Document Version
Final published version

Citation (APA)
Ağırsoy, Ö. F., Triggianese, M., & Kaan, C. H. C. F. (2025). Space, Time, and Affordance: Experimenting with computational methods to visualize human-building interaction. In S. P. Hernández, S. Boccolini, & P. C. Herrera (Eds.), *SIGraDi 2025 Proceedings Book* (pp. 173-184). SIGraDi -Sociedad Iberoamericana de Gráfica Digital .

Space, Time, and Affordance: Experimenting with computational methods to visualize human-building interaction

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Abstract. Despite growing interest in human-building interaction (HBI) studies to improve performance and comfort in building operations, existing architectural design and representation methods primarily focus on static layouts and material forms, overlooking the spatio-temporal, invisible characteristics of interactions. This paper proposes a novel visualization method grounded on affordance theory, dynamic network graphs to computationally model HBI in Grasshopper. Using a multipurpose educational space as a case study, the study illustrates a multilayered workflow that visualizes material components, immaterial affordances, and dynamic multimodal interactions in three programmatic scenarios. Resulting representations and animations spatialize the footprint, distribution, and modalities of afforded interactions in relationship with occupant patterns. This scenario-based, computationally-driven HBI model supports the qualitative assessment and strategic allocation of sensing, actuation, and control interfaces, identifying spatial opportunities and challenges. This study offers an architecturally informed HBI visualization framework to enhance interdisciplinary communication and critical early-stage decisions in designing responsive environments.

Keywords: Human-building interaction, Computational design, Visualization, Responsive environments, Affordances

1 Introduction

The complexity of buildings and their services requires the collaboration of multiple stakeholders, experts, engineers, and architects in the integrated design process (Moe, 2008). Architects, engineers, and inventors have relied on visualization methods for centuries to understand systems and complexity as part of intuitive thinking, streamlining communication, and problem-solving processes (Ferguson, 1994). The design teams developed numerous tools for drawing and modeling building elements, forms, materials, and layouts to deal with the complexity of buildings and their services in design (Banham, 1969). Spatial analytics and visualization methods, such as space syntax, utilize dynamic graph networks for evaluating spatial layouts, their variations, and configurations (Hillier et al., 1976; Hillier, 2015). Computer-Aided Design (CAD) technologies facilitate new representation tools and generative integrated design methods (Kalay, 2004). BIM models allow design teams to visualize all the anatomical details of forms, materials, and machinery, facilitating clash detection, performance simulations, and optimizations to avoid problems during and after construction (Eastman et al., 2011).

Recently, IoT devices, embedded systems, AI, and ubiquitous computing have become an integral part of architectural space, extending the dynamic interactions between humans, buildings, and the environment (Wiberg, 2015). Human-building interaction (HBI), an extension of human-computer interaction (HCI), is a developing interdisciplinary research field focusing on the interplay between human experience and the built environment (Nembrini & Lalanne, 2017; Alavi et al., 2019). Integration of new sensors, actuators, communication networks, and smart devices in buildings extends forms of sensing, agency, control, and feedback in HBI, aiming to enhance the well-being of building occupants and optimize environmental performance and efficiency (Becerik-Gerber et al., 2022). As illustrated in Figure 1, the architectural space becomes a medium of bodily interaction (Spyropoulos, 2016), blurring distinctions between material-immaterial, digital-real, and visible-invisible layers of interaction (Wiberg, 2018). Spatializing HBI becomes essential in architectural practice for designing responsive environments, which necessitates integrated methods for visualizing the immaterial, invisible, spatio-temporal interactions.

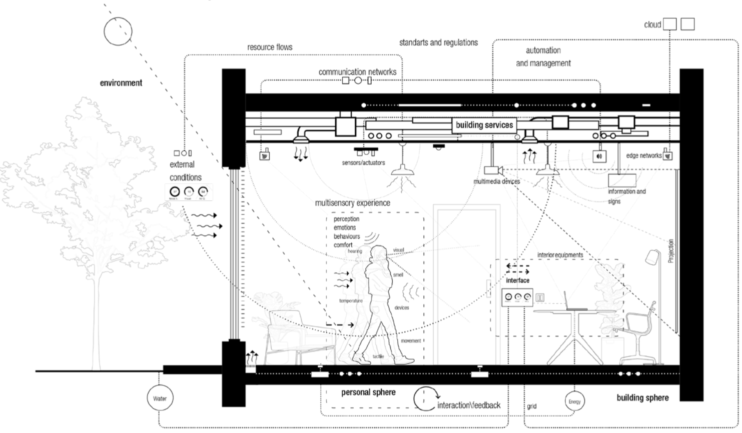

Figure 1. Architectural framework of the material and immaterial layers of interaction.

However, existing architectural drawing, information modeling, and spatial analytics methods have been primarily developed to visualize material forms, static conditions, or physical layouts. They have shortcomings in representing

HBI. Conventional methods lack the dynamics of human and non-human agents in space, solidifying the inanimate perception of architecture (Latour & Yaneva, 2008). Time and change in building dynamics are underexplored in architectural research and experimentation (Kolarevic & Parlac, 2015). Occupant behavior models, except for movement models, are still not an integral part of the typical design workflow of buildings (Gaetani et al., 2021). Simulations are usually considered as a separate technical task by architects, missing clear, iterative, representative results and smooth integration with existing tools to inform the decision-making in the early design stages (Attia et al., 2009; Gaetani et al., 2021). Similarly, building automation and control studies mostly focus on optimization of individual services instead of an integrated approach that addresses the interaction between systems (Park et al., 2019). It remains an important question for this study how visual methods can extend design methods for HBI.

This paper addresses this gap by proposing a new predictive, computational design method to support the visualization of the dynamic and complex nature of interactions between digital technologies, physical systems, and dynamic agents. By combining the affordance theory and computational design, the proposed method develops a generative HBI model for qualitatively assessing, visualizing, and spatializing ambient interactions in early (re)design stages. The results of the three-stage representation method are utilized in the case study of a multipurpose hall within a university building. Mapping of affordances, information flows, and interchanges between architectural space, systems, and people generates a form of knowledge representation to visualize the spatial footprint of communication and control. The presented HBI model aims to effectively visualize interaction to provide occupant-centered insights for architectural design practice and collaboration.

The theoretical framework of the study is developed based on complex dynamic systems theory, where interactions are fundamental to generate novel structures, properties, and information (Erdi, 2008; Juarrero, 2023). Complex systems emphasize dynamic relationships between systems and the environment over time, emerging new properties in the whole, which cannot be deduced from its individual components (Erdi, 2008; Juarrero, 2023). Buildings and their services are great examples of complex dynamic systems, as they operate within the intricate interplay between the environment, human behavior, and technologies. Similar to complex systems, the architectural design process deals with *ill-structured problems,* where representations are crucial for breaking down complex design problems (Simon, 1973).

Drawing on Actor-Network Theory, Latour and Yaneva(2008) argue that *a building is not a static object but a moving project,* transforming over time through a complex network of interactions between humans and non-humans. They criticize conventional architectural design and drawing methods for reducing buildings to a fixed image, failing to represent their dynamic and evolving nature. By using the metaphor of Étienne-Jules Marey’s *chronophotographic gun,* which was invented to capture the movement of bodies by recording multiple moments over time in a single photograph, they call for similar architectural tools and methods to reveal the complex, dynamic transformations of buildings. Similarly, Easterling (2021)'s notion of *Medium Design* emphasizes designing the spatial *interplay* between systems, forces, environments, and technologies instead of individual objects and problems to augment productive combinations. Affordances here become an essential concept for revealing the relational capacities of potential interactions.

The term affordance was coined by James Gibson (1979) in environmental psychology as: *The affordances of the environment are what it offers the animal* and he continues that *… what we perceive when we look at objects are their affordances, not their qualities.* Don Norman (2013) later adapted the concept for design, defining affordance as *interaction potentials* between the *user and an object*, changing the design focus from formal attributes to relational properties. Davis (2020) extends this theory by introducing mechanisms and conditions of affordances, moving from what things afford to how things *demand, allow, or refuse* specific interactions to operationalize these relations between users and technologies. For instance, a window typically affords the action of opening for view and ventilation, but automated control may constrain this user agency, or wi-fi routers afford signals within a certain range, allowing or limiting end-user devices to connect with internet networks. In this study, these mechanisms help to spatialize the affordances of building components through footprints, flows, and digital networks. Grounded on this relational ontology, the proposed visualization method utilizes this theoretical framework to move beyond static forms to represent the dynamic medium of interactions between humans, architectural space, and digital technologies.

2 Methodology

This paper utilizes a case study method to present the computational design workflow for visualizing human-building interactions. A case study is adapted to test the visualization framework with varied parameters and scenarios for methodological validation. The multipurpose hall within the Faculty of Architecture building at Delft University of Technology (Netherlands) is selected for demonstrative purposes due to its public character, dynamic, multipurpose program, international users composed of students and staff, as well as the empirical observability of occupant and event patterns. It provides architectural layout and evidence for developing detailed representations. The multipurpose hall is located centrally on the west side of the building, hosting public presentations, exhibitions, and informal daily activities (Figure 2). During daily use, it serves both as a transition space between the main circulation, the west entrance with coffee bar, and classrooms, in addition to facilitating a flexible space for studying, seating, and relaxing for its users. The hall also hosts public presentations, thanks to its big central amphitheater, and provides a flexible area for temporary exhibitions and events. Both the building and the hall are public and accessible not only to students and staff but also to visitors.

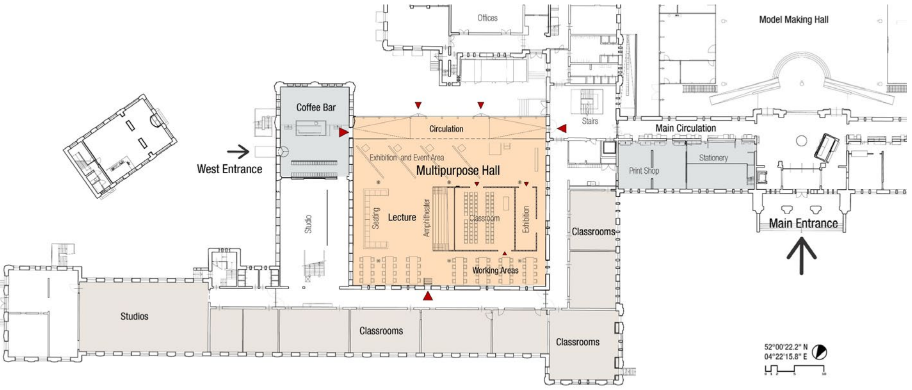

Figure 2. Architectural layout and functional program of the multipurpose hall.

For the visual framework, the vocabulary of network graphs and space syntax, composed of nodes, links, networks, and fields, is utilized to visualize both static components and dynamic operations (Figure 3). The coverage, footprints, and proximity are modeled and animated in time through dynamic parameters of line, arc, range, colors, gradient, boundary, meatball, and proximity functions in Grasshopper. The direct and indirect interactions between agents and building components are illustrated with varying line types and colors. Passive reactions, in which users lack control (Haque, 2023), are visualized with dotted lines, whereas the active interactions, where agents get feedback, are visualized in dashed lines. Different modalities of interactions (visual, audio, kinesthetic, digital) are illustrated using distinct colors and graphical cues. Human library components, such as custom preview colors, lineweights, dash patterns, and gradients, are used for visualizing networks.

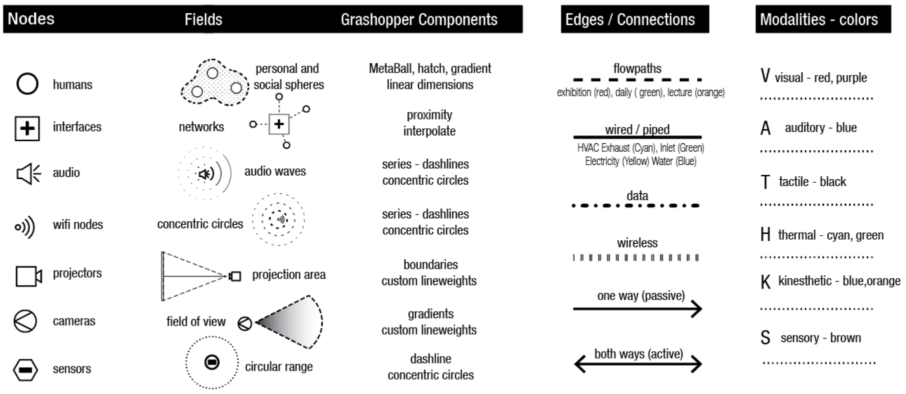

Figure 3. Graphical cues for visualizing interactive components

The proposed HBI visualization workflow is organized into three stages. The first stage primarily focuses on the material components and static objects in the architectural plan drawing. It illustrates architectural layout, building elements, furniture, hardware, devices, and projection of building services, including HVAC installations, electrical trays (Figure 4a). The second stage, on the other hand, focuses on the immaterial components, referring to digital, invisible, and dynamic affordances of building components (Figure 4b). The drawing not only annotates the allocation of routers, multimedia devices, sensors, and control interfaces in the drawing but also illustrates their visual, acoustic, digital, or kinesthetic affordances. The drawing maps the projective footprints of multimedia devices, coverage of sensors, the field of view of cameras, and the range of audio devices with gradients and concentric circles in Grasshopper to visualize the topological condition of afforded interactions. Illustrating components with their sensory footprints reveals the territory of ambient intelligence, hence spatializing their affordances.

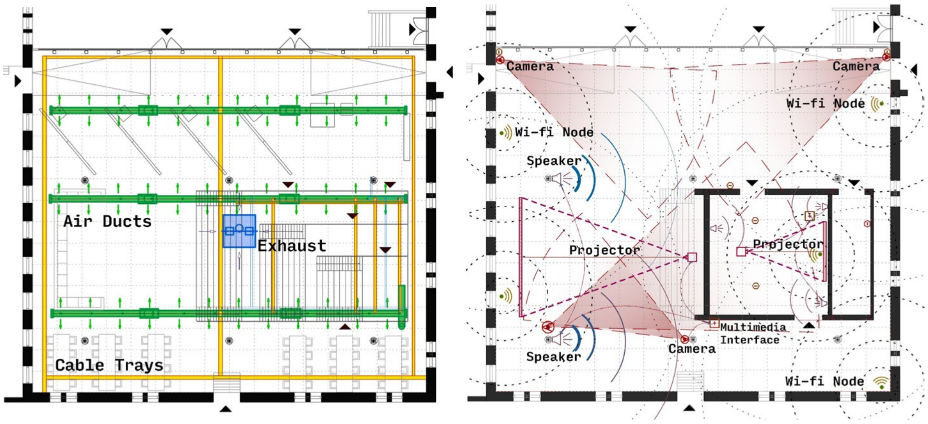

Figure 4. (a) Architectural layout and ceiling projection of building services. (b) Footprint of multimedia systems and digital devices.

In the third stage, occupancy is visualized through flow paths and human agents on the floor plans (Figure 5a). Since the main objective is not to optimize real-world data but to develop a design visualization framework for HBI, occupancy is mapped using program-specific flow paths. These paths are manually annotated, juxtaposed, and sequenced based on ethnographic observation and photographic records over a 20-minute time period in each scenario. The distribution of people and their movement in three scenarios of public lecture, exhibition, and informal daily settings are annotated to define distinct flow paths in Grasshopper to represent expected occupancy patterns. To ensure legible visualization and comparable data across scenarios, the number of agents is standardized at 25 per scenario. Occupants illustrated as agents with 60 cm diameter nodes in Grasshopper are animated along the flow paths to represent their presence and movement within the space. The

MetaBall definition of grasshopper is utilized to represent both the personal (1.2 m) and social spheres (3.6 m), which merge with others when the agents get closer to each other, representing local density and social clustering of agents. Size of the cluster connected to gradient colors from blue (small) to orange (bigger) to annotate the field of group formations. Ultimately, these three layers are juxtaposed to animate multimodal interactions between building components, digital footprints, and human agents (Figure 5b).

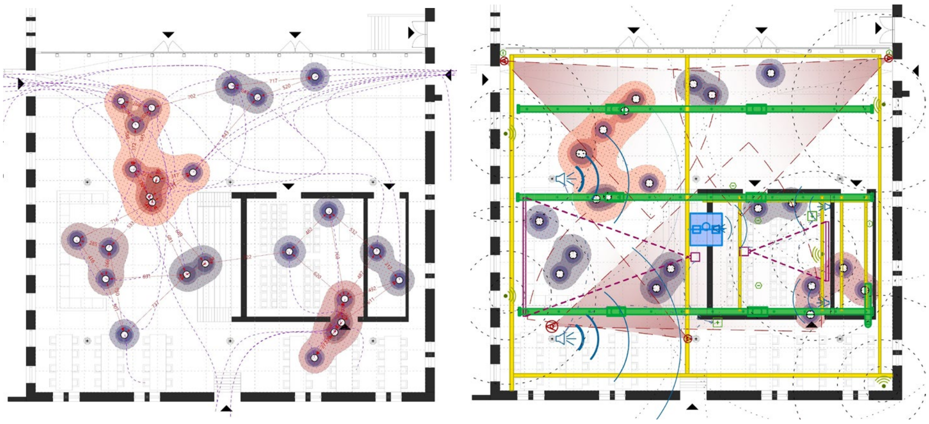

Figure 5. (a) Occupant moments animated along the flow paths. (b) superimposed model of occupant patterns with material and immaterial affordances.

To inform long-term spatial design decisions, these dynamic interactions are also visualized as heatmap drawings. The flow paths are divided into 20 steps to visualize the relative duration of 20 minutes with 1-minute step increments. Inspired by Marey's chronophotographs, all the steps of the agent movement are superimposed into a single image to translate dynamic, ephemeral occupant patterns into long-term analytical heat maps (Figure 6). This technique illustrates the spatio-temporal distribution and density of human flows within the space. It visualizes the afforded networks, revealing the space as a topology of dynamic interactions between humans and the building.

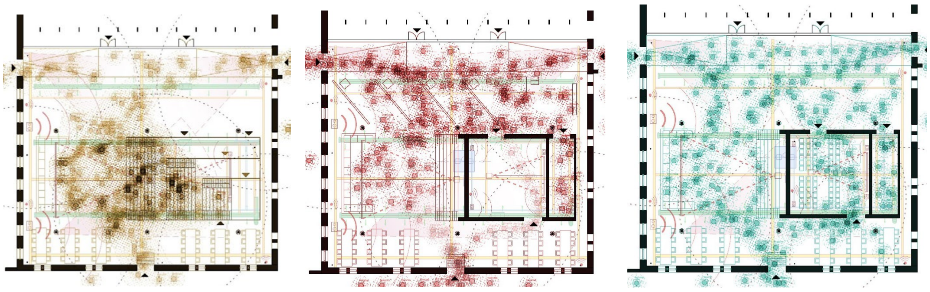

Figure 6. HBI chronophotographs in three scenarios. (a) Public Lecture (Yellow-Brown). (b) Exhibition Setting (Red). (c) Informal Daily Use Setting (Green).

3 Results

The results present the experiments with the computational model for visualizing human-building interactions. The proposed three-stage methodology provides a multilayered representation of HBI. The first layer focuses on the architectural layout and building services. The second layer visualizes the invisible fields by spatializing the affordances through footprints of control and interaction. The third layer shows human presence and movement in three scenarios. The final stage combines these layers, presenting the dynamic interplay of physical and digital components, revealing interactive relationships/potentials between occupants and the spatial environment. Representing both material (furniture, architectural elements, devices, and services) and immaterial components (affordances, flows, occupancy patterns, audiovisual, and sensory footprints) reveals how different systems and agents communicate and exchange information. The visuals in Figure 6 map three different programmatic scenarios of HBI. The occupancy patterns generate not only the spatial distribution of dynamic and static components, but also qualitative insights into the distribution, proximity, number, and intensity of interactions over time for design decisions.

The public lecture setting visualizes a scenario where occupants use the hall for public lectures. Occupants densely cluster in the central amphitheater, presenting a highly localized, densely networked, mainly static, large group dynamic. Audiovisual systems, such as projection devices and speakers are actively used during lectures. During the presentation, the number and quantity of interactions stay stable, whereas the durations of interactions among people, space, and services increase. The visuals serve as an indicator to detect potential problems, such as cooling, ventilation, air quality, and overload on building services and digital devices, due to the static, densely located occupancy. Since occupants remain passive and lack control over systems, the environmental control systems and services should be designed intelligently to respond to these potential needs for improving their experience.

The exhibition setting presents a scenario of the exhibition opening in the hall where occupants mainly gather around the exhibition posters. Here, occupants present a moderately centralized, heterogeneous network, with low-density clusters. The occupants have more dynamic behaviors in the exhibition scenario than in lecture settings. Since their movement is relatively slow, their footprint densifies around the exhibition materials. Different sizes of occupant groups form and dissolve through in-person interactions. Multimedia systems operate at an ambient level for audio and visual needs in this scenario. The hall and specifically the exhibition area require precise control of lighting and multimedia systems to display materials and generate immersive experiences for accommodating visitors.

The third visual presents the informal daily use scenario with a lack of one specific programmatic function. This scenario refers to a mix of daily circulation, resting, and working activities. In this scenario, occupants are more scattered within the space, forming individual and localized clusters. This results in a more homogeneous distribution within the space, combining static and dynamic behaviors in the form of a highly decentralized network. The hall partially serves as a transition area around the circulation zones. Due to the constant movement, the number of occupants fluctuates constantly, the duration of interactions is shorter, resulting in relatively smaller footprints with more uniform distribution on drawings. Some students also use the hall as a working space, setting up around the desks for longer periods. They connect to power and wireless networks with their personal devices, which requires continuous and robust wi-fi coverage and communication within the big space. Since occupant patterns and interactions are decentralized in this scenario, there is a low chance of overloading specific systems and services, yet their stagnant behavior requires varying environmental controls on thermal conditions and personalized task lighting in working areas.

4 Discussion

The proposed HBI model presents the preliminary results from ongoing research on developing a novel visual language for designing spatial interactions. Beyond conventional drawings of architectural forms and layouts, the model represents the dynamic interplay and communication of users and building components, resonating with Latour and Yaneva's (2008) call for new visual tools to capture the architectural space in action. This framework offers a new approach to affordance theory by revealing spatial mechanisms and the timely conditions of afforded interactions (Davis, 2020). The model integrates the occupants beyond traditional flow diagrams, highlighting their agency and interaction potentials within the architectural space (Gaetani et al., 2021). By combining spatial, digital, and occupancy data, the model provides a multilayered, topological representation to support qualitative comparisons between programmatic scenarios. Therefore, the resulting visuals spatialize feedback mechanisms by revealing invisible networks to strengthen the productive emergences between technological, social, and spatial systems.

Overall, the computational method advances design optioneering and HBI visualizations by offering a meta-representational language for designers, which can be applied to different architectural typologies. This workflow acknowledges the recursive and iterative nature of the architectural design process, highlighting the architectural drawings agency (Evans, 1997). It provides a repeatable workflow allowing rapid adjustments and iteration of different user scenarios, interior layouts, and digital system allocations. In this sense, the method extends space syntax analysis (Hillier, 2015) by incorporating immaterial, digital layers of building components (Wiberg, 2018). It provides an *architect-friendly* alternative for envisioning HBI in spatial decisions, without complex, data-intensive simulations, particularly in the early design stages, which often lack real-world operational data (Attia et al., 2009). It can serve as a powerful communication tool for stakeholders for dealing with complex tasks in the integrated design process (Moe, 2008). The generated HBI model could potentially support architecturally informed human-centered design decisions for the following spatial implementations:

- **Building interfaces and multimedia systems:** Evaluating the allocation of controlling, sensing, and actuating interfaces and multimedia systems, in terms of visibility, accessibility, coverage, range, and distribution for improving building design and operation.
- **Spatial Intelligence:** Designing spatial affordances and constraints in occupant, device, or system-level interactions for advancing ambient intelligence.
- **Building services:** Advancing design and integration of building services through time-based, programmatic scenarios for local climatization, ventilation, heating, cooling, and lighting needs.
- **Spatial Experience:** Designing human interaction, control, agency and feedback for improving human experience, satisfaction, and comfort in relation to human activity within the space.
- **Privacy and Surveillance:** Critical adoption of digital technologies by visualizing digital footprints of security, surveillance, and control for responding to safety and privacy concerns in buildings.

Limitations and Next Steps: The proposed model remains limited to architectural plan drawings and graph-based analysis. It currently does not include the cognition, behavior, and motivations of the users, which are essential for understanding spatial experiences. Human movements are defined based on manual annotations for demonstrative purposes, yet this computational method features a flexible model that can integrate more robust agent-based simulations or real-time data for existing buildings. Moreover, while the method in this research primarily serves as a qualitative, comparative design communication and collaboration tool, it also offers potential to quantify proximity, number, distribution, and network of interactions between agents and components for data-driven predictions and multi-objective optimizations. Although the public character and multipurpose program of the case study were helpful, its legacy services and systems limit higher levels of user interaction and precise data collection. Future work aims to extend this preliminary visual language towards comprehensive HBI models by integrating real-time and long-term sensor data to validate assumptions. The visual methods will be tested in real-world interdisciplinary collaborations to assess design teams' comprehension and ability to solve conflicting interaction problems.

To conclude, this paper addresses the gap of an overarching representational method for visualizing HBI in the early architectural design process. Affordances and complex dynamic systems theory, combined with computational tools, are used to propose a computational method for mapping the spatial mechanisms of control, feedback, and communication. This computational method is demonstrated in a multipurpose educational space.

The model reveals both visible and invisible dimensions of interactions through building components, occupancy patterns, and sensorial footprints. Animated interactions and their superimpositions reveal a dynamic temporal aspect in spatial representation, which enables insights for designing architectural experiences. Ultimately, the method aimed to provide a new visual method for architects and interdisciplinary teams to integrate HBI into the design stages of intelligent responsive environments.

Acknowledgements. This work benefited from the Academic Writing Retreat course organized in TU Delft by Paul Chan, Christine Räisänen, and Marietta Haffner. The specific comments received from Christine Räisänen from Chalmers University were particularly helpful in improving this manuscript.

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