Oosterhuis, 2012), by embedding intelligent (Cheng, 2016) and robotic (Menges, 2015; Oosterhuis & Bier, 2013) constituents, affecting conception, construction and use. Human-Architecture Symbiosis, as HiLCPS, makes the built environment more adaptive and responsive by establishing systems where designers, users and technological artifacts strive for a dynamic fit in their ecological niches amidst changing balances between them.

Bringing IS into Praxis

The research effort in IS originated at the Hyperbody group at Delft University of Technology. Situated originally in the department of Design Methodology of the faculty of Architecture, the group investigated non-standard and interactive architecture. Leading visions of adaptive built environments were given with the concept of *e-motive* environments (Oosterhuis, 2002; Oosterhuis, 2003), which are relatively coherent and relatable to the inhabitant, and with the paradigm of out-of-control *swarm architecture* (Oosterhuis, 2006). Within Hyperbody's educational and research agenda, a series of prototypical IS, or components of IS were developed. For the protoSpace collaborative design laboratory, a data exchange system was conceptualized and prototyped as graphing tool for actionable relationships between parameters in different software applications. The system would allow users to construct ad-hoc real-time information feeds between diverse and specialized applications used in the daily work of building industry professionals, and bind them to live parametric models made in the swarm architecture paradigm (Oosterhuis et. al., 2008). Another field of investigation were prototypes of CAD modeling tools that offer real-time volumetric design exploration, and should allow users to interactively model and ad-hoc reconceptualize geometry, topology and components of architectural assemblies (Friedrich, 2007, 2009). A combination of these techniques with digital fabrication and interactive building components lead to the most encompassing IS prototype, an attempt to realize an open-ended building system that encompasses simultaneous design, adaptation, construction and reconfiguration as interaction possibilities embedded in the built environment (Friedrich, 2013).

Conclusion and Outlook

The application of IS in architecture can be understood in a threefold manner: an adhocist mode of action, as accelerated design transfer, and as human-architecture symbiosis. These three approaches consider the same phenomenon from different perspectives respectively, that of the lived experience of the user-designer, that of the designer's methodology and technology, and that of ecology.

The ongoing digital revolution and emergence of ubiquitous computing, and cyber-physical systems may affect the form and feasibility of each of these readings:

A The New Adhocism approach is no longer fully dependent on make-shift solutions
B Accelerated Design Transfer may shift architectural praxis from sequential process towards a network of simultaneous activities
C Human-Architecture Symbiosis may emerge as a reading of HiLCPS with the agenda of making the built environment more adaptive and responsive

Research in IS re-examines these visions in their historical context and in the context of new technology. As was discussed, it is primarily through praxis that humans encounter the world. Design research that is limited to the technological mediation perspective of design technologies is in danger of falling back onto remote design thinking. IS research is an attempt to escape this circularity, it seeks to unveil the hidden affordances of design-by-use praxis.

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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

DOI

https://doi.org/10.7480/spool.2020.3.5492

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.

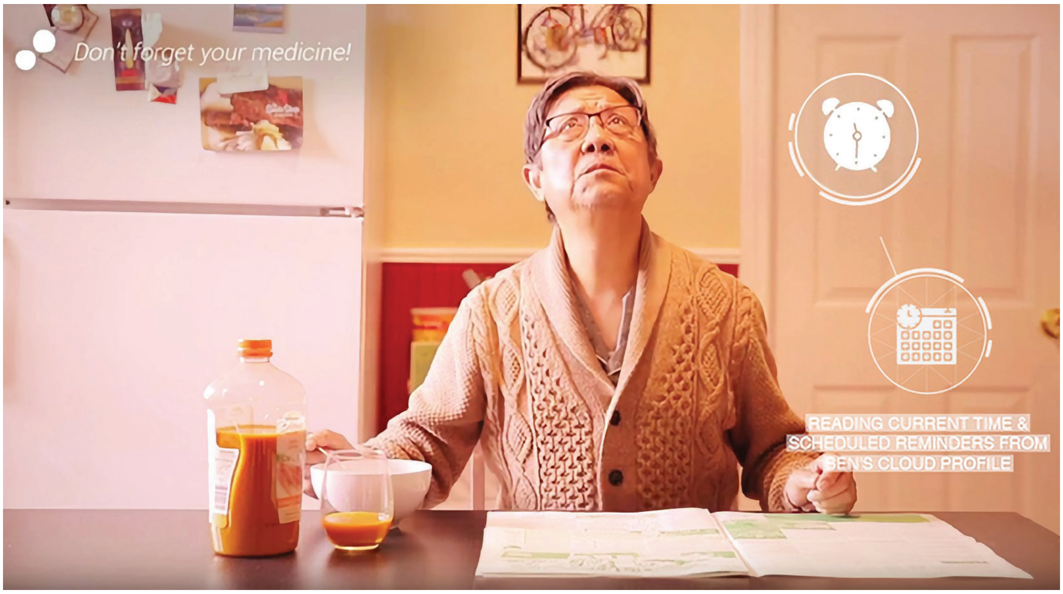

FIGURE 2 AI system reminding an elderly user when it is time to take the medicine by adapting the lighting in his/her home environment, *Connected Lighting for a Caring City project*, MIT Design Lab (2018).

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).

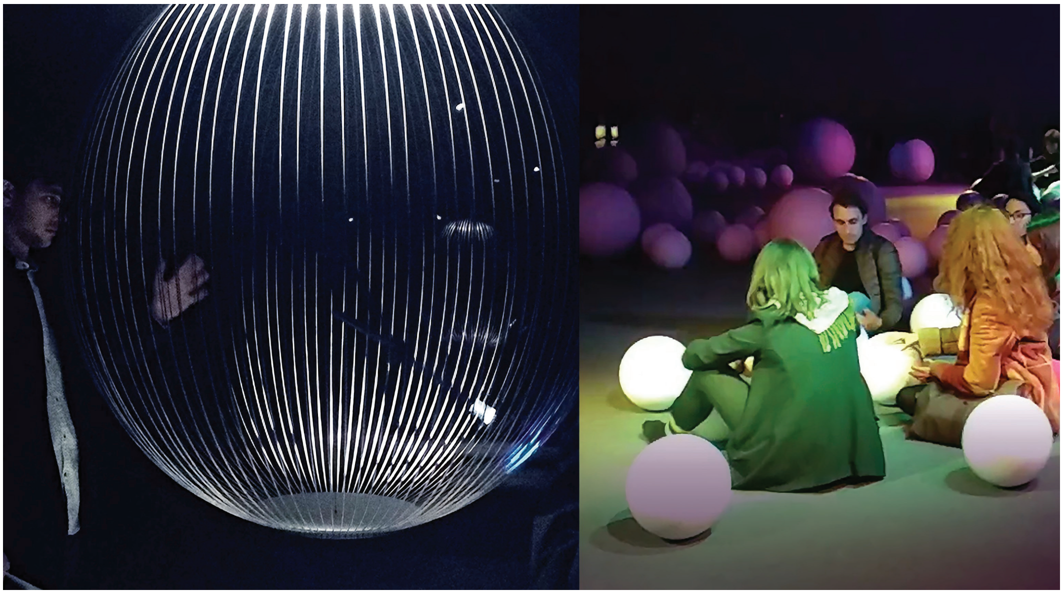

FIGURE 3 *Affinity in Autonomy* interactive environments exhibited at the Milan Design Week, Sony Design (2019).

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.

Acknowledgements

This paper has profited from the contribution of students and researchers from TU Delft, Hyperbody and Robotic Building Lab, Politecnico di Milano Interaction & Experience Design Research Lab, and MIT Design Lab, involved in the presented projects.

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Interview

Dialogs on Architecture

Grazia Maria Nicolosi [1, interviewer], **Henriette Bier** [2, Interviewee], **Maria Vogiatzaki** [3, Interviewee]

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Abstract

Dialogs on Architecture is a series of dialogs between researchers and practitioners. who are embracing the intellectual model of high technology and are involved in its advancement and application in architecture. The present dialog focuses on the role of parametric design and cyber-physical systems in architecture. It has been inspired by a lecture given by Henriette Bier at the Italian Institute of Architecture in Catania (2019) and addresses the question of the current paradigm shift in architecture and its impact on the role of the architect and the user. The dialog is led by Grazia Maria Nicolosi (GMN) with Henriette Bier (HB) and Maria Vogiatzaki (MV).

Keywords

Cyber-physical Systems, algorithms and computational processes, Human-Computer and Human-Robot Interaction

DOI

https://doi.org/10.7480/spool.2020.3.5493

Grazia Maria Nicolosi: The 'particlizing' of matter (Kuma, 2007) and its simplification to elementary components is a complex act and a singular condition that comes from the arrangement of a series of distinct and separated elements into units. This coincides with making the invisible visible. Do you think this corresponds to a change of paradigms in architecture?

Henriette Bier: Architecture has always worked with arrangements of distinct elements into structures as for instance stones that are stacked into walls, etc. Only the scale at which these elements are addressed has changed. Hence, architecting materials and material systems in particular for additive manufacturing may represent a paradigm shift, however, architecting cyber-physical systems seems to be encompassing what the paradigm shift in architecture is about.

Maria Vogiatzaki: Materiality can, nowadays, be thought of at a micro-scale such as dust that can 'powder' and granulate geometries producing random otherness thereafter. Algorithms are like managing and manipulating matter in its dust existence. Dust geometries are a cognitive construct; they are abstractions, therefore could potentially bring about a new kind of architecture. The big data idea and its relationship with materiality allows to consider thousands of particles at the same time and moment, what ordinary limited and small data sets could not achieve. Particles not only change under observation, but also under the way they interact with other entities.

Grazia Maria Nicolosi: In 2014, in Barcelona, you took part in a conference titled 'What's Matter'. Could you explain what you mean by materiality and materialism in the age of computation?

Henriette Bier: At the time, the discussion on materiality and materialism has been put forward by Maria Vogiatzaki, whom I asked to join this interview. My own take on materiality is that in architecture the range is vast, from the perceived materiality of images, 3D models and other virtual representations to the materiality of physical prototypes, building components and buildings, where the full range of their virtual and physical aspects needs to be considered. Buildings are not anymore physical but cyber-physical systems (fig. 1).

Maria Vogiatzaki: To date issues of Ethics, Aesthetics and Politics have either been flattened, naturalised or ignored in favour of matter's self-organised capacities or worse they are still mobilised, understood and applied within a given anthropocentric framework of judgments and evaluations. After a long period of fierce experimentation with matter, the discussion, which was what was unfolded at the Barcelona conference, has been recently focusing onto what matters; to the radical realisation that materiality's dynamism suggests a post-human framework within which architecture as a creative act could possibly prototype spatiotemporal constructs that suggest alternative conceptions of ethics, aesthetics and politics.

Grazia Maria Nicolosi: In the design of architectural form by means of programming with algorithms what role does nature and natural processes play?

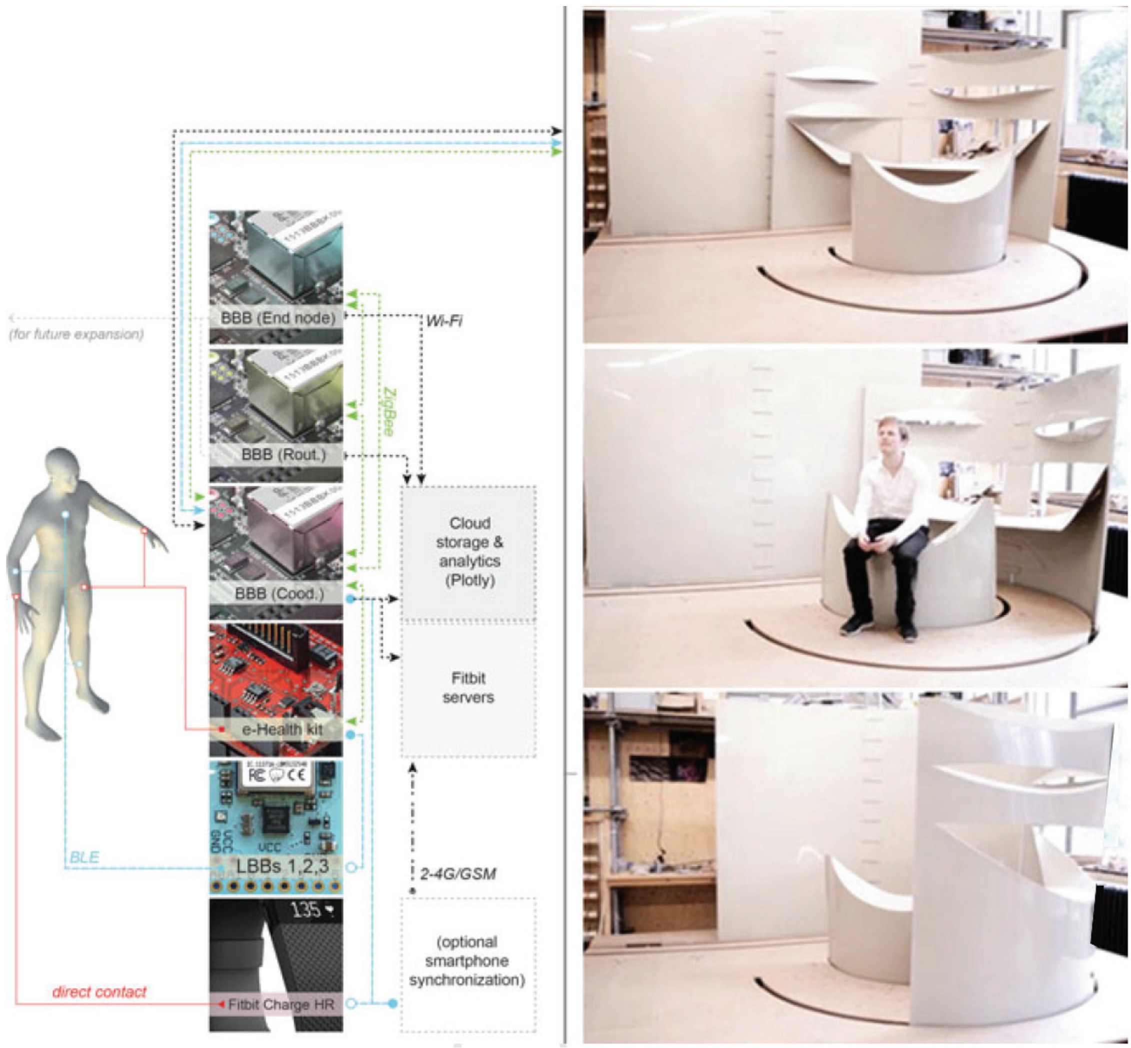

FIGURE 1 Sensor-actuators networks integrated into the reconfigurable physical-environments © Robotic Building, TU Delft

Henriette Bier: In my work with researchers and students at TU Delft, we implement multi-agent simulations for programmatic distribution as well as embed distributed sensor-actuators into the built environment. These operate as multi-agent systems and consist of autonomous entities which act towards achieving goals together by observing through sensors and acting through actuators. Their behaviour may be similar to a swarm of fish or flock of birds (Reynolds, 1987) that exhibits a bottom-up coordinated behaviour in absence of top-down control.

Maria Vogiatzaki: Materiality has been reconsidered extensively with the appearance of computational models that allow material to be encoded and with hardware that allows even for real time and simultaneous manipulation and malleability of matter. The shift that this perception has altered radically, is that in computational times the creation of any form is understood as yet another natural and systemic process which, through the computation power of the search and retrieve, can be modelled and tested. Any artefact and, consequently, any architectural creation are now conceived as material entities, generated as parts of a broader natural, social and cultural eco-system.

Grazia Maria Nicolosi: In your opinion, what is the future of Human-Computer interaction?

Henriette Bier: Human-Computer Interaction and Human-Robot Collaboration are most relevant developments that affect architecture and society at large. I expect that the physically built environment and building processes are increasingly imbued with ICTs and robotics. Architecture and building construction are at the very beginning of identifying the interaction between human and non-human agents participating in all phases from design to production and operation of physically built environments.

Maria Vogiatzaki: Experimentation on the project of architecture is about speculations and about the ways in which qualities can be embedded in this experimentation but also about the ways in which new qualities of crafting can be discovered by humans working with machines. It is about the exploitation of the granularity (dustism) that large data sets can provide. The future and the huge potential are for human and non-human symbiotic and synergetic creativity that would yield new and unthought of scenario, such as new material systems that can potentially self-organise and create flows of heterogeneous spatiotemporalities and variations, etc.

Grazia Maria Nicolosi: If technology develops faster than the human ability to understand it , how will this impact architectural design?

Henriette Bier: The development of technology has a huge impact on architecture. My plea with schools of architecture is to not let technology surpass the understanding of its impact and introduce students as early as possible to most advanced technologies to keep up the pace. It is obvious that architectural design, production, and operation rely increasingly on new technologies and our responsibility is to identify ways to employ this technology in a manner that potentially increases our cultural and material contribution to society, and the approach addresses societal challenges such as overpopulation, material depletion, climate change, etc.

Maria Vogiatzaki: Contemporary contemplation is focusing on reconnecting sensing and making and therefore thinking with a material base that is primarily imperceptible and outside the strict limits of human's sensorium domain. In such a post-human realisation, architectural design emerges as a result of the co-creativity/co-creation process between human and non-human agents.

Grazia Maria Nicolosi: On several occasions, you (HB) have argued that man remains the protagonist in the process of creating form and that technology and algorithms are tools. What do you mean?

Henriette Bier: Non-human agents such as algorithms and robots are from my point of view tools and/or instruments designed by human agents to implement certain tasks. The human and non-human agents (computational or robotic) are working together and the production of value is not allocated to the one or the other but emerges in the interaction between the two.

Maria Vogiatzaki: Algorithms are tools indeed, but very powerful tools that can offer inconceivable ideas, that humans would be unable to create without them. The point is not to harness technology in a competitive human-centred context. The algorithmic governance via computational platforms can augment the human's infinite virtual perfectibility. Hence, the mission of architecture is to contribute to this perfectibility both of the creating subject, the architect, and the appropriating subject, the user.

Grazia Maria Nicolosi: During a research investigation, we undertake systematic work to advance knowledge and amongst others we experiment and speculate. What are in your opinion significant phases that should be addressed during drawing up or reviewing research in architecture?

Henriette Bier: The architectural research that I am implementing with my researchers and students, is applied research aiming at solving practical problems. It generally employs empirical methodologies and conceptual frameworks that work with hypotheses. The hypothesis that seems to me most relevant for today's research is based on the assumption that building processes and buildings are increasingly imbued with ICTs and robotics and the question for the future is not if but how these technologies impact architecture.

Maria Vogiatzaki: In particular, research on AI could acquire an added value in the exploration of unprecedented fabrication techniques and unimaginable scales of construction. By pulverising, we aim to revise our concepts, in other words to re-cut the world and to allow for the constitution of new events, new materials, new construction methods, new scales. Machines provide us with a new sensibility.

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ISBN 978-94-6366-358-8
9 789463 663588