# Sustainable Development of Heritage Areas:

## Towards Cyber-Physical Systems Integration in Extant Heritage Buildings and Planning Conservation

https://doi.org/10.3991/ijes.v5i1.6623

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**Abstract**—Although architectural heritage reflects the evolution of human civilization throughout history, nevertheless, civilized and social changes of heritage areas in many countries led to their degradation. Historical building management and planning conservation raise two important issues: the restoration and improvement of historical areas features and adopting a framework of sustainable development in heritage regions. Recently a number of processes have arose to aid in the aforementioned problems, namely the heritage building information modelling (HBIM) and the cyber-physical systems approach (CPS), where the latter is believed to achieve great potentials hereby integrating virtual models and physical construction and enabling bidirectional coordination. Since HBIM has recently been investigated through a number of recent research and application, the aim of this paper is to explore the potentials offered by the CPS, to move from 3D content model to bi-dimensional coordination for achieving efficient management of built heritage. To tackle the objective of this paper, firstly, a review of the BIM use in the field of cultural heritage was undergone, Secondly, reporting the existing BIM/HBIM platforms, analyzing cyber-physical systems integration in extant heritage buildings and in planning conservation were performed. Results of this paper took the form of detailed comparative analysis between both CPS and HBIM, which could guide decision makers working in the field of heritage buildings management, in addition to shedding light on the main potentials of the emerging CPS.

**Keywords**— Cyber-Physical Systems (CPS), Heritage Buildings Management, Heritage Building Information Modelling (HBIM), Sustainable Development.

## 1 Introduction

Although architectural heritage reflects the evolution of human civilization throughout history, nevertheless, civilized and social changes of heritage areas in many countries led to severe degradation of such areas. There are many interpretations in the development of heritage buildings and planning; however, there is deterioration in those areas as a result of non-sustainable development and non-specified ranges for the framework development planning.

The approach of Historical building management and planning conservation raises two important issues: the restoration and improvement of historical areas features and adopting a framework of sustainable development in heritage regions. Recently a number of processes have arose to aid in the aforementioned problems, namely the heritage building information modelling (HBIM) and the cyber-physical systems approach (CPS). On one hand, HBIM (Historic Building Information Modeling), a plug-in for Building information modeling (BIM) [1], was introduced as a process for modeling historic structures from laser scan and photogrammetric data [2]. Thus HBIM is specially tailored to the application on heritage buildings and on the long-term management of the built environment [3]. On the other hand, employing the "cyber-physical systems" approach achieves more potential by integrating virtual models and physical construction, enabling bidirectional coordination [4]. This will serve as a digital archive to help in conserving the heritage buildings and to test future development proposals within the context of these historic buildings.

The present study contributes to the body of knowledge by exploring the cyber-physical systems (CPS) approach to innovatively integrate Heritage building information modeling (HBIM) and physical construction. The aim of this paper is thus to explore the potentials offered by the CPS, to move from 3D content model to bi-dimensional coordination for achieving efficient management of built heritage.

The structure of this paper consists of four sections relating to the comparison of cyber-physical systems and BIM, illustrating the possibility to move from a 3D content model to a bi-dimensional coordination for conservation and management of built heritage. The first section introduces the needs of built heritage conservation and management. The second section briefly follows a history of the BIM use in the field of cultural heritage, reporting the existing BIM/HBIM platforms, in order to obtain a 3D representation of extant heritage buildings and planning. The third section contains a summary of analyzing cyber-physical systems integration in extant heritage buildings conservation. Finally, a comparative analysis is being intended between both CPS and HBIM that could guide decision makers working in the field of heritage buildings management.

## 2 Management and Conservation of Built Heritage

In the field of conservation of heritage buildings, a method linked to documentation and management of historical buildings is required to carry out regular maintenance. In the last decade, many traditional surveying methods have been used to record and represent such buildings [5]. Conservation of built heritage is progressively linked to the regular maintenance of buildings, defining the heritage building management as a real necessity. In this view, it is necessary to have a tool that allows to collect, compare, share and manage all the data available concerning the state of conservation of the buildings (surveys, drawings, thematic and historical contents), and where to add future information about maintenance or restoration activities [6].

For historical conservation, digital archive of high quality three-dimensional models would give improvement in the restoration science field. This virtual approach took advantage of the expansion and long-term saving, where cultural heritage needs these data for sustainable monitoring. In particular, the heritages in real environment are irreversibly damaged by environmental disaster or atmospheric damages, which high accuracy 3D scanning could instantly detect. These data of monitoring are the fundamental knowledge for heritage building management. Where the 3D documentation archives the spatial data of cultural heritage in the form of as-built and spatial data. This data include columns, beams, walls, roof and more other geometrical shape, texture and color. Digital archives thus can be used as reference for monitoring and restoration of cultural heritages [7].

The Jing-Tong train station, shown in "Fig. 1", is an example of historical buildings digital archive, where the model was defined through the point clouds from survey stations and its 3D data registered for as-built and environmental drawing documentation, as shown in "Fig. 2".


**Fig. 1.** Point clouds of Jing-Tong Train Station (Source: H.Cheng et al. 2015)

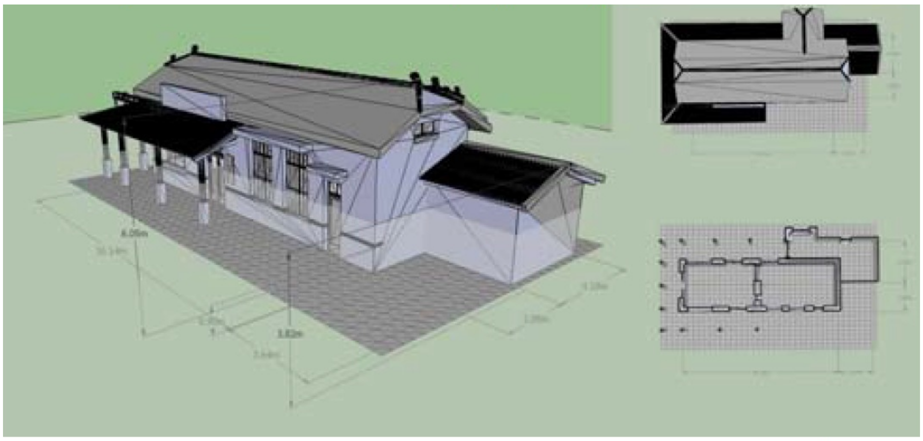

**Fig. 2.** 3D Documentation (Jing-Tong Train Station) (Source: H.Cheng et al. 2015)

## 3 The Use of Building Information Modelling in the Field of Cultural Heritage

In order to improve the framework for 3D modeling, an accurate virtual model of a historic building is digitally constructed, using BIM (Building Information Modeling), where the building is being maintained through its entire lifecycle, including demolition This integration of heritage recording and BIM is now a method to document and manage historic buildings, in which parametric objects are built, taking into account historical data, and layered-in plug-in libraries representing building components [8], [9].

Lately, many developments in the BIM field have been established, where the developed technology and methods challenged the cultural heritage community in the documentation framework. BIM has been a growing development within the past decade in the field of cultural heritage documentation, paving the way towards a future in the virtually built environment. In addition, BIM can also enhance the application of sustainable retrofitting of such buildings in particular, as HBIM provides review of the building's exterior and interior, and it also eases the availability to survey renovations and changes that either took place through different time periods or changes that will take place upon applying sustainable retrofit [10].

### 3.1 The Process of Heritage Building Information System

The HBIM process involves a reverse engineering solution whereby parametric objects representing architectural elements are mapped onto laser scan or photogrammetric survey data. The HBIM process generally includes a number of phases, starting with collecting and processing of laser/image survey data, identifying historic details from architectural pattern books, building parametric historic components/objects and finally correlation and mapping of parametric objects onto scan data and the final production of engineering survey drawings and documentation, (Murphy, M., 2013).

Creating an as-built BIM is considered the first step of applying the HBIM process. It includes a number of steps as follows:

1. Data collection: in which dense point measurements of the facility are collected using laser scans taken from key locations throughout the facility. The product of the laser scan takes the form of a point cloud that represents the coordinates of the scanned building.
2. Data processing: through this phase of the HBIM process, the sets of point measurements (point clouds) from the collected scans are filtered to remove artefacts and combine into a single point cloud or surface representation in a *common coordinate system*. This system is then textured from image data to create a virtual 3D model. Data processing includes surface meshing, texturing the point cloud, ortho-image and digital photo modelling processing separate to laser scan data [11].
3. Geometric modeling: in which the low-level point cloud or surface representation is transformed into a *semantically rich BIM.* The modeling of a BIM involves three tasks: modeling the geometrical form of each element, assigning object category and materials to each element and finally establishing relationship between building elements.
   - Modeling the geometrical form: this process constructs simplified representations of the 3D building elements. In general, this process includes modeling of surfaces (planar surfaces, curved surfaces and extrusions), modeling volumes and modeling complex structures, like windows, doors and ornaments.
   - Representation of Knowledge: there are several techniques that are implemented for the modeling and recognition. In general, the as-built BIM model includes the representation of knowledge about the building objects shape, identities of the objects and their relationships. Regarding knowledge about the objects shape, shape representation could be either explicit, implicit, or parametric, non-parametric or global vs. local. This type of knowledge representation is extremely vital in creating a BIM model, as it provides contextual information to assist in object recognition [12].
   - Relationship modeling: this included establishing relationships between objects of the BIM model. The representation of knowledge about relationship among different objects, includes three different categories of spacial relationships: aggregation, topological, and directional relationships.

## 4 Introducing Cyber-Physical Systems (CPS)

A number of researchers including ( [13] ;[14] ;[15] ; [16] ) have attempted to link virtual models and the physical construction using different data acquisition technologies (e.g. digital cameras, laser scanners, radio frequency identification tags). However, the existing approaches do not offer opportunities for two-way integration or communication between the virtual models and the physical construction. This two-way integration/communication is important for enhancing feedback or controlling the constructed facility. To maintain bi-directional coordination, computational resources are required to tightly integrate the virtual models and the physical construction, such that changes in one environment are automatically reflected in the other. This is termed a cyber-physical systems approach [17].

Cyber-physical systems approach has long been adopted in information systems research, and in other industry sectors. A number of authors have defined the term in different ways, Table.1, summarizes different definitions of CPS that have been introduced by authors through extant literature, from 2006 to 2013.

**Table 1.** Definitions of The Term Cyber-physical Systems

| Literature Source | Author | Year | Definition |
|---|---|---|---|
| "Cyber-physical systems - are computing foundations adequate?." | Lee, E. A. | 2006 | Cyber-Physical Systems are integrations of computation with physical processes [18]. |
| "The simplex reference model: Limiting fault-propagation due to unreliable components in cyber-physical system architectures." | Crenshaw, T. L., Gunter, E., Robinson, C. L., Sha, L., and Kumar, P. R. | 2007 | Cyber-Physical Systems are networked, component- based, real-time systems that control and monitor the physical world [19]. |
| "Cyber Physical Systems: Design Challenges." | Lee, E. A. | 2008 | Cyber-physical systems are dynamic systems that integrate physical processes with computation, often in feedback loops, where physical processes affect computations and vice-versa [20]. |
| "Towards Linking Virtual Models with Physical Objects in Construction using RFID - Review of Ontologies." | Sørensen K. B., Christiansson P., Svidt K., Jacobsen K., Simoni T. | 2008 | Integrating virtual models with the physical components on the job site offers opportunities for improving information handling, thus enhancing access to real-time information or communication between the design and construction team [21]. |
| "Cyber-physical systems: The next computing revolution." | Rajkumar, R., Insup, L., Lui, S., and Stankovic, J. | 2010 | Cyber-physical systems are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core [22]. |
| "Tru-Alarm: Trustworthiness Analysis of Sensor Networks in Cyber-Physical System." | Tang, L., Yu, X., Kim, S., Han, J., Hung, C., and Peng, W. | 2010 | A Cyber-Physical System are systems that integrate physical devices (e.g., sensors, cameras) with cyber (or informational) components to form a situation-integrated analytical system that responds intelligently to dynamic changes of the real-world scenarios [23]. |
| "Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review." | Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., and Dickinson, J. | 2010 | Systems integration has been identified as one of the key approaches to help the construction industry to improve its productivity and efficiency [24]. |
| "From wireless sensor networks towards cyber-physical systems." | Wu, F. J., Kao, Y., andTseng, Y. | 2011 | Cyber-physical systems bridge the cyber world (e.g. Information, communication and intelligence) to the physical world |

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| | | | through the use of sensors [25]. |
| "Towards cyber-physical systems integration in construction." | A. Akanmu | 2012 | Cyber-physical systems approach can be defined as a tight integration and coordination between virtual models and the physical construction/constructed facility, to enable bi-directional coordination. |
| "An RTLS-based approach to cyber-physical systems integration in design and construction." | A. Akanmu, C. Anumba, J. Messner | 2012 | Presented an approach to facilitate bidirectional coordination between physical construction components and their virtual models [26]. |
| "Scenarios for cyber-physical systems integration in construction." | A. Akanmu, C. Anumba, J. Messner | 2013 | Described the role of the cyber-physical systems approach in improving the construction project delivery process through enhancing bi-directional coordination between virtual models and the physical construction. |

Based on reviewing different definitions and authors' contributions towards the evolution of CPS, "Fig. 3," shows a concluded timeline for the different phases of the evolution of the CPS, which would help in the analogy and comparison between this approach and the HBIM process later on .

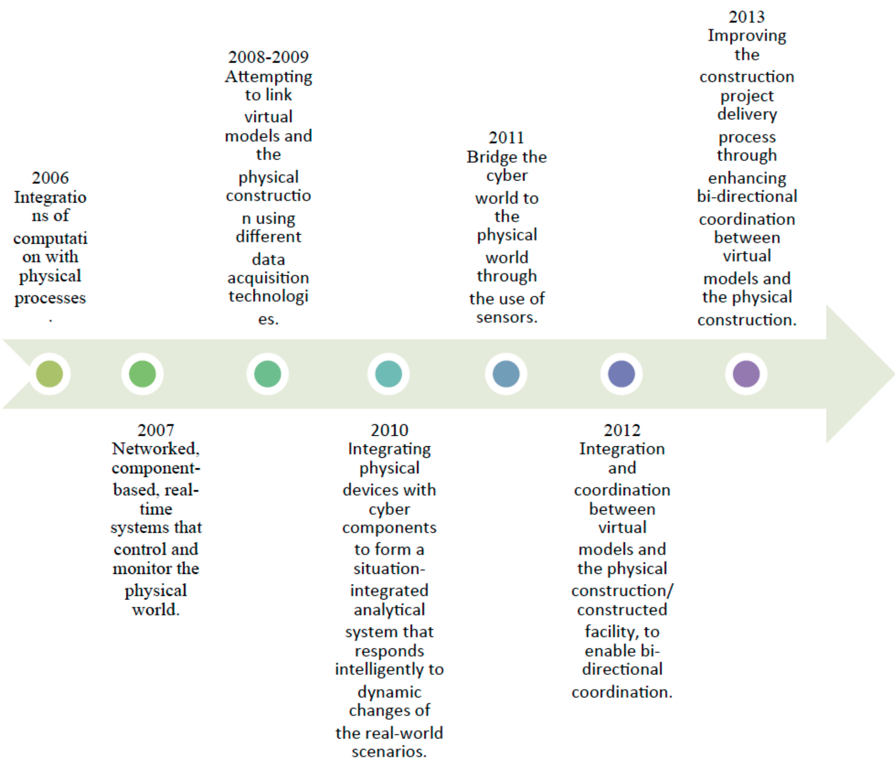


**Fig. 3.** A timeline for the evolution of the Cyber Physical Systems (Source: Authors, based on extant literature)

### 4.1 The Process of the Cyber Physical System

A cyber-physical systems approach consists of two-way integration, shown in Fig.4, the physical to cyber-bridge and the cyber to physical bridge. The physical to Cyber Bridge is the sensing process, which involves using sensors to acquire information about physical components or phenomena (A. Akanmu ,2012).

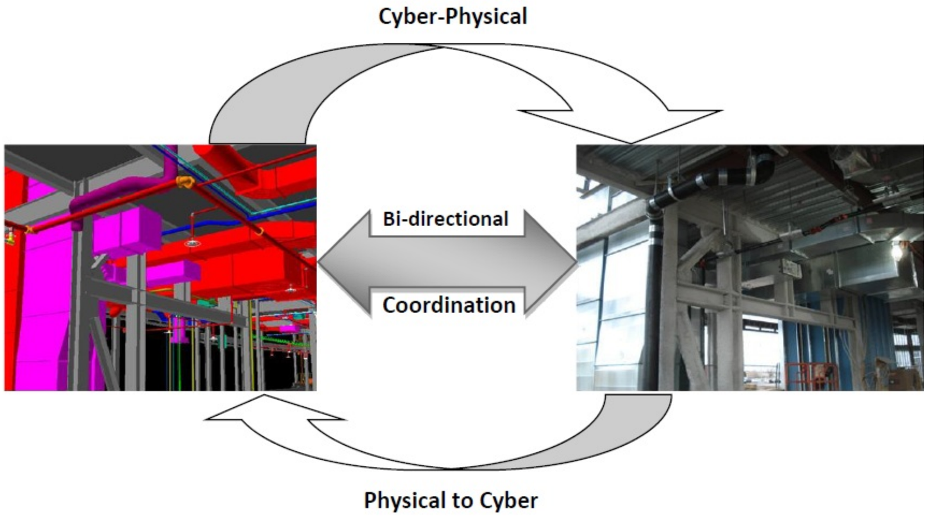


**Fig. 4.** Two-way Integration of Cyber-Physical Systems (Source: A. Akanmu ,2012)

In construction, this process includes enabling active monitoring and control of construction activities. When building components are erected on site, the corresponding virtual model is updated to reflect the changed status of the component. Conversely, when changes are made to the virtual models, appropriate updates can be automatically sent to the relevant physical components in real time.

Virtual models have long proved their worth in construction industry as a means of visualizing the construction process. These models contain virtual representations of building components which can be linked to the corresponding physical components on the construction site and in the constructed facility. As a facility moves through the life cycle from planning to design to construction and to facility management, changes in the status of physical components can be automatically updated in the virtual representations of the building components and this provides another integrated database of relevant information that can be used by the project team during the construction and post construction phases of the constructed facility. Integrating virtual models with the physical components on the job site offers opportunities for improving information handling, thus enhancing access to real-time information or communication between the design and construction team (Sorensen et al. 2008).

## 5 Findings: Comparative Analysis Between Cyber-Physical Systems and HBIM

Findings of this paper took the form of a detailed comparative analysis between HBIM and CPS. The comparative analysis was mainly based on the review of extant literature discussing both HBIM and CPS in the recent years. Table.2, shows the main points of comparison.

**Table 2.** Comparison between Cyber-Physical Systems and HBIM

| **Points of comparison** | **CPS (Cyber-Physical System)** | **HBIM (Heritage Building Information Modelling)** |
|---|---|---|
| Definition: | Two-way integration or communication between the virtual models and the physical construction (A. Akanmu et al., 2013). | HBIM (Historic Building Information Modelling), a plug-in for Building information modelling (BIM), is defined as a process for modelling historic structures from laser scan and photogrammetric data(Laila M. Khodeir et al. 2016) |
| Aim: | Link virtual models and the physical construction using different data acquisition technologies (e.g. digital cameras, laser scanners, radio frequency identification tags), combining various modeling methods to address systemic properties like safety, stability, efficiency, security, and others (Sorensen et al. 2009). | HBIM is specially tailored to the application on heritage buildings The HBIM thus plays an important role in achieving conservation of heritage buildings, thus it automatically produces full engineering drawings for the conservation of historic structure and environments, including 3D documentation, orthographic projections, sections, details and schedules, [27], [28]. |
| Computational Resources: | These models contain virtual representations of building components which can be linked to the corresponding physical components on the construction site and in the constructed facility. | Integrates a three-dimensionalvisual model of construction projects and digitaldata of various fields with properties into a file or a database [29]. |
| Consistency Between The Virtual Model And Physical Construction: | Maintaining consistency between the virtual model and physical construction components (through bi-directional coordination of information between both representations) offers considerable scope for new tracking and communication mechanisms in project control | Does not provide opportunity for providing feedback or control of construction activities; specifically, there are still little or no mechanisms for ensuring bi-directional coordination between the virtual models and the physical construction. |
| Communication Between Design Team And Field Personnel: | Better communication between the design team and the field personnel in the design-build delivery method(A. Akanmu , 2012). | Allows project designers, project managers, construction units, owners, and clients to view the design through a three-dimensional visual model and to obtain relevant digital data of the project. |
| Design Changes: | Changes are shared accurately, consistently and in a timely manner between the project team members and the construction site so as to reduce risks such as time and cost overruns(A. Akanmu et al., 2013). | Parametric models are related to data collected in a database and every change of a parameter causes a change in the shape of the elements [30], [31]. |
| Tracking And Control Of Building Components: | Enhance the ability to identify and control each fixture, thus offering the potential to improve facilities manage- | A lost opportunity for the use of sensors and other embedded instrumentation to control the construction process/constructed facili- |

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|---|---|---|
| | ment and energy management(A. Akanmu et al., 2013). | ty(A. Akanmu et al., 2013). |
| Changes In Site Conditions: | These changes are documented in the virtual model for 'as-built' documentation, which is vital for the operation and maintenance of the building facility(A. Akanmu et al., 2013). | Requires that the contractors raise change orders if there is a change in the scope of work, design or conditions on site before the change is implemented(A. Akanmu , 2012). |
| Temporal Conditions Required For Constructability: | Have access to real time information from the jobsite, by flagging and embedding information in the virtual components, thereby enhancing reduction in project cost and schedule. | During the pre-construction phase, certain temporal conditions required for construction may not be accurately predicted. |
| Capturing Changes in Real-time: | Enables formal capture of changes made late in design or in the field. | Needs further integration of new systems for real-time project information management. |
| Facility Changes Through Life Cycle: | Through the life cycle from planning to design to construction and to facility management, changes in the status of physical components can be automatically updated in the virtual representations of the building components(A. Akanmu et al., 2013). | BIM can be used throughout a building's life.(Motamedi and Hammad ,2009). |
| As-built Documentation: | Accurate documentation of the as-built condition. | As-built models are presently manually updated after construction and as such are prone to errors as not all the changes are adequately captured. |
| Preventive Maintenance: | Useful for preventative maintenance. This approach has demonstrated potential for enabling tracking and identification of components within the model(A. Akanmu, 2012). | Information about building mechanical equipment stored in BIM models is valuable in creating the database needed for ongoing preventive maintenance. |
| Potential Applications: | Building enclosure tracking, and the tracking of other components (such as window blinds, electrical components, and heating, ventilation and air-conditioning (HVAC) components (A. Akanmu, 2012). | Heritage building modelling, retrofitting , rehabilitation, renovation of existing heritage buildings. |

## 6 Conclusions

The aim of this paper was to explore the potentials offered by the cyber-physical systems to move from 3D content model to bi-dimensional coordination for achieving efficient built heritage management. Based on the discussion and findings of this paper the authors were able to extract the main potentials of cyber-physical systems as follows:

- Being more distributed, autonomous, and embedded in physical world.
- Being software-controlled and specified by the ability to interact with complex physical Facilities.
- Offering accurate documentation of the as-built condition.
- Useful for preventative maintenance applications.
- Enhancing real-time construction consistency.

- Accessibility to design model updates in real-time, which can help project managers make informed decisions.
- Enabling improvements in progress monitoring, construction process control, as-built documentation and sustainable building practices.
- Offering better communication between the design team and the field personnel in the design-build delivery method

Moreover, the authors undergone a detailed comparative analysis between both CPS and HBIM, which could guide decision makers working in the field of heritage buildings management. This analysis showed that HBIM plays an important role in achieving conservation of heritage buildings producing full engineering drawings for the conservation of historic structure and environments. The analysis also proved uncovered the main difference between HBIM and CPS, where the later offers more potential by integrating virtual models and physical construction; achieving bi-dimensional coordination, enabling better communication between the design and in site teams with accurate documentation of the as-built condition.

However convergence is increasingly prevalent for both processes, as for maintaining consistency between the virtual model and physical construction components, enabling preventative maintenance throughout the life cycle of the facility and finally the require of many potential applications in building enclosure and components.

Hereby, the paper has partially fulfilled its aims by exploring the potentials offered by the CPS, since the topic is still newly highlighted and needs further investigation on real case studies and further research. Also the paper recommends that further research should take place on the return on investment of both HBIM and CPS, especially when applied on management of built heritage in developing countries which lacks enough funds and expertise for such noble purpose. The leading developed countries could give an anchor to such countries with poor financial resources to achieve efficient management of their scarce heritage, while exploring the application of such innovative processes in different contexts in the meanwhile.

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Submitted 07 January 2017. Published as resubmitted by the authors 23 February 2017.