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Published in:
Frontiers of Architectural Research

DOI:
10.1016/j.foar.2022.02.008

Publication date:
2022

Document version:
Final published version

Citation for pulished version (APA):
Mulder, H. (2022). Building cognition through material engagement. *Frontiers of Architectural Research*, *11*(4), 642-652. https://doi.org/10.1016/j.foar.2022.02.008

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Frontiers of Architectural Research xxx (xxxx) xxx

Higher Education Press

Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.keaipublishing.com/foar

SOUTHEAST UNIVERSITY

RESEARCH ARTICLE

Building cognition through material engagement

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Received 14 December 2021; received in revised form 8 February 2022; accepted 24 February 2022

KEYWORDS
Robotic architecture;
Material engagement;
Building cognition;
Agency

Abstract With the ascent of robotic architecture in academic discourse, we ought to reconsider how we understand building cognition. This paper revisits the Rietveld Schröder House from 1924 as a precursor of robotic building. With a built-in capacity for change, the building (now a museum and listed as a UNESCO World Heritage site) has a highly adaptable space plan that could be continually reconfigured by its occupants. The agency of change is shared between the house and its occupants, most notably Truus Schröder, who lived in the house for 60 years. This paper takes a material engagement approach to explore the relation between the occupant and the house and speculates how this might be a model for designers of contemporary and future robotic architecture to rethink concepts of autonomy and agency in building cognition.

1. Introduction

Since at least the 1960s, architects have speculated about buildings that operate autonomously and with a built-in capacity for change. In some cases, analogies were drawn between buildings and robots, so much so that Steven Groák writes in 1992 that "buildings have been moving towards the status of robots for some time" (Groák, 1992, p. 115). The extent of autonomy, however, of most buildings that were built since the 1960s, has been rather limited, the widespread use of thermostats to regulate building temperature notwithstanding. But developments in design, in building technology and also in construction, have more recently led to an increasing number of buildings across different scales and functionality, with a capacity for physical transformation and with increasing levels of automation and self-regulation. The debate about the future of buildings has in some circles been dominated by new forms of digital design and fabrication performed by robots. But apart from buildings that are made *by* robots, we now also see a category of buildings emerge that are made *as* robots.

Definitions of robot and robotics have been various. Robotics has been defined for example, as the science of "the intelligent connection between perception and

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Peer review under responsibility of Southeast University.

https://doi.org/10.1016/j.foar.2022.02.008
2095-2635/

Please cite this article as: H. Mulder, Building cognition through material engagement, Frontiers of Architectural Research, https://doi.org/10.1016/j.foar.2022.02.008

action" (Siciliano and Khatib, 2016, p.2), a robot as "an autonomous system which exists in the physical world, can sense its environment, and can act on it to achieve some goals" (Mataric, 2007, p.2), or as "an embodied intelligence" (Winfield, 2012, p.8). And thus, it seems that to discuss buildings as robots, is raising the issues of *intelligence* and *cognition*, and of *autonomy* and *agency*. The first set of terms refers here to the capacity for, and effectuation of understanding the world; the second set of terms to the capacity of an agent to act by itself. These are terms that originally applied to natural organisms, but that have gained a broader meaning with advances in technology. The development of robotics has in fact gone hand in hand with the development of artificial intelligence, and in some areas has shown similar insights as contemporary cognitive science and the philosophy of mind. Robots, in short, are supposed to be artificially intelligent machines that feature a capacity for autonomous action. But, other than robots, buildings are typically designed for habitation. And the operation of buildings would be seldom left to the building alone. What we might call *building cognition* could therefore be understood as a hybrid interweaving of artificial and human cognition.

With a renewed interest in robotic architecture (see e.g., Bier, 2018; Claypool, 2019; Daas, 2018; Green, 2016; Lynn, 2016), we ought to reconsider how we understand building cognition—both in terms of cognition itself, but also in terms of the relation between occupant and building. The pervasive understanding, for example, of *intelligence* in a building context has become skewed towards a particular subject. The term *Intelligent Building* has been used extensively in the pragmatic discussion about energy preservation and human comfort in buildings (Buckman et al., 2013, 2014; Hegger et al., 2016; So and Chan, 2012; Wong et al., 2005), making for a very narrow reading of intelligence. And the established relation between occupant and building is up for a re-examination after its cybernetic origins have staled and, in some cases, have been superseded by new insights. The work of cybernetician Gordon Pask (1969) still is influential in describing the relation between occupants and buildings in terms of a control language—Pask writes about a *mutualism*, where buildings form "an environment with which the inhabitant cooperates and in which he can externalise his mental processes" (p. 495). But the control systems of larger buildings, often centralised in a *building management system* use traditional control architectures that connect sensors and actuators to dedicated computers, translating input to output. The representation of humans in those systems is often a single parameter that describes comfort, with an upper and lower limit value. In order to be useful in the contemporary discourse on robotic buildings, a notion of building cognition should therefore address at least (1) the view on cognition, and (2) the relation between occupant and building.

Contemporary views of cognition allow us to clarify and reanimate both issues. Cognition, in those views, is understood as being fundamentally entwined with the body of the agent and with the interactions of that body with the world, thereby renouncing traditional views that emphasise the brain as the locus of human thought. Positioned firmly within this context, the *material engagement* perspective (Malafouris, 2013) builds on these contemporary views to establish how agents understand their environment, and it puts forward a position that explains the relation between agent and environment as constitutional in the emergence of agency. Rather than an active agent acting on a passive material object, Malafouris specifies agency as an emergent property of the process of interaction. This perspective is relevant because it broadens the possibilities for a robotic architecture to become engaged in the process of living. Not only can architecture be *active* by making decisions independently of occupants, it can also actively engage by providing affordances and become part of a mental process that includes occupant and building. The question about who is acting, the occupant or the building, is not an either/or—material engagement theory allows us to address this as a hybrid process. With that, it provides a model for designers of the built environment occupied with building cognition.

In Section 2, this paper will first discuss the role of cognition in architecture by sketching some historical tendencies. This section expresses the need for renewal of ideas if we accept the premise of the robotic building.

In Section 3, the paper introduces Material Engagement Theory (MET) and applies it to a building context. MET offers a particular view on the relation between agents and material objects, and it explains how agency emerges as a function of this relation.

In Section 4, the Rietveld Schröder House from 1924 is presented as a precursor of robotic architecture. In the house, physical transformation of space was enacted daily by the long-term inhabitant Truus Schröder. Some of her experience of living in and with the house has been extracted from written communication between her and her daughter. The paper argues that these experiences reinforce the view that material engagement supports an understanding of the relation between Truus Schröder and her house—and between occupant and building more generally—that can be transferred to a new class of buildings that is truly robotic.

In Section 5, the paper puts forward several proposals for implementing measures in existing or new buildings, following the newly established insights of building cognition.

2. Architecture of cognition

In his seminal essay Animate Form (1998), Greg Lynn explains a process of designing architectural form through animation. It is a fundamentally dynamic process of building design, that is frozen at a point in time in order for it to be built. Although Lynn at that time does not rule out actual movement of the resulting architecture, he certainly steers away from it and argues that virtual motion may be significantly richer: "Actual movement often involves a mechanical paradigm of multiple discrete positions, whereas virtual movement allows form to occupy a multiplicity of possible positions continuously with the same form" (p. 10). In 2014 however, he writes on his website: "Motion is currently being integrated into buildings at an unprecedented scale and scope. [...] Twenty-five years ago I decided to focus on the PHENOMENAL motion of the digital design medium while dismissing LITERAL motion. Today, literal motion and its phenomenal partner seem worth returning to". In 2016 Lynn is guest editor of Log 36: Robolog, that investigates the building as a robot through a series of essays, and he puts robotic buildings back on the agenda.

Even though the early Lynn (along with Groák and others) saw the potential of a kinetic, transformable robotic architecture, the technology—especially at building scale and for building lifetime—may not have been there to build it. Some notable early work that was never built includes the *Fun Palace* project from 1964 where Cedric Price and Joan Littlewood worked with the cybernetician Gordon Pask to design a new form of leisure centre that was extremely adaptable. The configuration of the building and the activities it offered to occupants would be commanded by a cybernetic system that sensed and analysed patterns of use (Mathews, 2005). And for the *Generator Project* (1978–1980), Price worked with system consultants John and Julia Frazer to devise what would be described as the first intelligent building, even though it was never fully realised (Emery, 1980; Furtado, 2008). A centre for the arts on private land, it was thought of as a kit of parts that could be reconfigured by mobile cranes—upon user request, or on its own initiative.

The Festival Plaza at the Expo in Osaka of 1970 is a built example of what Arata Isozaki would later describe as *soft architecture*: "Architecture no longer needs to be fixed, space gains a temporal aspect [...] and obviously architecture must incorporate software" (Daniell, 2016, pp.46-47). The plaza was covered by a spaceframe roof, equipped with mobile installations for lighting, stages and seats (Fig. 1). Deme and Deku, two building-sized robots that were occupied by human performers, would freely roam the plaza, only tethered by power cables. Architecture soft as software was also the focus of Nicholas Negroponte's Soft Architecture Machines (1975) that set out a future of responsive and intelligent environments. Rather than a computer system that controlled a building, in Negroponte's view the computer would become space—"a physical environment that knows me".

Industrial buildings such as modern greenhouses, have an advanced capacity to autonomously control their internal climate (air quality, air flow, humidity, temperature, lighting)—sensing inside and outside conditions, anticipating weather changes and operating vents and shading devices. Even some of the functional agricultural operations inside the building have become automated, such as planting, watering, and harvesting (Castilla, 2013). Sports venues like the Saitama Super Arena and Sapporo Dome in Japan feature partly automated building-scale mechanical systems that transform their interiors to accommodate different activities and varying number of spectators (Kobori and Hosozawa, 2002; Nakai, 2003). And on a smaller scale, Ori, a spinoff from the MIT Media Lab, represents a movement to optimise floor space of small apartments by introducing robotic interior elements that work as furniture and space dividers (Larrea-Tamayo, 2015).

As advanced as some of the more recent built examples may be in terms of building and mechanisation technology, their capacity for autonomous operation has been locked in a dated paradigm for self-governance that exhibits parallels with pre-1980s robot technology. Early forms of robot intelligence have been developed in a context of cognitive science and computationalism, and until around the mid 1980s *sense-plan-act* was the dominant robot architecture. This implied a robot had various sensors that would scan the environment, a computer for a brain that would map the environment and plan some action, and finally a series of actuators that would act out the plan (Pfeifer and Scheier, 2001).

Rodney Brooks famously challenged this approach by showing that robots did not need a map of the environment to navigate their surroundings and that specific behaviour could emerge from a robot interacting with its environment. Brooks argued that the central issues of research in artificial intelligence until then were holding radical development back: "explicit representations and models of the world simply get in the way" (Brooks, 1991). Even though Brooks steered away from the philosophical debate, the parallels between his work and the enactive approach in the philosophy of mind seem clear, and his work was extensively referenced by Varela et al. (1992) in their treatise on cognitive enaction.

The enactive view on cognition is sometimes considered together with other contemporary views that are collectively referred to as *4E*, which explains cognition as *embodied*, *embedded*, *enacted* or *extended* (Rowlands, 2010, p. 219). These are distinct but overlapping positions that share a rejection of the emphasis that traditional cognitivism put on the brain as the central sense-making organ. Instead, the *e*'s propose that cognition should be understood in the context of the whole body and on the interactions of that body with the world. Enactive cognition herein emphasises the role of active engagement and the movements of the body in the world, and extended cognition asserts that cognition should, at least in part, be sought in the environment outside of the body.

Currently, different views exist alongside each other. Some major research programmes in AI for example are fundamentally rooted in traditional cognitivist or computational paradigms, where other fields of engineering such as robotics, have out of necessity embraced aspects of 4E. Along with algorithmic developments in artificial intelligence, for some time, autonomous robots have been designed that rely less on predefined patterns, feedback loops and computational thinking, and more on distributed and embodied forms of intelligence that allow open-ended interactions with the environment to give rise to new ways of being in the world (Siciliano and Khatib, 2016). It seems unavoidable that a field that is reliant both on software and hardware for its devices to operate in the world, fundamentally investigates how one affects the other and seeks to optimise performance in the integration of both. But where this is true for robotics, the plight of robotic buildings seems to be that autonomy and intelligence are sought in the building management system, stuck in a classical and centralised understanding of cognition.

3. Material engagement in buildings

The architect Mick Pearce is known for his work on passive cooling and natural ventilation in buildings, notably in Harare's Eastgate Centre. While on a mission in Guangdong

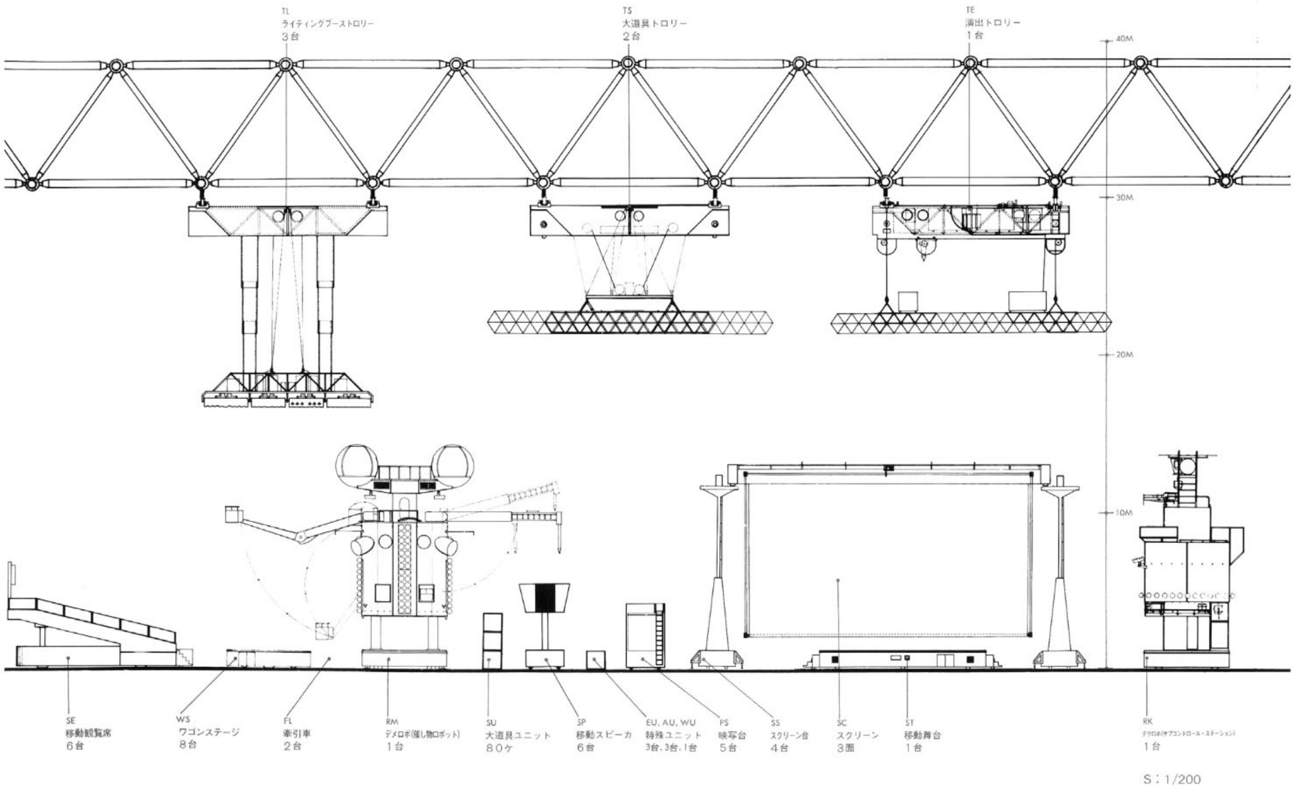

Fig. 1 Section of Festival Plaza for Expo 1970 in Osaka by Arata Isozaki. Spaceframe roof with movable elements and robot. Courtesy of Arata Isozaki & Associates.

in China in 2010, he encountered traditional houses along the Zhujiang river that featured a superior indoor climate than the modern buildings that were erected alongside it. Comparative analysis of the buildings alone did not explain the differences, but Pearce had noticed that the occupants of the houses kept changing the open and close states of the various vents to direct the airflow through the house. It was Pearce's theory that the occupants' ability and skill to operate the many vents around the house allowed them to optimise indoor conditions for their own comfort to a much higher degree than the building systems could optimise the newer buildings (personal communication with Mick Pearce and Rupert Soar, 2020).

Pearce refers to the work of biologist Scott Turner, who describes animal structures, such as termite mounds, as external organs, or extensions of organisms (Turner, 2002). Building on Richard Dawkins' *extended phenotype*, Turner explains how "in such structures, organisms co-opt the environment into a physiology that extends well beyond their conventionally defined boundaries" (p. 212). The termites for example, in their mounds, cultivate fungus gardens that can be understood to be part of the termites' digestive system. Ezequiel Di Paolo brings up the example of water boatmen, aquatic insects that cultivate air bubbles for breathing during their sustained submersion. Such air bubbles, although technically not part of the physical body of the insect, *mediate* the coupling with their environment. "The mediation in cases like this is so intimately connected with vital functions that the living system itself might be called extended" (Paolo, 2008, p.17).

Are the river houses in Guangdong also extensions of their inhabitants? Even without more specifics of that case, we can speculate that they are. By living in there long enough, some inhabitants will have become attuned to the affordances of their houses, expertly handling the vents to configure and reconfigure the system depending on the changing conditions outside and the demands inside. Through their skilful operation of the vents, the houses could be said to mediate the occupants' environmental coupling. Not only will this bring about a comfortable indoor condition, the active handling of the house also makes the occupants perceive the environment in a particular way that is specific for the building they inhabit—occupants perceive the environment in a building way (Mulder, 2018).

But rather than understanding the building as a bodily extension, an external organ, or prosthesis, we might consider the building in its own right. Unlike termite mounds or boatmen's air bubbles, the handling of the vents does not offer a coupling that is so intimate our survival depends on it (although arguably, human survival does depend on the existence of built structures more generally). Nevertheless, we might say the building enables a cognitive extension in our engagement with it—the building brings forth a world through its affordances.

Referring to the symmetry between human and nonhuman agents that is inherent in Latour's Actor-Network Theory, Malafouris (2013) argues for a transformation of the artifact from a "passive instrumental mediation" to an "actor-entity" (p.130). When a building is physically moving, it is easy to see how we might ascribe agency to the building—the building *does* something. Looking through the recently renovated southern facade of the *Institut du Monde Arabe* in Paris, observing the Tour Montparnasse, the closing or opening diaphragms of the elaborate facade mechanism keep reframing the view of the Paris rooftops (Mulder, 2018, Fig. 2). And the Burlington Northern Railroad Bridge 5.1 across the Willamette River in Portland, US, as depicted in Richard Serra's film *Railroad Turnbridge* (Fig. 3), "clearly has times, rhythms and modes of effect that are independent of, or at least broadly indifferent to, those of users, viewers, filmmakers, and even of the environment in which it sits", writes John Biln (2010, p.5).

And even though, in the context of this paper, architectural movement as a form of acting is of particular interest, Malafouris' actor-entity does not require a capacity for movement for its agency to unfold. Observing potters at work, Malafouris describes in detail the induction of agency in the forming of a pot from clay, as he analyses the dynamic interplay between the hands of the potter, the centrifugal force applied by the spinning wheel and the resistance in the texture of the inanimate clay. Both the potter and the clay can be said to act in this process and the different actors take turns in having the upper hand: "In the dynamic tension that characterises the processes of material engagement, sometimes it is the thing that becomes the extension of the person. At other times, however, it is the person that becomes the extension of the material agent" (Malafouris, 2008, p.34).

The metaphoric force that forms the clay into a pot is not merely the skilful handwork of the potter, and neither is it just the possibilities the clay offers for transformation—we should understand agency as the middle way where both parts specify each other: "Agency is a property or possession neither of humans nor of nonhumans. Agency is the relational and emergent product of material engagement" (p.34).

We can now return to the Guangdong river houses, which allow themselves to be manipulated in specific ways. Their many vents can be adjusted, resulting in changing climate conditions inside. The occupants have learnt to manipulate the houses when the need arises. We might say that agency emerges when occupants adjust the vents and sense the changing flux as air flows through the house. Neither the occupant, nor the building possesses agency, but it emerges when occupant and building engage.

4. Rietveld Schröder House: a building as clay

To better understand how material engagement might be understood in the context of robotic architecture, we now turn to the Rietveld Schröder House in Utrecht, The Netherlands, that was built in 1924. The house can hardly be described as robotic, but it features an elaborate reconfigurable first floor that would be operated by its occupants. Because of the reliance of the occupied space on a mechanised system of partitions, we can characterise the house as a precursor to robotic architecture, containing critical aspects of what we would expect in a contemporary, more autonomous robotic building.

Because Truus Schröder has lived in the house for approximately 60 years, it is a unique case where an occupant has become intimately familiar with a transformable space. In analysing some of her experiences, extracted from archived written communication, we can use Material Engagement Theory to interpret her interactions with the house, especially with its adaptability.

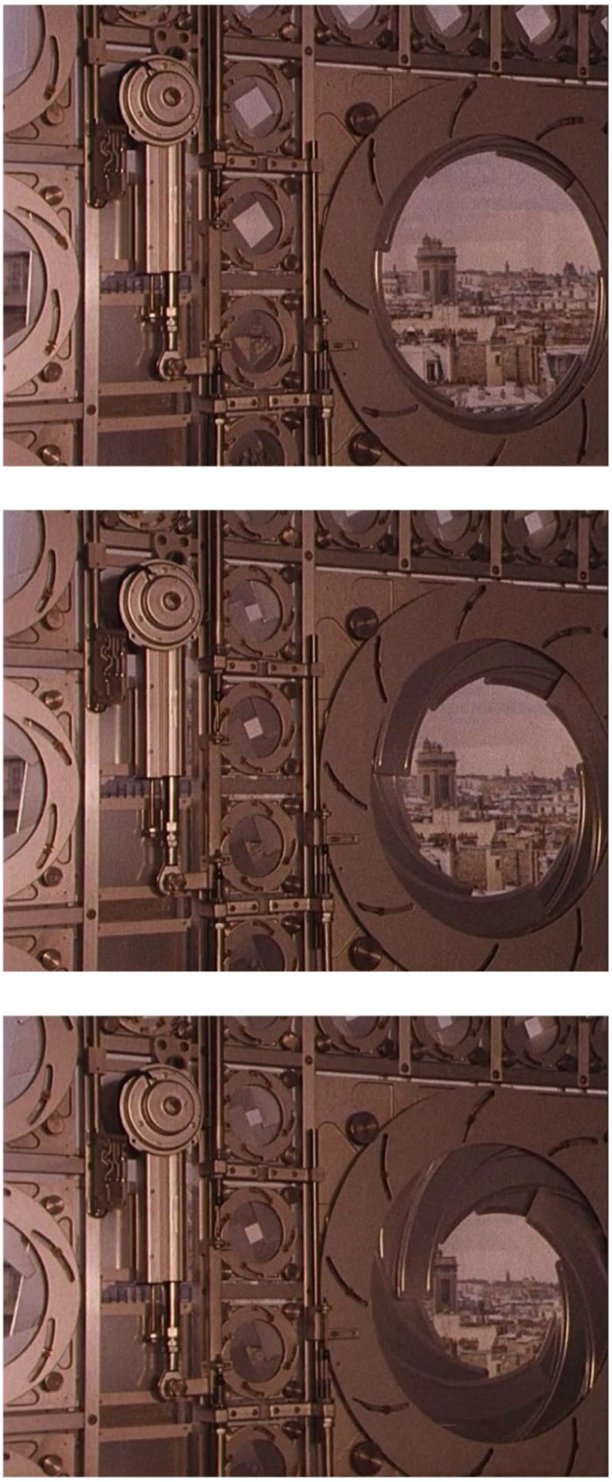

Fig. 2 Stills from Les Diaphragmes de L'I.M.A by Pascal Bony. Looking out from the Institut du Monde Arabe in westerly direction.

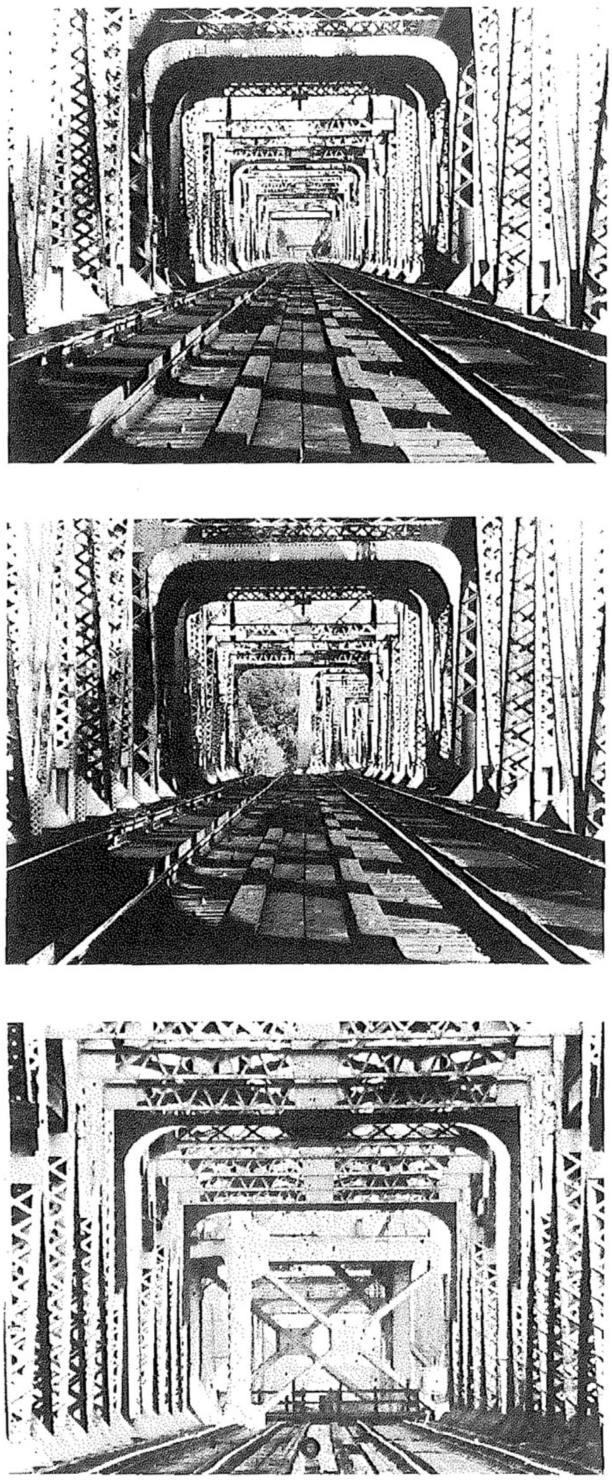

Fig. 3 Stills from Railroad Turnbridge by Richard Serra. Looking through the rotating part of the bridge.

From this analysis we may tentatively extract and extrapolate what could be relevant aspects for interactions between occupants and mechanised building elements in contemporary robotic buildings.

The Rietveld Schröder House was designed for Truus Schröder and her children—a son and two daughters. She had strong ideas about the future of living and commissioned the furniture maker and aspiring architect Gerrit Rietveld to design the house with her. The project became a collaboration. The house was built with one side connecting to a conventional row of terraced houses, but after almost 100 years, the house still stands out because of its distinct appearance (Fig. 4).

Following the tenets of the *De Stijl* movement, the house was an example, in the words of Theo van Doesburg, of a new plastic architecture (Jaffé, 1971), in which conventional ideas of form and symmetry were done away with. The new architecture was constructed in a field of "four-dimensional time-space" (p.187) which was expressed by its use of colour, the organisation of spatial elements, and a dynamic open plan. The walls of the house were "disrupted" (p.186), leading to a separation of the load-bearing structure and the facade, and critically, also to the omission of fixed internal separation walls on the first floor. At the request of Schröder, this floor was organised as an open plan with a number of sliding and folding partitions that could divide the space into three bedrooms, a living room, a bathroom, and a hall. The partitions ran on wheels and were guided by rails in the floor and ceiling. They were manually operated.

4.1. Open plan, closed plan

Fig. 5 shows two plans drawn by Rietveld, with the open and closed configurations of the first floor. An overlay on the closed plan labels the partitions and indicates their deployment. There are seven movable partitions on the first floor, of which only two (E and F) are single sliding elements. The other partitions are assemblies of two or more elements that slide and fold. Most of the partitions are opaque in order to separate rooms, apart from partition G that runs on top of the balustrade around the stairwell. This partition is glazed to allow light from the skylight into the living room in case the partitions are closed during daylight hours.

The three partitions A, B and C, that form the two bedrooms for the children in the south-western side of the house are the most complex. The elements of those partitions run in stages and have both sliding and folding elements.

Fig. 4 Rietveld Schröder House, Utrecht, The Netherlands. Centraal Museum Utrecht/Stijn Poelstra.

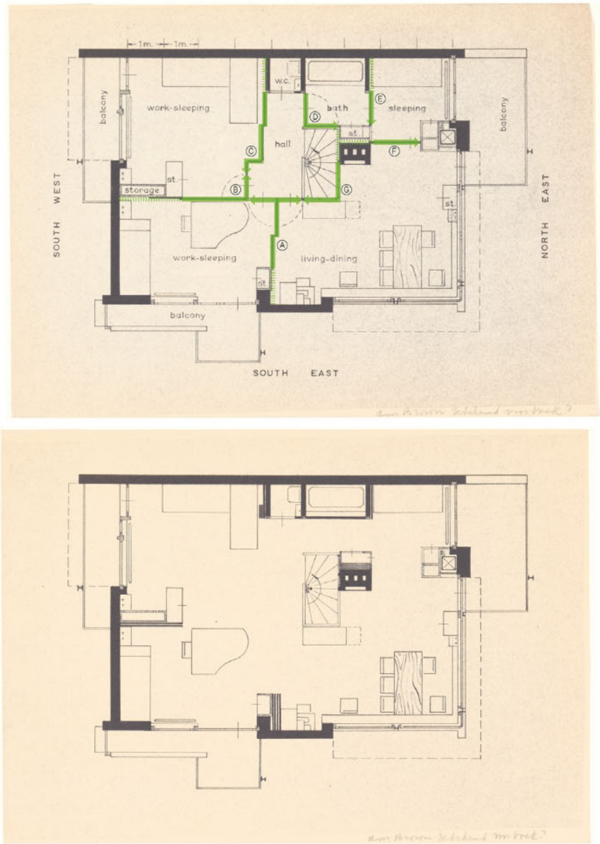

Fig. 5 Two plans of first floor Rietveld Schröder House, in closed (top) and open (bottom) configuration. Arrows and labels added by author. Rietveld Schröderarchief/Centraal Museum Utrecht.

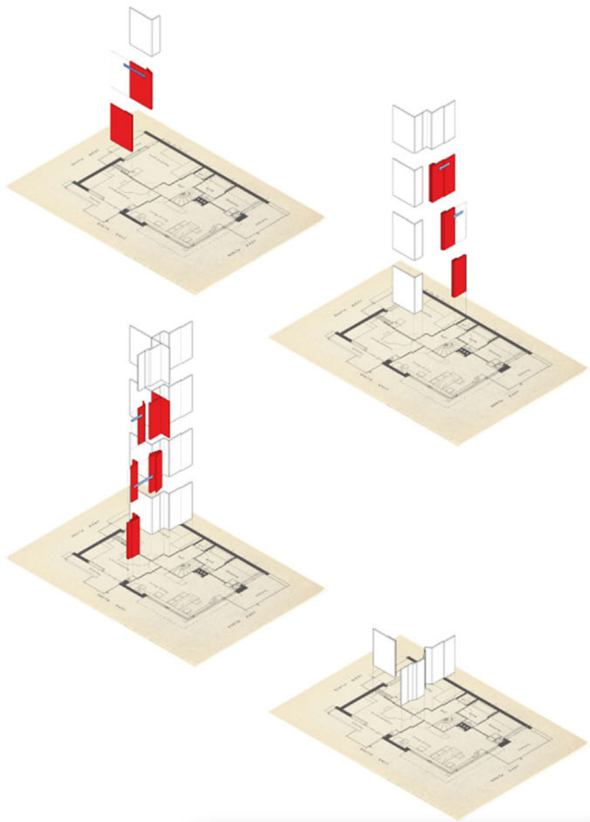

Fig. 6 Diagrams illustrating stages of deployment of movable partitions. From top to bottom, deploying partition B, C, A, and retracting B to combine the two children's rooms (compare Figs. 5 and 7).

Partition A consists of five elements. In order to deploy this partition, it is slid out in two stages. The first stage contains three elements, is slid into the room, after which two of the elements fold outwards, creating a T-shape. These two elements serve as doors to the rooms when the partitions are deployed. The second stage contains two elements of which one slides and the other unfolds to close the gap with the elements of the first stage.

Partition B consists of a large sliding element and a smaller folding element. Together with partition A, the room that was designed for Schröder's son is formed. The folding element of this partition is the door to the room of the daughters.

Partition C consists of four elements, of which the two large elements slide, and the two smaller elements at the end unfold to create a corner that connects to the door from partition B. Together with partition B the room of Schröder's daughters is formed.

Fig. 6 illustrates the deployment of partition B, C and A in order to form the two rooms. With partition B retracted, the two rooms can also be joined by slightly rotating the corner of partition C and using the door of partition A (also see Fig. 7, bottom left).

Partition D, in two elements, was used to form the bathroom. When closed there is effectively no bathroom, but by unfolding the elements, the hall and the stairwell are closed off and the sink and a bathtub become available. Partition D can be seen left from the stairwell in Fig. 7, middle row.

Partition E is effectively a sliding door to the bathroom, for access from Schröder's bedroom.

Partition F is another sliding door that separates the living room from the bedroom. After the children had moved out, this bedroom was converted to a kitchen. During the restauration of 1985 it was brought back to its original state.

Partition G consists of two glazed elements that sit on top of the balustrade. The two elements slide, after which one unfolds to form a corner. Apart from the glazed elements on top of the balustrade, two smaller sliding and folding elements could be deployed inside the balustrade to close off the stairwell from the living room completely. The transition can be seen by comparing the photographs in Fig. 7, top row.

4.2. Inhabitation

Truus Schröder had lived in the house for most of 60 years when she passed away in 1985. When her children had moved out, she rented out the ground floor rooms, while she lived on the first floor. Until the end of her life, she used the movable partitions to shape and reshape her living space, and this continuous use arguably made her an expert in operating the flexible space.

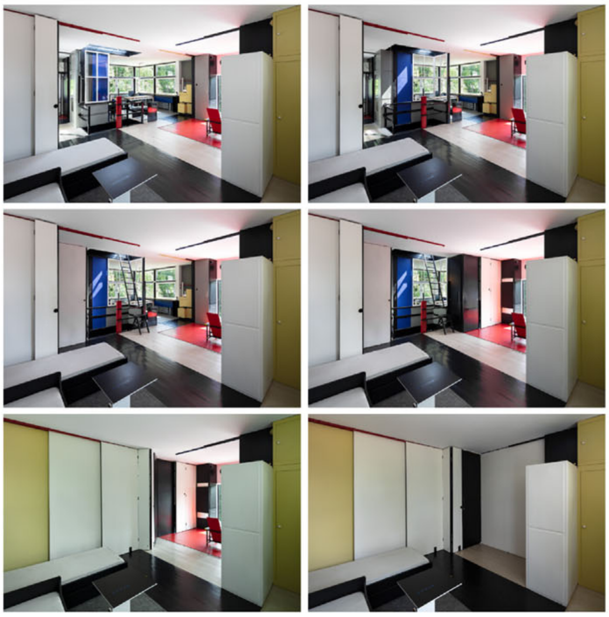

Fig. 7 Interior view of Rietveld Schröder House, stages of deployment of movable partitions. Looking across the first floor, from girls' room in west corner to living room in east corner. Centraal Museum Utrecht/Stijn Poelstra.

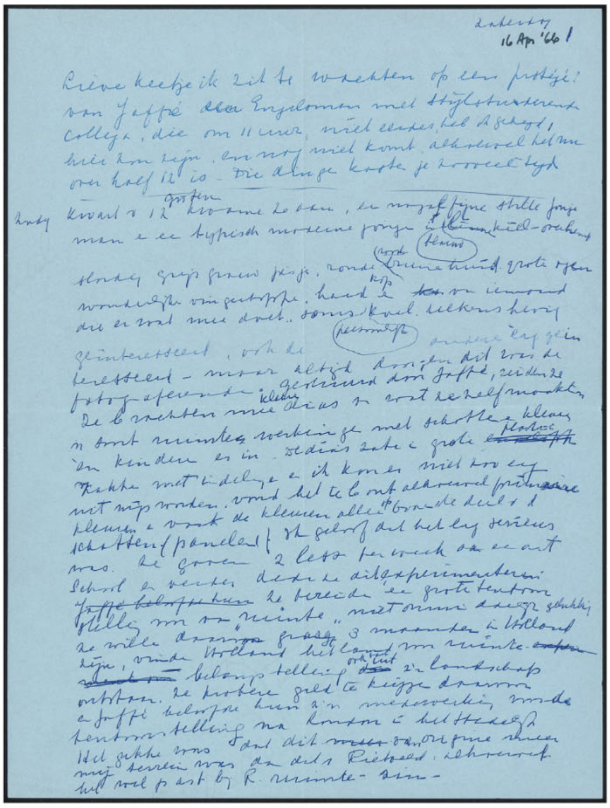

Fig. 8 Page one of six from letter Truus Schröder to daughter Han, dated April 16, 1966 (D1884). Rietveld Schröderarchief/ Centraal Museum Utrecht.

Jessica van Geel, who studied the archives of Truus Schröder, explains how the house allowed Schröder to play with the space (2018). In the chapter *Ruimtekunstenaar* she writes that retracting all partitions in the morning would allow the light in from all sides. And on cold winter days all partitions could be closed to keep the warmth inside. When her son had to do homework, his room would be made by deploying some partitions. When adults were talking and the children wanted to play, a large play area could be created from their combined bedrooms. And one partition could be positioned to be used for video projections.

Schröder has spoken in interviews about the design of the house, but very little is known about her experience of living in the house and operating the partitions. Recently a trove of almost 800 letters has been transcribed that were written by Schröder to her youngest daughter Han, who was living in Switzerland and later in the US. The letters were written over a period of more than 40 years and there are snippets in these texts that give us some indications of day-to-day life in the reconfigurable living space.

In the letters, Schröder hardly mentions using the partitions or changing the living space, which could indicate it was such a normal part of her using the house that it did not register to write about it to her daughter, who had after all lived in the house with her. And this is also what she writes in a letter from 1966 (see Fig. 8), referring to movable partitions more generally: It is all quite normal and natural and nothing new to us, but it is rarely encountered anywhere else, or is it? (Schröder, D1884).

4.3. Resistance

When the partitions are mentioned in the letters, it is often related to them not functioning as intended. Schröder writes for example about a derailed partition and asking visitors to help her put back the partition on its rails (D2010); about the carpenter Gerard mentioning that two partitions were in need of new rollers (D2134); or about jerking a cupboard forward to unblock a partition (D2173). In 1976 she writes: The partition between the red room and bedroom was derailed. This happens about twice a year when someone makes the wrong move with one of the doors, or something is misplaced behind my wardrobe. The daughter of Mrs. Draad was also here for a few hours, and the three of us got it back in without much effort, but working together (D2343).

The mentions in Schröder's letters of the broken partitions confirm first of all that the partitions were in use at the time—they would not derail if they weren't used, and it would not be worth mentioning their malfunctioning if the partitions were inactive. It is significant that the partitions were used by Schröder throughout her time living in the house, because it indicates, first, that they were a fundamental part of the living space. And second, the long time using the partitions contributed to her skilful operation of the partitions and configuring space. According to Van Geel (2018), the partitions were the result of Schröder's input in the design, while Rietveld had invented how they were positioned in the space and how they were made. Maybe Schröder kept using the partitions because of her sense of authorship, or her ongoing belief in the underlying ideas of modern living that led to the partitions. Or simply because the reconfigurability worked so well. But it seems the partitions had throughout the use of the house been a critical part in how it operated. Thus, Truus would have been impeded by a stuck partition, and so they were repaired time after time.

The suggestion in one of the letters (D2134) that some rollers needed replacing soon, suggests that they were worn, rather than broken (Fig. 9). Schröder may have spoken about the partitions to Gerard van de Groenekan, a carpenter and long-time employee of Rietveld, as she would have felt that moving the partitions was different than normal. After using the partitions for a long time, it is safe to assume she got intimately familiar with their peculiarities (perhaps one squeaked, or another rumbled when it moved). Because of the function of the partitions, and their deliberate use, the physical sensation of moving the panels would have also been related to her use of space. Having a bedroom for the night, or a large living space for the day, could be felt through the resistance of the rollers on the rails and the inertia of the partitions. Any changes to this habitual sensation, would affect the sensation of creating space. It is not unimaginable that a lubricated or supple movement would make the space feel more open, and that a scuffed movement would make it feel more constrained.

We could say that the movable partitions with their mass and size, with their rollers, their hinges and with the rails on the floor and ceiling, form the materiality of the reconfigurable space, that make the shaping of the space tangible. With increasing mass the elements of the partitions will be harder to bring into motion and to stop again. With increasing resistance of the rollers on the rails, it requires more effort to keep them moving—a misplaced item or a skewed wardrobe will cause additional resistance. Other senses are involved too, as moving the partitions will create sounds and the changing positions of the elements will affect the light conditions. Moving a partition is an active form of perceiving the space. Like any form of sensing requires some form of movement (or the sensation would just dissipate), perception in the enactive view (e.g., Noë, 2004), is part of an active process that requires an agent to move in the world and to interact with it. Not just does the interaction with the partitions allow the occupant to perceive the space as it is at any given moment, but moving the elements and the related sensations bring forth a perception of the changing nature of the space.

Fig. 9 Replacement of roller at the bottom of movable partition during repair works in 2019. Jurjen Creman.

4.4. Moulding space

On a few occasions, Schröder does write in her letters about using the partitions to change the space. For example, in 1966 she writes about how the partitions allow her to use the space differently: The strange thing is, these days I have discovered something new with the partitions, a little open, a little closed, because I don't need the large undivided space so much when I am alone (D1884). And in 1968 she writes how a particular partition is used different than before: It is now half past two in the afternoon and the fog gets denser and it looks cold. How lucky to be in this house!! Nowadays I often open the partition along my bed a fair bit (the one opposite the stairs) (D2003).

Schröder writes in 1976 about a routine and a related emotion that involve the state of the partitions: When I wake up in the morning, I go to the kitchen and slowly make tea. I get a zig-zag chair from the living room, close the sliding door, and place the chair against it. With my back to the partition, I look gleefully at the pan rack with mostly pans I got from you. And blissfully I drink my tea there (D2327). Notice that she uses sliding door and partition interchangeably here. And in the same letter, she writes about her use of the space and the configuration of the partitions: At that time, in the red room, I have already opened the sliding door to the bedroom as I try to distribute the warmth of the night across the two rooms. I hardly get in the living room anymore, but I live in the combination red room — bedroom. I try to temporarily make the red room a little homy (D2327).

Where Malafouris discusses the engagement between the potters and the clay in forming pots and vases, he writes: "The potter's perception-action loops and movements are dynamically coupled and resonate with the affordances and physical qualities of the material at hand" (2014, p.150). Even though Malafouris discusses a process that is practically held in the hand, with a material that is extremely malleable, we might extend the idea of a dynamic coupling to that between the materiality of the changeable space and its occupant. It is possible then to see how material engagement applies to Truus Schröder living on the first floor of the Rietveld Schröder House.

Having become skilful at operating her living space, Schröder would think about changing her space in terms of what the house afforded her. She would create a bedroom by exerting an exact amount of force on a partition to get it moving, then feel the rolling resistance of the wheels on the floor and the friction with the guide rail at the ceiling, and stop the movement at just the right time. All the while, she would experience the nature of the space changing. A large open space with natural light entering from three sides and above, would partition after partition, transform into a closed plan with smaller rooms and windows on one, or maximum two sides. And that this engagement with the materiality of the house exceeded the creation of space becomes clear when Schröder writes, in a parallel with the Chinese river houses, how she used the partitions to influence the indoor climate, distributing warmer air to where she wanted it.

Schröder would change the space in whatever way the house would let her. We may think of the guide rails and the hinges not as restrictions of movement, but as possibilities for change. The house allows it to be used in a certain ways, and it offers these ways to the occupant. Schröder's interactions are therefore not attributable solely to her, but the interactions are an interplay between her and the house. As she skilfully moves a partition, she actively perceives the space in ways that are afforded by the house. The agency for change lies between them, it emerges from the interactions, as it does between the potter and the clay. Compared to the flexible clay it may seem that the discrete movements of the partitions in the house offer less degrees of freedom for interaction. But even though the positions and open and closed states of the partitions had been architecturally predefined, the writing of Truus Schröder shows that within those constraints, there is a wide range of options and experiences that have allowed her to—even after 50 years of use—discover new ways of using them.

5. From Rietveld to robot

In a letter from 1975 Schröder recalls from memory the state of the partitions in the context of something else. She writes to her daughter: Light from the lamp shone on the grey partitions of the living room. They were closed and it was a beautiful backdrop (D2300). After 50 years of living in the house, the movable partitions had likely become deeply ingrained in her awareness of the space, so much so, that her memories of specific experiences included the configuration of the space. Is it even possible to transfer that level of experience to something more universal, that would apply to occupants of robotic architecture more generally?

An important aspect of what we have seen in the Rietveld Schröder House is that the occupants were physically involved in the transformation. Their pushing and pulling activated the movements that led to the changes of the space. These are very human actions. Because the occupants walk on two legs and have arms, they are able to push and pull the elements along their rails. The house was designed to allow the occupants to do this. In one of the letters that has been cited before, Schröder reflects on a conversation with two visitors from overseas, that came to study the house: He said that to do it yourself (moving the partitions), and not just to push a button, is what makes it so good. That is a human need, to get movement, change of space, change of what you see and experience. And because this does not exist in most places, people drive in their cars without purpose, from here to there. They then see change, but don't actually do anything for it (D1884).

The interactions in the Rietveld Schröder House are of a kind that require a physical engagement—they involve the occupant do something beyond pressing a button. This kind of interactions, in ways that are natural to us, allow occupants to perceive the materiality of the mechanised systems and let it inform their actions. Understood this way, we might extrapolate the importance of the interactions in the Rietveld Schröder House to contemporary buildings where transformation, mechanisation or automation are design requirements. This could apply to the indoor climate, as would be relevant in many buildings for human occupation, or to the configuration of space, as in the Sapporo Dome or the Ori tiny houses with robotic furniture. As a way of example, three approaches are sketched that could achieve this.

A first approach develops the now familiar system of retractable walls. Given the development of modern building technology and adopting a material engagement approach to the design of a reconfigurable building, we could imagine that certain operations would be assisted rather than completely taken away from human interaction. If the situation asked for, say, large and heavy wall elements to be moved, those elements could be equipped with a force-sensitive drive mechanism. Any force an occupant would apply to move this wall, could be amplified as to give the human superpowers, but still maintain feeling with the actual movement of the element.

A second approach would be to inject modes of feedback into otherwise mundane operations, such as the handling of a door. The more conditions between inside and outside a building are diverging, for example, the more resistance a door could offer to being opened. This would present a mediated engagement with a door, allowing an occupant to feel in-situ and in normal building use, what in fact a series of sensors around the building would have registered. In this case the materiality of the mechanised system would artificially be varied to affect the perception of the occupant.

A third approach concerns the operation of artificial lighting in buildings. Most building occupants are used to flipping an on-off switch to operate the electrical lighting in a space. But if light is one of the most important aspects to even experience space, the level of control most occupants are allowed over how a space is lit seems rather limited. If for example occupants were invited to direct a light source in order to light a space, or to move it through the building, a direct experiential relation would emerge between the effect of lighting on the space and our particular way of moving through a building. Our understanding of the space would now come to be through a more active way of sensing, facilitated by the building.

These sketches suggest that beyond the supposed intelligence of the *Generator Project*, of *Soft Architecture* or of industrial greenhouses, there might be another way to consider building cognition, that is by definition much closer to the occupants because it involves their active engagement with the building. In a contemporary setting, the reconfigurability of the Rietveld Schröder House could have been automated. A single button, or probably an app, would allow the occupants to choose a configuration, and motorised partitions would all move to the agreed positions. But it were the visitors in 1966 that told Schröder that doing it yourself was what made it so good. We could interpret *good*, as allowing the intertwining to occur—-where our acting in the world, our natural form of sense making, is the mode with which we shape and reshape the space in which we live.

6. Conclusion

The Rietveld Schröder House, as occupied by Truus Schröder, shows us that a building from 1924, built well before the establishment of computers and electronic robots, had a capacity for mechanical transformation that would be effectively enacted throughout the occupancy by

Schröder. The design of the house included the means to manually operate several movable partitions that could significantly alter the character of the space by functionally dividing it into separate rooms.

The house needs occupants for it to operate, and it invites them to use the partitions, creating spaces for use by day and night. The occupants need the house to operate in this way, allowing them the privacy of separate bedrooms and a comfortable and beautiful living space during the day. To employ a phrase of Malafouris: sometimes it is the occupant that becomes the extension of the house, and at other times, it is the house that becomes the extension of the occupant. Agency in this understanding of the relation between occupant and building, should not be attributed to the human occupant that pulls and pushes the partitions in place, nor to the building that allows and invites these interactions: "there is a constitutive intertwining between intentionality and affordance" (Malafouris, 2013, p.149). Agency emerges when skilful occupants interact with the materials, or the material systems of the building.

This view on agency as emerging between occupants and building could lead us away from a predominantly digital approach to automation and self-control in buildings and take us towards a strategy of carefully designed affordances that activate occupants as extensions of the building. Where humans—by virtue of being human—naturally extend, buildings can be *designed* to do so, using the very technology that makes them buildings. Rather than adding layers of digital augmentation to make a building artificially intelligent, we can now imagine building cognition to be activated by facilitating engagement between the physical building and its occupants.

The material engagement perspective, explored in this paper for the case of robotic architecture, allows us to move beyond simplified representations of human occupants and provides a much-needed clarification of the problem of agency in occupied buildings by ascribing it to neither building nor occupant, but to the process of interaction between them. To design buildings as robotic and develop building cognition, building designers can adopt this perspective and then turn to the materials and material systems they already know.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

I would like to thank the reviewers for their constructive feedback on the first version of this paper. I would like to thank Kjell Yngve Petersen for his ideas and Natalie Dubois for granting me access to the archive.

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