Modularized cyber-physical system as an enabler of interoperable and collective approach for responsive cities

Tomonari Yashiro
Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro, Tokyo, Japan 156-0054
yashiro@iis.u-tokyo.ac.jp

Abstract. This paper discusses the relevance between the sustainable built environment and cyber-physical system (CPS) that are now surrounding us. Previous research suggests that CPS has the potential to enhance the performance to achieve SDGs. However, from the aspect of open building theory, there exist the problems to be solved, such as 1) restricted accessibility, 2) invisible intervention, and 3) difficulty in local customization. The paper discusses the approaches that could solve or at least mitigate the problems. Those are; 1) modularity of cyberspace that clarify accessibility by the specific social entity, 2) transparent inter-connection, and 3) context description & adaptability enhancement by interoperable modules. The paper indicates the principles of responsive cities; those are 1) fair access to the benefits generated by digital brain 2) strictly protected privacy of citizens 3) diversity by an adaptive combination to the context 4) easiness and incentive for new entrants and entrepreneurs. The principles can be satisfied by a dis-centralized system that is supported by the approaches above.

1. Introduction
Due to the rapid progress and diffusion of advanced ICT technologies, we are living in the technological circumstance where the built environment is filled with embedded sensors and mobile and/or web-based application. Prospecting on such circumstance, the author had proposed the idea of "information embedded building" where the users and operators of the building can extract and utilize information from any place of the building (Yashiro 2008, 2009). In a sense, the idea of "information embedded building" represents use-cases of IoT (Internet of Things) in the built environment.

The idea is deployable to enhance the performance of buildings that contributes to achieve SDGs. For example, a machine-learning-based application can optimize the operational energy use of the building by analyzing data from embedded sensors and by controlling actuators in the component of the building (Yashiro 2013). The author termed such technology system as a smart energy management system. The system could be one of the enablers of the zero-emission building (Yashiro 2011), thus, the enabler to double the global rate of improvement in energy efficiency (SDGs 7.3).

Recently, respecting on the social aspect of sustainability, the term "responsive city" is used to represent the cities with the built environment are filled by embedded sensors and mobile and/or web-based application. It is a city that local government and private institution can satisfy the needs of inhabitants by providing information almost anywhere (Williams 2014).

The idea of "information embedded building" is a basis to realize "responsive city". It is an enabler to empower and promote the social, economic and political inclusion of all (SDGs 10.2), to enhance capacity for participatory, integrated and sustainable human settlement management (SDGs 11.3),

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to ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature (SDGs 12.8), and
to improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early (SDGs 13.3)

In case the idea of "information embedded building" (i.e. IoT used in built environment) is diffused, people will live in the two kinds of city: One is a city as a physical existence, and the other is as a city that exists in cyberspace. Whether the ideas could contribute to achieve SDGs depends on how could we link and manage physical and cyberspace integratedly.

However, urban design theories that target physical space and emerging digital city models that originally target cyberspace have been developed by different domains of experts. Consequently, so far, only a few research attempts have been made about the theory on the method to link and manage physical and cyberspace. This paper aims to discuss the architecture that could help to link and manage physical and cyberspace to enhance the performance of built environment relating to SDGs.

2. The world we live in: Techno-paradise that compose of physical space, cyberspace and society

Figure 1 represents the world we live in now. Here entity implies individuals, groups of people and organizations. Since ancient civilization, human beings have belonged to society, and have lived, worked, and played in physical space. Since the end of the last century, people have started to act in cyberspace. Now people participate in society by putting ourselves not only in a particular place of physical place but also in cyberspace. People control the place in physical space by manipulating physical objects, while people control the place in cyberspace by creating, receiving, transforming and sending information. Conventionally, people recognize what is happening in physical space through five senses. Now, people also can identify the events in a physical space through cyberspace by analyzing data from embedded sensors in the built environment. Additionally, due to the diffusion of IoT in the built environment (i.e. “information embedded building”), we can now control things in physical space by sending a command through cyberspace.

The concept of coexistence cross-interaction of physical space and cyberspace is termed as a cyber-physical system (CPS). Figure 1 indicates three dimensions of the world we live: physical space, cyberspace and society. In other words, Figure 1 shows the triangles of CPS and society. Assuming that this triangle could be the framework of techno-paradise in the near future, this paper deploys the following consideration.

Then, how could design and manage this world of triangles so that the built environment could enhance its performance to achieve SDGs?

A theory developed in the relationship between the physical system and society could be the template to prepare the answer to the question above.

3. Open building theory

The theory is originated by John Habraken and is called as “open building” (Habraken, 1972, 1998). As is shown in Figure 2, the physical space of the built environment is subdivided into three levels: Urban Tissue, Support and Infill. In open building theory, the level of decision making is distinguished

![Figure 1. World we live in: Physical space, cyberspace and society](image-url)
and separated by modularization of elements. Stakeholders can freely accessible to the designated level and make autonomous decision making regardless of the decision by other stakeholders who are allowed to access other levels. For example, in Figure 2, stakeholders of urban tissue (e.g. local authority, urban planners), that of support (e.g. architects), that of infill (e.g. residents) are freely accessible to the decision making for urban tissue, support and infill respectively without any intervention by stakeholders of other levels. Open building theory embodies suggestion how the interoperable groups of modularized elements (e.g. components, territories, domains) can enhance the sustainability of the built environment. The theory could be a basis to discuss the architecture of the relationship among the triangles of society, physical space and cyberspace that is illustrated in Figure 1.

4. Problems of built environment related CPS
Then could we extend the scope of open building theory to the world of triangles illustrated in Figure 1? There exist at least the following problems to be solved for the deployment of open building theory to the world of triangles.

- Restricted accessibility
- Invisible intervention
- Difficulty in local customization

The following is the consideration of those problems.

4.1. Restricted accessibility
As is shown in the left side of Figure 3, the relationship between physical space and society has been locally and ethnologically modified over a number of generations since civilization. The boundary of domains of physical space (e.g. walls, doors) are visibly made. Accessibility to specific domains of space (e.g. rooms, facilities etc.) by the specific entity are defined by explicit and tacit code (e.g. unwritten custom etc.) which have been locally brushed up over long years based on consensus among stakeholders (e.g. social custom) and/or by the regime (e.g. regulation) depending on social context. In a sense, physical space has modularized through the cross-interaction with society. Then how about the relationship between cyberspace and society? As is shown in the right side of Figure 3., the boundary of domains is ambiguous; inherently domains are invisible because the architecture of cyberspace is not yet well standardized, though there exist several meta-modelling of the structure of digital cities. So far, in a sense, there is not socially well-recognized rooms and doors in cyberspace. Due to such ambiguity, for the general public, sufficiently clarified answer is available to the following question.

“Which part of cyberspace is accessible for me?”

It could often happen that the access to some area in cyberspace is restricted not because of the clear rejection but by no explicit permission based on the clarified definition of domains. The access control could be beyond public governance. Consequently, there exists the risk that software developers arbitrarily restrict somebody’s access to a specific place of cyberspace. Such
arbitrary manner allows intentional blocking of the entry of competitors who have the potential to provide better service.

4.2. Invisible intervention

In the age when the big-data transaction is made invisibly in cyberspace, probably, some party successfully collect a considerable amount of data through associated data transaction. In the process of IoT, where things in physical space are controlled by cyberspace, very often, commands raised by actions of a social entity are transmitted through the domain of platformer who interconnect and/or assemble data from varieties of sources. Consequently, a platformer can collect and stock varieties of data and could utilize the power of big-data analysis to expand its business opportunity. Such a big-data transaction could be a source of innovation that brings benefit to the stakeholder of the built environment (see Figure 4). However, this process is invisible to most of the general public. It seems to be not acceptable for the most of the people in the world if her/his information is invisibly utilized by an anonymous party who could exclusively concentrate brainpower without which we are not able to operate and manage the world of triangles illustrated in Figure. 1. Such invisibility could generate not only the risk in privacy protection but also allow the invisible intervention by parties who can deal with big-data anonymously. Such intervention can cause some violation of the vision behind SDGs. The concentration of knowledge extracted from the big-data analysis onto the single or the limited number of parties facilitates a sort of oligopoly. Presuming form historically experienced disadvantage or disasters due to oligopoly, an invisible intervention by the limited number of parties could violate the dignity of people and the value of diversified culture due to arbitrary abuse of
big-data. In addition, some anonymous entity probably tries to controls physical space with unjustifiable intention through the invisible intervention. It can raise the security-related risk that objects in physical space lose their controllability.

From the vision behind SDGs and the idea of the responsible city, how facilities in physical space are operated and managed should be based on transparent consensus among stakeholders, and how we live and work should be decided on our own will. Invisible dominance of big data holders/operator could be adversarial challenger against some SDGs such as equal opportunity and reduce inequalities of outcome (SDGs 10.3). Therefore, probable intervention could be problematic for enhancing the social sustainability of the built environment.

4.3. Difficulty in local customization
Harmony with local context is a basis of the sustainability of the built environment because social sustainability can be enhanced if every citizen could have her/his place where she/he could be relaxed by customizing the place comfortable for her/him. Accumulation of individually customized “my places” facilitates the demonstration of the diversity of the district and the city. However, there exist a kind of barriers that confine local customization of places. Those are:
- Insufficient cyber-physical correspondence as for spatial territories, and
- Insufficient interchangeability

4.3.1 Insufficient cyber-physical correspondence as for spatial territories. As it is illustrated in the left graphic of Figure 5, cyberspace can easily define and represent components that correspond to the components in physical space (e.g. structural members, finishes, building services) by using BIM (Building Information Modelling). However, as is shown in the right of Figure 5, cyberspace has difficulties in defining territories that correspond to spatial territories where a set of physical components belong.

![Figure 5. Correspondence between physical space and cyberspace](image)

The control of single components via cyberspace is possible because of the easily distinguishable correspondence between physical space and cyberspace. This situation can be called as “digital twin”. However, integrated control of components that belongs to the same territories is not so easy because it is difficult to define the territories corresponding to the territories in physical space. In terms of spatial territories’ delineation, a digital twin is not yet realized.

The difficulty of the integrated control undermines the opportunity to enhance environmental sustainability through local customization of each place by CPS.

4.3.2 Insufficient interchangeability. The open building theory suggests that interoperable modular are the basis of local customization of each place. Then, how about the case where the objects in physical space are controlled via cyberspace? Generally, the software can provide an interface by which the user can customize respecting on the context. However, so far, the combination of software and physical objects controlled by the software are not universally interoperable due to the difference of protocols; specific software is only workable on the specific group of objects in physical space. For
the method of control via cyberspace, insufficient interoperability among cyber-physical objects generates a barrier that limits local customization to adapt to a specific context.

5. Approaches that could solved or mitigate the problem
Then how could we solve or mitigate the problems? The following is the list of approaches that could be the countermeasures to the problems.

- modularity of cyberspace that clarifies accessibility by social entities
- transparent inter-connection
- context description & adaptable combination of interoperable cyber-physical module

5.1. Modularity of cyberspace that clarifies accessibility by social entities
In order to overcome the problem relating to restricted accessibility, consensus on architecture must be established globally by which we can define the system boundary of domains within which all or specified set of social entities are universally accessible as is shown in Figure 6. Most of the currently proposed and/or diffused architecture of the digital city is composed of the logic of cyberspace. Desired architecture from the aspect of this paper is the architecture that assists in composing consistent relationship among cyberspace, society and society. As it is illustrated in Figure 6., the architecture should provide the framework by which the boundary of domains could be incontrovertibly encircled between the social entities and “the governors of cyberspace (e.g. software developer)”. Universal or at least a broader range of accessibility should be available based on the distinct definition of domains in cyberspace that aims to protect the privacy of personnel and intellectual property in a broader sense. By such modularization of the relationship between cyberspace and society, a broad range of accessibility for specific entities can be clearly defined.

5.2. Transparent inter-connection
The reason why invisible intervention could happen is rooted in the way how we assemble and process the data from varieties of social entities. In many cases of control of physical space by cyberspace (i.e. IoT), useful IoT application service providers also perform the role of platformer. This bundling structure facilitates invisible concentration of data on an application-plus-platform service provider who can access any data that go through the platform. To exclude such a possibility, unbundling of an application service provider and platform service provider is effective. Figure 7 illustrates the example of unbundling of an application service provider and platform providers developed by the author and the industrial collaborators (Yashiro, 2019). Here, IoT-Hub takes the role of platformer by interconnecting the data from different domains (e.g. private clouds). However, the provider of IoT Hub service is not able to access to the data that
goes through IoT-Hub like telephone service providers can not access to the contents of the information transmitted by law. Consequently, transparent data transaction and processing can be made between physical space and society via cyberspace (see Figure 8).

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5.4. **Context description & adaptable combination of interoperable cyber-physical modules**

In order to mitigate the barriers against local customization, the following approaches seem to be effective.

- Context description by defining spatial composition in cyberspace
- Adaptable combination of interoperable cyber-physical modules

5.4.1. **Context description by defining spatial composition in cyberspace.** BIM used from the design to construction focuses on production and assembly of physical components. This focus is a reason why the concept of spatial territories is challenging to be defined so far. If BIM is modified in operational stage of building by defining objects relating to spatial territories (e.g. name and spatial scope of the room) together with their attributes including list of physical components that belong to the spatial territory (e.g. room), cyberspace can embody virtual units corresponding to the spatial territories in physical space (see Figure 9); In a sense, digital twin is established as for territories. It enables integrated control of components in physical space via cyberspace.

5.4.2 Adaptable combination of interoperable cyber-physical modules. Interchangeability supported by interoperable connection presented in Figure 7. as well as digital-twin based on the left of Figure 5, and Figure 9. enables to combine cyber-physical modules adaptable to the local context. The diversity that could be generated by such an adaptable combination can assist local customization of place for stakeholders.

6. **Discussion: Principles that can be enhanced by the approaches**
If we are successful in solving or mitigating the problems relating to restricted accessibility, invisible intervention, difficulty in local customization by the approaches described in the previous clause, we can construct a responsive city based on the triangle framework illustrated in Figure 1. Such a responsible city can satisfy the principles shown in Table 1.

Table 1. Principles that modularized cyber-physical approach can satisfy for responsive cities

|   |                                                                 |
|---|-----------------------------------------------------------------|
| 1 | Citizens and participating organization could have fair access to the information and the benefits generated by digital brain powers through varieties of CPS. |
| 2 | Privacy of citizens is strictly protected, while citizens are assured the freedom to use or not to use the CPS based services (i.e. IoT based service). |
| 3 | Varieties of CPS services (e.g. mobility, healthcare, securities, energy service, etc.) can be collectively combined to adapt to the social, economic, cultural, technological and business context. |
| 4 | New entrants and entrepreneurs are attracted and welcomed as drivers to create the locally customized CPS. |

It should be insisted that the principles shown in Table 1 premises the system illustrated in Figure 10. The system is a dis-centralized system that enables interoperable and collective approach for responsive cities that satisfy the vision behind SDGs.

7. Concluding comment

CPS has a vast potential to enhance the sustainability of the built environment. However, in order to realize such potential, we need to construct the architecture that clearly defines the relationship among society, physical place and cyberspace as is illustrated in Figure 1; this is the architecture based on three pillars; society, cyberspace and physical space. Definition of modularized elements (e.g., components, territories, domains) within the pillars are the significant premise to compose the architecture needed to enhance the responsible city. This paper intends only to raise the concept level of architecture. It should be noted that interdisciplinary collaboration by the specialist around the three pillars is indispensable to make the architecture workable.

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