Investigating the Evolving Robot-Building Relationship via a Past-Present-Prospect Model

Junjie Chen[a], and Weisheng Lu[a]

[a] Department of Real Estate and Construction, The University of Hong Kong, Hong Kong, China
E-mail: chenjj10@hku.hk, wilsonlu@hku.hk

Abstract –

Architects and construction engineers have long been intrigued by a future where robots become pervasive in the built environment. Recent technological advancement has made this once utopian vision appear more feasible than ever. However, in the discourse of construction robotics, there seems to be insufficient discussion on the relationship between robots and buildings, the two key entities involved. This study delves into the robot-building dyad by taking a historical perspective to examine how their interactive dynamics evolves over time: (a) from an objectified dualism in the past, (b) to an increasingly blurry boundary in the present, and (c) to a prospective symbiosis with mutual benefits. We argue that this shifting dynamic is underpinned by large-scale digitalization and the empowerment of artificial intelligence. Blue-sky prospective scenarios are discussed, where the robots become an inherent part of the building (like the MEP system), or the building itself becomes a robot (like Howl's moving castle). It is our hope to stimulate further discussion on the critical robot-building relationship, gaining a clearer view of which could help overcome the theoretical dilemma hindering wide-spread robotization in the built environment.

Keywords –

Construction robotics; Robot-inclusive built environment; Robot-building dynamics; Robot-oriented design.

1 Introduction

The architecture, engineering, construction and operation (AECO) sector is facing enormous challenges in recent years. Deeply rooted in the complexity and fragmented nature of the industry, its productivity has been stagnant over the past 20 years [1]. The problem is further exacerbated by the lack of skilled labor force, and the increasingly stringent environmental requirements imposed by climate change. To make the situation even worse, many developed economies in the world are experiencing simultaneous deterioration of their building mass and demographic profiles, which is usually referred to as a "double aging" issue [2]. The aging building stock is awaiting proper maintenance or redevelopment on the one hand; and on the other, the shrinking population fails to provide solid workforce for facility upkeep.

Robotization offers a promising solution for the demographic challenge, as well as performance improvement in the AECO sector. For their superiority over humans in terms of consistency, precision, efficiency, and durability, the use of robots is expected to enhance productivity, ensure safety, and reduce wastes [3]. The benefits of robotization have been recognized from early on. In 1980s, pioneering attempts were first made to deploy robots in construction, with Japen as the leading player [4]. These explorations were profit-driven in essence, and thus were largely spearheaded by industrial practitioners. It was not until ten years later that the academia started to follow up. Signified by the establishment of The International Association for Automation and Robotics in Construction (IAARC) in 1990, systematic research efforts have been made to examine construction robotics from a theoretical perspective. The research input has been stagnant afterwards due to technological limitations, but the advancements in AI and automation in recent years re-attract significant attention to this area.

Despite its ups and downs, the discourse on construction robotics seems to be predominantly technology-oriented. Seldom has previous research taken a broader view to examine the relationship between robots and buildings – the two core entities explicitly expressed in the terms "Construction Robotics". Clarification on this somewhat overlooked dyad is essential because of a mutually reliant but also exclusive nature. They are mutually reliant, in a sense that the robots require the physical environment provided by the building to carry out their activities, whereas the building depends on the robots to materialize, inspect, and maintain. At the same time, the distinctive differences between their inherent characteristics also lead to a series of compatibility problems, whether it is regarding the autonomy level, functional purposes, or just the sheer size of them.

The few attempts to research the topic mainly happened during late 1980s and early 1990s. Back then, the field of construction robotics was still in its infancy. Inspired by the success of robotics in manufacturing, research at that time tried to draw useful experience by separating the building as individual entity from the dyad and comparing it to the production line [5]. Similar to "lean" production in the manufacturing industry, Koskela [5] proposed a process improvement in construction to embrace robotization, but the fragmented and project-based nature of construction makes it more difficult to achieve standardization. Warszawski and Sangrey [6] conducted an in-depth analysis on the respective features of industrial robots and building activities, and proposed possible adaptations of the construction process and building components for efficient applications of robots. Skibniewski and Nof [7] evaluated the readiness of existing construction environment for robotization, and recommended required changes in work organization and construction system. Despite the foundation laid by these pioneering studies, the robot-building relationship has never been formally defined and investigated. Nor has it been examined via a systemic framework in terms of how the relationship evolves over time.

To fill in the gap, this paper aims at examining the dyadic relationship between robots and buildings and its evolvement through a historical perspective. A "Past-Present-Prospect" model is conceptually proposed, which views robots and buildings as dynamically evolving entities that change with the advancement of technologies such as digitalization, industrialization, and AI. The research contributes to the field of construction robotics by theorizing current dilemma faced by construction robotics as a robot-building compatibility problem, and paving the way to its resolution with a clearer view on the robot-building relationship.

2 A conceptual model of the evolving robot-building relationship

A "Past-Present-Prospect" model is proposed to help interpret the evolving robot-building relationship, as shown in Figure 1.

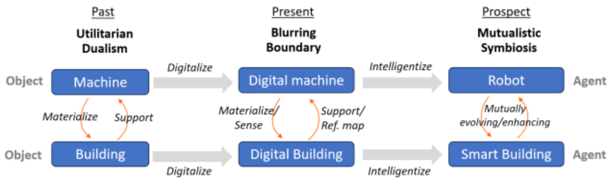

Figure 1. Conceptual model of evolving robot-building relationship.

The study of a subject matter would not have been possible without a clear definition of it. This is also the same when it comes to investigating the robot-building relationship with a historical perspective. The connotations of term "robot" and "building" shift gradually over time, and the scope of objects they refer to does not remain static. For the sake of discussion, we tend to adopt the broadest possible definitions of both. According to the Cambridge Dictionary, a building is a structure with walls and a roof; it can also refer to the process or business of making structures. As for robots, they are generally accepted as machines capable of carrying out a complex series of actions automatically. Despite the varying level of autonomy (e.g., Teleoperation, Supervisory control, Autonomous) [8], an object has to be a machine to become a robot.

As shown in Figure 1, with the risk of over-simplification, both robots and buildings are going through a process of transformation from objects — passive entities that cannot react to external stimulus, to agents — proactive entities with the ability to perceive, plan, and react.

In the past, a robot is nothing more than a deaf-and-dumb machine. Despite being through several revolutionary innovations in terms of their power source (from horse power, to steam and to internal combustion) [9], they were used merely as objective tools to materialize the built environment. The building, on the other hand, is solely made of bricks and mortar [10]. As objects, they can neither sense nor think, let along reacting to a change of the environment. With this objectified nature, the relationship between the machines and buildings is purely utilitarian. Machines are used to construct the building, and the building, as gradually being materialized, offers the physical environment where the robots operate.

At present, with the arrival of the digital era, this relationship gradually changes. A widely accepted but less radical solution is to retrofit existing machines and buildings with an array of digital technologies, in particular the ability to sense intrinsic or environmental changes [11]. As they are being digitalized, the boundary between robots and buildings are becoming vague. The interaction between digital machines and digital buildings not only happens in the physical space, but also in the digital world. This is because the robot can simultaneously sense the built environment and update it to the corresponding digital model as it is being materialized. The other way around, the digital building model, e.g., a building information model (BIM), not only serves as an environment model in the virtual space useful for robot simulation, but also provides a reference map for the robots to perceive their environments.

In the long run, as robots and buildings become gradually intelligentised, they would eventually become agents. On the one hand, the machines will eventually become robots in the most rigorous sense, meaning that they are able to sense environmental changes, to process and interpret them, and to response independently. On the other hand, the once bricks-and-mortar structures will be turned into smart buildings, which perceive and proactively response to internal (e.g., occupancy) or external changes (e.g., weather, sunlight). This dyad would then eventually become a mutualistic symbiosis, where they are nurtured by each other, and mutually enhanced. However, as a millennium-old profession, construction is deeply rooted in its history, local culture, geographical conditions, etc., and notoriously reluctant to changes. The road to autonomy (and the resulting symbiosis) would be by no means easy. Therefore, researchers [11, 12] have suggested distinct paradigms, which either propose an incremental shift based on existing mature tools and techniques, or strive for a radical change by adopting emerging technologies.

3 Past-to-Present: Blurring boundary between robots and building

The shifting robot-building dynamics from the past to present is underpinned by digitalization. Augmented by an array of digital technologies (e.g., smart sensing, automation, IoT, CAD, simulation), the once deaf-and-dumb machines and buildings are empowered by a sensing ability to understand a change of their environments and their digital representations for simulations. They thus become digital machines and buildings.

The various construction machines used in the building sector evolve as the broader industrial context changes. From an energy source perspective, they have gone through a transformation from being steam-driven to diesel-driven. The latest equipment of computer systems and various sensors elevate them to another level as digital machines, which are able to perceive their own operating status and external environment. When it comes to a digital building, interpretation concerning its definition, and connotation varies. Watson [13] confined the scope to only include a digital model that contains structured information of a physical building, whereas others consider a building augmented by an array of IT infrastructure (e.g., a building control system) as a digital building. This study accepts both interpretations, and defines a digital building as an IT-augmented man-made structure, and its digital representation used in various phases of project cycle.

The digitalization of machines and buildings means they can escape the constraints imposed by their specific physical embodiment. Therefore, interaction between the digital machines and digital buildings no longer remains at a materialism level, but enters the realm of cyber space. This allows the digital models of the machines and buildings talk to each other, and boundary lying in-between becomes blurry. On the one hand, the digital machines not only materialize the buildings, but can also map their surroundings simultaneously along the way; on the other hand, the digital building not only serves as the physical environment indispensable for the machines to operate, but also provide a digital model of the environment to empower the machines (e.g., to understand the environment).

3.1 Mapping buildings with digital machines

A major stream of recent works has been focused on sensifying traditional construction machinery. They are aligned with the incremental approach proposed in [11, 12], which renovates legacy machinery with suite of sensors and computing units. The purpose is to turn the machinery from purely a production tool to instruments with both production and measurement utility. Examples can be drawn from a field called intelligent compaction. In these studies, an array of sensors is installed to a conventional roller used for earthworks/pavement compaction. A typical setup includes an accelerometer mounted on the drum to infer material compactness from vibration, a GNSS unit to track position of the measurement, and some other sensors to collect values deemed necessary, e.g., temperature for asphalt pavement [14]. Thanks to the empowerment of sensors, the rollers can measure whether the materials have reached a desired level of compactness as it carries out the compaction work. Therefore, the moment the compaction finishes, a quality map of the entire working area can be expected. Such sensory augmentation goes beyond compacting machines. Any mechanical-based construction machinery can be given senses to with the help of modern computing instruments. Niskanen et al. [15] developed a 2D profile-augmented excavator, which can dynamically map earthwork surface as it operates. Sun et al. [16] sensified a dozer system with RTK GPS and inertial measurement unit (IMU) to collect machine pose information for construction guidance. The digital machines not only materialize the built environment in a physical sense, but also enrich the digital building/infrastructure model by constantly updating its condition information from the physical world.

The mapping function of digital machines does not stop at the construction phase. They have a critical role to play in facility operation and maintenance as well. These include, but not limit to, flying drones to inspect high-rise façade [17], and quadruped robots or unmanned ground vehicle (UGV) for indoor inspection. In many cases, such robots still rely on humans to remotely control their movements. With high-resolution cameras or LiDAR scanners onboard, they are able to collect first-hand data of the facility condition. These data are then automatically processed by AI, which can detect defects of various types (cracks, dampness, spalling, etc.). 3D reconstruction and registration techniques are then applied to incorporate defect information (semantics and geometries) into the digital building model such as BIM. Figure 2 summaries a typical workflow.

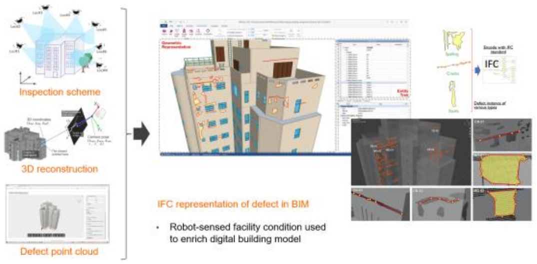

Figure 2. Workflow of mapping building condition with drones.

3.2 Empowering machines with digital buildings

The other around, a digital building can empower digital machines in various ways. Most notably, a digital building model like BIM can contribute to robot perception of its surrounding by providing a readily available reference map. Two typical problems for robot perception are a) positioning and pose estimation, and b) object recognition/scene understanding.

In terms of robot positioning, several previous studies attempted to explore BIM as an internal world model to estimate the robot's spatial location and orientation. However, there is a cross-domain gap to overcome, which is caused by distinct texture and appearance differences between BIM and its corresponding real-world scene. To address this domain gap, end-to-end training-based approaches have been applied to directly regress robot pose information from BIM renderings [18]. A different approach is to use BIM renderings as a pool of space-aware features that can be compared with real-life photographs for pose estimation. Ha et al. [19] used high-level visual features extracted by CNN as registration targets to avoid the domain gap. Chen et al. [20], on the other hand, proposed a neural rendering approach to turn textureless BIM renderings into photorealistic ones with vivid texture. The synthetic images are not only more plausible to humans, but also more machine-readable (see Figure 3). Rich feature correspondences can be found between robot-collected photos and the synthetic renderings, which then allows pose estimation by solving a typical PnP problem.

By positioning current robot view in BIM, the rich semantic information from the digital building model becomes easily accessible for the robot's perception of the world. This typically involves: (a) Extracting current view from BIM; (b) Overlapping it onto camera view; (c) Retrieving semantics of arbitrary pixel in BIM; (d) Facilitating robot perception with the semantics from BIM. Figure 4 shows the perception of a drone in a building façade scene, where no training has been conducted for object recognition. Instead, it purely relies on semantic information from BIM.

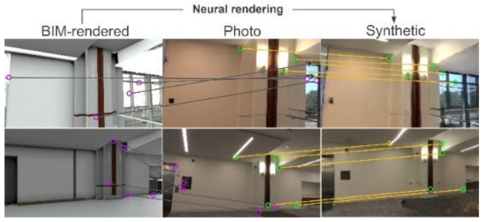

Figure 3. Addressing domain gap between BIM and real scene via neural rendering (with SIFT as an example) [20].

Figure 4. Aligning aerial photograph with BIM rendering to facilitate robot perception.

4 Present-to-Prospect: Towards mutualistic symbiosis as intelligent agents

Looking ahead, both robots and building would eventually become agents with the ability of independent decision-making and autonomy. As agents, they will form a mutualistic symbiosis, where robots and buildings would rely on each other to grow and develop, and benefit from the association. To embrace this future, we need to (a) make robot smart, (b) make building smart, and (c) facilitate robot-building communication. Thanks to the advancing AI, many of these transformations are underway [21].

4.1 Making robot smart

Despite rapid development in the field of robotics, delegating robots fully with independency and autonomy remains risky and challenging. This is even the truth in the built environment with high occupancy dynamics, spatial complexity and affordance diversity.

It is thus imperative to make robots smart, especially regarding spatial intelligence [22], an ability for the robots to process spatial data, make predictions and act upon those predictions. As robots always function in a specific space context (e.g., the built environment), this spatial intelligence is particularly relevant. Connectivism and symbolism have long been two mainstream schools of thoughts in AI. While the super performance of neural networks in recent years has put connectivism under the limelight, it is believed a convergence of top-down symbolism and bottom-up connectivism is critical when it comes to empowering robots with spatial intelligence.

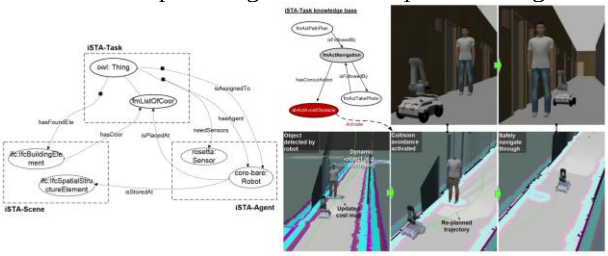

Figure 5. Knowledge graph for smart robot-based facility inspection.

Figure 5 shows a top-down knowledge graph for robot-based facility management (FM). It outlines how the robots should behave when facing different scenarios in the built environment. Combined with bottom-up connectivism neural networks (e.g., for human detection), it can empower robots to carry out advanced actions such as collision avoidance with humans in the corridor. FM robots are just an example. Thanks to the rapid advancement of AI, the entire AECO sector is adopting robots with increasing level of autonomy (LoA). Melenbrink et al. [11] conducted a comprehensive review of existing onsite autonomous construction robots, and rated their LoA according to a categorization system adapted from autonomous vehicle.

4.2 Making building smart

To make building smart, a plethora of studies have been conducted, either from a theoretical perspective or from an implementation standpoint. Ranging from smart home [23], cognitive building [24], to cognitive facility management [25], numerous terms have been proposed to explain and foresee how the once brick-and-mortar buildings would become intelligent with the empowerment of AI.

Different from the current digital buildings that are only able to sense and collect operational data, a smart building evolves to another level where it can react and response to a change of its external environment and internal occupancy situation. Such smart buildings can be built from the bottom up by the empowerment of intelligence to discrete building components (e.g., precast beams, columns, and walls) [26], and even to fine-grain construction materials [27]. As building components are intelligentized, they would eventually become agents that can better co-work with the robots as a material-robot system [28].

Once commissioning, the smart building can comprehensively analyse the data collected by the various sensors scattered in the building, and then independently make decisions given the current conditions. The decision would next be issued, activating actuators around the buildings to implement the decided plans. These smart building reactions can be as trivial as light control responding to room occupancy, or can be much more complicated in scenarios such as window curtain control in response to changing natural lighting. Figure 6 shows a smart living system adopted in the WCH student hostel project at The University of Hong Kong (HKU). It has integrated a smart light control system, an electronic lock system that can be controlled by students on their mobile phones, and a smart camera system to ensure safety of the dormitory area.

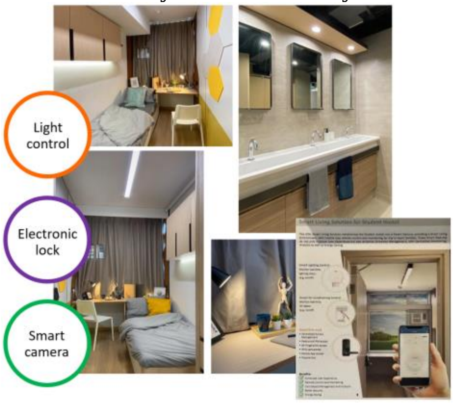

Figure 6. Smart building system adopted by HKU WCH project.

4.3 Facilitating robot-building communication

Smooth communication is a premise for taking advantages from each other between robots and buildings, further leading to the formation of the symbiosis. To this end, the robots and buildings need to be able to talk to each other, which entails a common language between the two parties. This, unfortunately, is not the case in current practice, as robotics and AECO industry have developed their own data schemas, i.e., the Unified Robot Description Format (URDF) for robots, and the Industry Foundation Classes (IFC) for buildings.

To mediate the gap, a potential solution is to create a common data environment between the robots and buildings based on IFC. The basic idea is to represent robots and relevant information with IFC, so that they can be compatible with mainstream building software for various applications, such as design, remote control, digital twin and so on. Figure 7 shows a model view definition for robot representation in IFC. Following this data model, a format translator has been developed to convert many of the existing URDF-based robot representations to IFC.

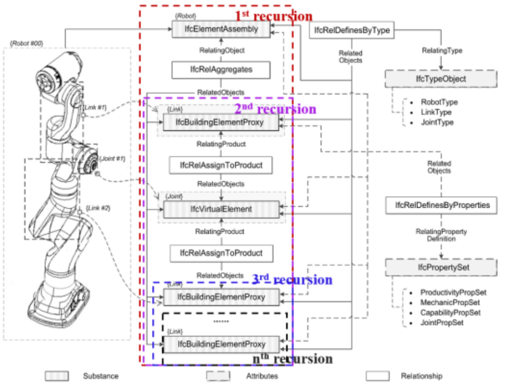

Figure 7. Model view definition for IFC-based robot representation.

Such an IFC-based common language can facilitate robot-building communication, enabling various applications such as robot-inclusive design. Many studies have underscored the need of rethinking building design and process improvement for robot adoption [29-31]. However, software tools are in absence to develop designs catered to the specificity of each project for robotic construction. IFC-based robot-building communication offers a means to resolve the fundamental interoperability problem in developing those design tools. Figure 8 shows an example of robot-inclusive design of a building MEP system. With the common language of IFC, the model of an MEP inspection robot can be directly imported into Revit. Since the robot and building models are in the same design software, one can easily identify clashes between them, and then timely adjust the design.

For construction/operation phase applications, as the IFC robot and building models are integrated in the same environment, the exchangeable information can be leveraged to enable application such as remote control. For example, as shown in Figure 9, by clicking a point in the building model, the robot can automatically navigate to that position. The robot arms and grippers can also be teleoperated by a remote human for more sophisticated tasks such as construction waste sorting.

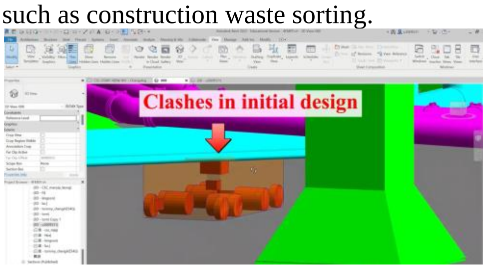

Figure 8. Inclusive design for MEP inspection robots.

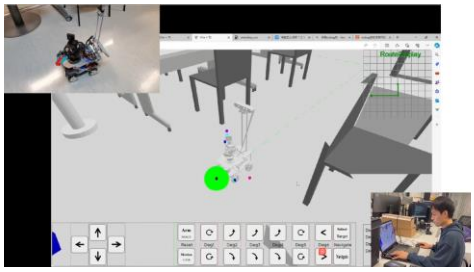

Figure 9. Robot teleoperation enabled by freely exchanged building information.

5 Discussion

Influenced by technological development, societal expectation, and cultural perception, the dyadic relationship between robots and buildings evolves over time. From a purely utilitarian dualism as objects, to increasingly blurry boundaries, and to a prospective mutualistic symbiosis, this shifting interactive dynamics calls for a fundamental rethink of what define a robot and a building, how they should be designed, and where their boundaries lie. Table 1 provides two different models to frame future robot-building relationship, and technological development required for their realization.

5.1 Robot as an inherent part of building

A way to formulate the problem is to consider robots as an inherent part of buildings. This requires a systematic thinking to take robots into account from the outset of building design. A comparable analogy can be drawn from the MEP in a building system, which needs to be considered at the design stage via multi-disciplinary collaboration for clash detection. This is gradually gaining attentions in the field of robotics. For example, in 2022, an office building called 1784 was constructed in Seongnam City, Korea, which claims to be the world's first robot-friendly building. The building was designed to allow a large population of autonomous mobile robots operating within it, and therefore is equipped with robot-friendly infrastructure, which includes world's first elevators exclusively for robots. During the Beijing Winter games in 2022, robots were widely deployed. Among them, there are robotic systems hanging from the ceiling in cafeteria, serving select cuisines individually. This is another example scenario where robots become part of the building system.

Table 1. Models and research required for future robot-building relationship

Model	R&D required

Robots as building parts	Integrated design and engineering, AI-powered generative design, IoT, BMS, Human-robot co-existence
Buildings as robots	Electromechanical building materials, Ambient intelligence, Urban science and design

Further research and development (R&D) are needed to widely deploy robots as parts of the building system. Fundamentally, an integrated mindset is required to design and engineer the building system with robots integrated. The robot design considerations, along with the uncertainty when it interfacing with buildings, is expected to significantly complicate the system design. The complexity can be mitigated by emerging AI-powered design tools. Once the robot-integrated buildings are put in place, the building management systems (BMS) will need to be substantially upgraded to ensure the robot swarms are under control, where the IoT is essential for robot-robot and robot-building communication. In the long run, with more and more robots entering the living environment, the problem of human-robot co-existence would become prominent to research for well-being.

5.2 Building as a robotic system

Taking a more radical step, would the building itself ends up becoming robots? We have been seeing buildings increasingly empowered and computerized by the use of electronics and mechanics. In certain smart home settings, it is already a reality that the furniture and layout of a room can automatically transform to meet occupants' need. In 1970s, when the idea of modular building was still popular in Japen, landmark projects such as the Nakagin Capsule Tower have been designed and developed following the broader context of urban metabolism. The Nakagin building was designed with intentional impermanence, following the principles of growth and transformation over time [32]. With all the mentioned precedents, a robotics building that can move and transform in response to external environment might not be as futuristic as it sounds after all.

R&D is required in the following directions. First, the science of building materials needs a fundamental rethink. For a building to sense and response like robots, its constituent components should be of electromechanical characteristics, so as to be compatible with the current silicon-based artificial intelligence. Second, ambient intelligence is critical to make computing pervasive in the built environment. In doing so, spontaneous response becomes possible. Last but not least, as robotic agents, the dogmatic view of building being places would be challenged. This will then pose new questions about what forms a city, which requires systemic research from a larger scale of the urban system. With continuous research input from the above directions, the Howl's Moving Castle will perhaps become a reality in the foreseeable future.

6 Conclusions

Despite being the most critical dyad in the robotization of the built environment, the relationship between robots and building has seldom been researched systematically. This paper fills in the gap by taking a historical perspective to examine the evolving interactive dynamics between robots and buildings over time: (a) from an objectified dualism in the past, (b) to an increasingly blurred boundary in the present, and (c) to a prospective symbiosis with mutual benefits. The shifting dynamics is argued to be underpinned by large-scale digitalization and the empowerment of artificial intelligence. Blue-sky prospective scenarios have been discussed, where the robots become an inherent part of the building, or the building itself becomes a robot. The paper hopes to stimulate further discussion on the critical relationship between robots and buildings. Its clarification is deemed indispensable to overcome the theoretical dilemma hindering wide-spread robotization in the built environment.

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