Abstract: While the Circular Economy in the built environment is often viewed in terms of recycling, more value can be obtained from buildings and physical components by their reuse, aided by stewardship and remanufacture, to ensure optimum performance capability. The use of cyber-physical information for online identification, examination and exchange of reusable components may improve their life-cycle management and circularity. To this end, a bi-directional data exchange system is established between physical building components and their virtual Building Information Modeling (BIM) counterparts, so that their life-cycle information—including history of ownership, maintenance record, technical specifications and physical condition—can be tracked, monitored and managed. The resultant prototype Cloud-based BIM platform is then adapted to support an ongoing product-service relationship between suppliers/providers and users/clients. A case study from a major new hospital, focusing upon an example of internal framed glazed systems, is presented for “proof of concept” and to demonstrate the application of the proposed method. The result of the case study shows that, informed by the life-cycle data from the Cloud-BIM platform, a “lease with reuse” service option is able to deliver a lower total cost and less carbon intensity for each unit of frame-glazed module. This leads to a higher level of eco-efficiency, coupled with decreased consumption of material resources and reduced generation of waste. The research is expected to serve as a step forward in the era of Industry 4.0 and illuminate a more sophisticated way to manage building assets.

Keywords: reuse; adaptability; RFID; BIM; Cloud platform; asset management; products-as-a-service
every building is an “adaptable platform” and a “material depot” [3,4]. Rose and Stegemann [5,6] highlighted the potential for existing buildings to be characterized as “material banks” (e-BAMB) to enable component reuse, while capturing timely information about existing components about to be discarded. Published guidelines (e.g., [7,8]), related to a circular built environment highlight the opportunity for a platform to be used to track and advertise products and components that are currently “locked in” buildings. Thus, when a building approaches the end of its life, these resources could be identified, retrieved and exchanged with another user, enabling their circularity and reuse. In this regard, Baker-Brown [9] envisaged an online market that quantified new material flows as soon as they became available: “Enlightened designers and manufacturers would borrow or lease the material before returning it to the “Material Flow Market”.

Despite such developments, extant digital data platforms do not enable the real-time identification of reusable building components by designers and others, coupled with real-time interrogation of their location, condition, performance, suitability and availability. Although the Madaster database can be accessed by ‘service providers’, it lacks a mechanism for these providers to remotely monitor and manage their components. Whilst automated identification of building elements is common on construction sites, it is rarely used beyond tracking movement to/from site and installation [10]. While Building Information Modeling (BIM) has the capability to capture and maintain the essential knowledge among relevant stakeholders, enabling them to examine the feasibility of reusing building components for projects by importing component models into new designs, there is limited research that explores the potential of BIM for improving circularity [11]. Jayasinghe and Waldmann [12] proposed a BIM-based online tool to enable a material and component bank for users to explore and extract material and component information for reuse. It relies on a predetermined library and the project data from user input to estimate recyclable/reusable volume, rather than from tracked data. In addition, the levels of sophistication in the use of Radio-frequency Identification (RFID), BIM and the Cloud have been uneven [10]. Cloud-enabled BIM and Bluetooth-based location detection sensors are integrated for mobile tracking and safety monitoring on construction sites [13], but not applied to the construction supply chain. Meanwhile, some tracking of items by using bar or QR codes is practised as inventory management. This, however, ceases when the items are in situ and does not extend to their life-cycle management.

Recent research has explored circular material and product flows in buildings and, of special interest, the role of alternative business models for the construction supply chains [4]. In that regard, a potential synergy between circularity and adaptability of buildings through a façade leasing project [3] has also been highlighted. In a similar vein, the authors previously theorized that connecting existing digital technologies may enable take-back and reuse of structural steel components, thus improving circularity and opening up new business paradigms [11]. This paper seeks to extend this research and thus, to answer the following two questions:

(1) Can a bi-directional data exchange system, connecting RFID, BIM and a Cloud-based data platform be developed that, firstly, enables reusable building components to be identified, managed and exchanged and, secondly, allows seamless cyber-physical interchange of information, through a web-based Cloud-BIM data management interface?

(2) Can the use of the digital platform support an ongoing product-service relationship between suppliers/providers and users/clients, which may offer the most potential for take-back and reuse of building components?

To this end, in Section 2, the paper first examines background literature on key concepts and research gaps. Then, it presents the methods applied to develop the data platform in Section 3, followed by the features of the proposed model and the testing of the prototype through a case study (Section 4) as well as the discussion of the results and implications in Section 5. The paper concludes in Section 6 with a summary of the findings, their limitations and possible further research.
2. Background Literature and Gaps

2.1. Service and Data Logic for Building Component Reuse

The notion that parts of buildings may be changeable and/or adaptable is not new. The concept of “Open Building”, introduced in the early 1990s, advocates that a building is a construct of structural components as well as replaceable, reusable and movable infill [14]. Brand [15] defined the construct of a building as “shearing layers of change” according to life span and adaptability (as shown in Figure 1). These range from less changeable, longer-life elements such as “site” and “structure”, to more adaptable elements of “space”, “services”, “skin” and “stuff” with less duration in use, and subjected to higher churn rate. Based on such a notion, the types of building components with the most potential for disassembly, exchange and reuse include framed glazed systems, ceiling systems (“space”); lighting and air handling systems (“services”); and façade systems (“skin”).

![Figure 1. “Layers of change” for building elements [15].](image)

Concerns over quality and performance of recovered building components are often major hurdles for their reuse. Employing digital means to support identifying, tracking, monitoring and managing building components not only provides capabilities to evaluate their physical fitness for reuse, but also opens up opportunities to add different kinds of services for further quality and performance assurance [16,17].

A similar concept can be applied to building components in such a way that original suppliers may still hold the ownership of those reusable components and provide stewardship and continuous services to the components over their life-cycle, resembling leasing and product-service solutions applied to mining equipment and construction machinery [18,19]. This could incentivize a better practice to make building components more physically durable and functionally adaptable for retaining or even extending their life [17,20].

Building component reuse incorporates both the data logic and the service logic (see Figure 2). The data logic defines the life-cycle information to be tracked, and its linkage with measuring the reusability of a building component, both functionally and physically. The evaluation can be supported by drawing upon the component’s type, location, original manufacturer, history of ownership and use, installation, maintenance and other accumulated data from various dealings over the life-cycle [10]. Such information, including maintenance record, installation and disassembly methods, manufacture and material properties, as well as location of use, also serves as a critical parameter for assessing environmental and economic implications associated with potential reuse. The data may be recorded and maintained by different players throughout the supply chain process from production to use. For project managers and service providers, this data can be interrogated to inform procurement and service options. Essentially, the data logic corresponds with and feeds
into the service logic that defines typologies of Product Service System (PSS) offerings. These include “product-oriented”, which supports the operational quality of the installed base with services such as installation and maintenance; “use-oriented”, whereby providers assume responsibility over the ownership and the life-cycle management of the products; and “result-oriented”, which offers advanced services for guaranteed performance, with providers taking operational responsibility for delivering the required functions [21–23]. Thus, various procurement and service options can be explored, ranging from product purchase or renting options with basic “add-on” services, such as delivery, repair and replacement, to more advanced services via a leasing or performance contract, by which the supplier is able to exercise performance monitoring and life-cycle stewardship over the component, and provide support applicable for the customer’s needs and the context of use.

Enabling building component reuse with advanced services can allow opportunities for service providers to offer better performance and quality assurance for the reusable components, thereby defraying manufacturing and supply costs. This has the potential to not only deliver higher customer confidence, but also establish ongoing product-service relationships that create additional profit centers and employment opportunities [24]. Meanwhile, customers can benefit by receiving continuous maintenance and performance support for the reused components, accompanied by contracted service-level terms and agreements.

Further to supporting the reclaim and reuse of building components, there could be more opportunities for novel offerings and new market positions in providing life-cycle data and information management for reusable building assets as services [19,25]. Having physical objects linked with their digital equivalent (also known as “digital twin”), through a joint data management system, can allow various stakeholders to have shared access to and a common view of the life-cycle data for decision making. As postulated by Swift et al. [10], an integration of RFID tags and digital models of building components through BIM gives designers additional capability to track, identify, locate and select appropriate objects currently in use, each with a unique ID allotted, to incorporate into BIM models for new buildings. The Uniclass classification system, based on the framework set out in ISO 12006-2: 2015 and able to be assigned to BIM objects, may also be used as a typology—with a focus on the “systems” level [26]. By doing so, Industry Foundation Classes (IFC), an open data format used in Computer-Aided Design (CAD) models, can be adopted to ensure the data captured

Figure 2. Data and service logics to support building component reuse.
and transmitted via RFID is coherent with the industry data standard for universally applicable and interoperable data expression.

The virtual model inside BIM is represented in the form of datasets encompassing all the constituents of a building, encapsulating their physical and functional attributes. For each element, data describes the state of the object and function, while expressing its behavior under certain conditions [27]. Such information about the life span, ownership, location and other details, once recorded on an RFID tag, can then be mirrored in a BIM as attributes of that unique element. This record can be housed as part of the BIM on a Cloud-based secure server. Therefore, any changes to the building components can dynamically update the BIM via a synchronous bi-directional cyber-physical data exchange system, providing comprehensive and consistent information support in life-cycle modeling [11]. By interrogating and incorporating such life-cycle data in BIM, additional functionality is provided to enable decision making and proper asset management measures on potential of building components for reuse, with the confidence that they are fit for the intended purposes of application.

2.2. BIM-Based Real-Time Cyber-Physical Data Exchange

Cyber-Physical Systems (CPS) utilize sensors to establish autonomous and integrated communication systems between physical assets to effectively maintain the optimized performance of the assets based on timely decisions for control and maintenance. The advent of Internet of Things (IoT) introduces hyper-connectivity in the industry and expands a spectrum of potential applications of CPS systems. Subsequently, CPS realizes real-time bi-directional communication as well as real-time-based decision making and control in various sectors, such as manufacturing supply chain integration and quality control [28], real-time remote monitoring and treatments in healthcare [29], and smart grid management for reliability and efficiency of renewable energy supply [30], as well as building design and automation [31]. It has been recognized that CPS has possibilities to establish bi-directional information exchange and coordination between physical components and their virtual counterparts by visualizing physical components virtually and tracking information of the components in real-time within a virtual environment, without manually updating information of building components [32]. Indeed, CPS has been examined and confirmed for its adaptability for ever-changing situations of a building over its life-cycle [33]. This is highly relevant for managing information on building components in an existing building over a couple of decades to maintain its expected performance and identify reusable building components.

Consequently, there have been diverse efforts to improve productivity of construction projects and maintain building and asset information effectively over a building or facility’s life-cycle by utilizing CPS [34,35]. Although instrumental for enhancing feedback or controlling the constructed facility, functions for two-way integration or communication between the virtual models and the physical construction are still uncommon in existing approaches, and represent opportunities for research. In response to this issue, BIM has been recognized as having the potential to serve as an information exchange and integration platform to establish bi-directional information coordination between virtual models and the physical building components [36,37]. Furthermore, various data restoration systems or technologies have been examined for the construction industry, including the use of 3D laser scanner and RFID to capture and exchange data between virtual and physical building components [38–40]. Among these attempts, a combination of Zigbee and RFID sensors to monitor near-miss accidents, as part of a RFID and BIM system, has been recognized as a possible solution to bridge the virtual and physical environments [41].

Real-time data exchange between physical building components and BIM-based virtual counterparts have recently gained attention to maintain and update information of building components over the building life-cycle [37,42]. In particular, the importance of BIM in managing existing buildings and their components for improvement of energy performance and refurbishment has been emphasized by researchers. According to Monostori et al. [43], computational entities, which are BIM-based virtual
building components, can be productively connected with the actual physical counterparts. This can provide an opportunity to capture the actual conditions of physical building components and maintain up-to-date information of an entire building as well as building components over a building life-cycle, by synthesizing a BIM-based building model with a physical building [44]. The characteristics of a structured connection established between cyber and physical components of a BIM-based CPS are shown in Figure 3. However, there are barriers in the communication between cyber and physical systems due to interoperability among BIM software, such as Autodesk Revit [45] and Graphisoft ArchiCAD [46]. To overcome the interoperability issues, recent research by Lei et al. [47] proposed potential use of a Cloud-based BIM system. This enables all key project participants to exchange design and construction information, regardless of types of peripheral software, within a web-based Cloud system.

![Figure 3. Architecture of BIM-based (Building Information Modeling) Cyber-Physical Systems. (Note: O&M—Operation and Maintenance).](image)

2.3. Current Gaps

Recent research has confirmed that CPS using BIM and RFID is feasible for the construction industry. For instance, Sawyer [48] embedded RFID within precast concrete and attempted to connect BIM and RFID. The work of Motamedi and Hammad [35] attempted to integrate BIM and RFID for life-cycle management of facility components. Although these researchers attempted to use RFID for generating information of physical components for BIM, the effort has been predominantly to boost monitoring capability for construction processes (e.g., [44]) and structural health (e.g., [49]) with adopting IoT and wireless sensors. Additionally, to date, the combination of BIM capability and RFID is largely limited to tracking status of building elements, such as structural steel and curtain wall, in terms of location and construction progress [38,50]. Remaining as a void in practice and for research, the bi-directional real-time information exchange (which is one of the most important purposes of CPS) in building and construction applications has not been examined. Clearly, there is potential to explore further the mechanism and the platform for RFID-integrated and BIM-based bi-directional real-time information update and data exchange between virtual and physical building components.

In addition, whilst it is known that providing products as a service may improve opportunities for reuse [20,21], and that BIM may support PSS for maintenance of equipment [17], there is a gap in research pertaining to provision of PSS for reuse of building components and, in particular, how this may be supported by a digital platform.

In sum, the literature and the current state-of-play appear to reveal two main gaps in knowledge and practice:

(a) limited development and applications of Cloud-based remote identification, tracking, exchange and management of building components, especially the lack of a universal, real-time interchange of data between physical components and their virtual counterparts over the life-cycle; and
(b) limited study of how such a digital mechanism may support the provision of components as a service and thereby improve opportunities for reuse.

Currently, information infrastructure is insufficient to identify reuse opportunities or to manage assets and their performance. Combining RFID and BIM within a Cloud-based information management platform, accompanied by cyber-physical connectivity, may enable designers to identify existing replaceable components online, compare their suitability and import selected items into new designs for reuse. At the same time, industry suppliers may find new profit centers by adopting a PSS business model, so that cradle-to-cradle products may be monitored and managed online through continued ownership, stewardship and provision as a service. Overcoming the gaps and realizing these opportunities constitutes the main focus of contributions of this research.

3. Method

In this research, a systematic approach is adopted to integrate RFID and Cloud-based BIM system for constructing and testing a seamless information exchange platform. Figure 4 presents a schematic view of the integrated data platform and the mechanism for enabling the information flows.

![Figure 4. RFID (Radio-frequency Identification) and BIM-Cloud platform and data interchange.](image)

The process to develop the data platform to explore, identify and access reusable building components for a new project involves the following steps:

- **Step 1.** As the first step to initiate the process, the BIM model of an existing building, which will soon be refurbished or dismantled, is created or made available by the building owner or service provider for access. Then, essential datasets of demountable components associated with the case study (e.g., framed glazed systems), for exchange of information for reuse, need to be identified as required by stakeholders including owners, renters, suppliers, and contractors.

- **Step 2.** The digital twin BIM model is converted to the IFC data attributes (a universal non-proprietary language) that is interoperable, regardless of authoring BIM tools and its data format such as Revit [45], ArchiCAD [46] and Tekla Structures [51] for data exchange, storage and tracking among local BIM, Cloud-BIM systems and RFID tags based on ISO 16739 and BS 11924 [52]. For example, the ArchiCAD data format is ".PLN" and the Revit data format is ".RVT".
".RVT", which are written in different formats within different systems. The IFC data format is recommended by the International BIM standard ISO 19650-3 [53] for operation and maintenance of built assets. Using the IFC format can improve the productivity of establishing feedback loops among different types of data format [54]. Subsequently, less time and effort are required for transmitting and decoding data in a Cloud-based BIM system in comparison with traditional stand-alone BIM software.

- **Step 3.** To examine IFC attributes, a virtually built BIM is chosen to capture and convert physical information of components into digital form within IFC data format and enable uploading to the RFID tags and Cloud-BIM system such as Autodesk BIM 360 Team. IFC data format can be easily converted from a virtual building model by a built-in IFC transforming function within any BIM software such as Autodesk Revit or Graphisoft ArchiCAD. Once IFC data is prepared, the essential datasets identified in Step 1 will be uploaded onto the Cloud-BIM system. After this, an RFID tag is attached (if not already integrated during manufacture) physically to a building component of interest for reuse, holding the initial data of the tagged object or system. This includes the “Uniclass” classification code according to ISO 1206-2: 2015 [26]. When there is any change to the tagged building component, the information contained in both the RFID tag and the IFC data is simultaneously revised and then recorded. These two steps allow users to make regular updates. Once the feedback loop between the tagged object and IFC is set up, the IFC data is transferred to the Cloud platform with the complete BIM.

- **Step 4.** When confirmed that IFC data attributes can manage essential information, RFID tags are mounted on physical components and the BIM model will highlight the components graphically. At this point, the feedback loop is extended to the Cloud platform and, finally, coherent information exchange and updates between a physical building component and its digital twin in the Cloud can be ensured. As a result, this loop of information exchange forms a Cloud-based BIM/IFC data system underpinned by the AutoID system.

- **Step 5.** RFID tags mounted on different types of components will upload the information into the Cloud-BIM system. Local BIM systems used by stakeholders can retrieve necessary information via the Cloud-BIM system and confirm if reusable components are suitable for new buildings/locations. When the information of initial and reused components in IFC data format can be seamlessly exchanged between the local BIM systems, Cloud-BIM system and RFIDs, the development of data exchange format will be a success.

- **Step 6.** A mock-up web interface is constructed to interact with the Cloud-BIM-based system through exchanging and unpacking the IFC data. By translating the life-cycle data logic to the service logic (as shown in Figure 2), the functions of the web interface presents a platform for service providers and potential clients to effectively communicate regarding reusable building components and their status, including location, availability, condition, costing and embodied carbon information. These also help to enable exploring service options and setting up physical transactions for the available stock.

Then, a prototype platform for life-cycle information management and services is tested through a case study of a major new hospital building, focusing upon an example of internal glazed systems for “proof of concept” and for demonstrating the application of the proposed model. Part of the hospital building, which incorporates the various system elements (e.g., internal framed glazed systems, façade systems), is chosen as the case study context. The building utilizes BIM not only for construction, but also for life-cycle facility management. It has been extensively documented, offering ample scope for identifying a bounded test site appropriate to the project. This encompasses the Uniclass code (a widely accepted classification system for the buildings and their elements) “Ss” category of functional element systems.

In this case study, the focus of data tracking and product-service scenarios for reuse concentrates mainly on component modules or product assemblies rather than individual parts or materials. RFID tags are attached to components identified as reusable, which include internal glazed partitions,
door assemblies, ceiling panels, and HVAC grilles) to enable data tracking and logging. Additionally, mechanisms for interrogating RFID tags in a short-range distance and for interacting with the BIM modules in the Cloud are developed based on Arduino micro-controller and UHF RFID reader. For a purpose of demonstration, two procurement options, i.e., “buy-and-sell” and “lease with reuse”, are examined and compared against economic and environmental measures, based on the life-cycle data tracked and managed through the proposed data platform:

- “Buy-and-sell”: The procurement follows the conventional sales contract for one-off payment. The product will be replaced with a new one and disposed of after each cycle of internal renovation. For every new project or client, new modules are supplied without including take-back and reuse.
- “Lease with reuse”: The offering is covered by a lease-and-service arrangement. The revenue is through regular lease fees over the period of the contract. The modules are reclaimed after each contract cycle and provided to other clients.

4. Results

A Cloud-based cyber-physical data exchange platform connecting physical components with their virtual (BIM) counterparts is constructed for effective tracking and managing the life-cycle information of building components. The platform allows designers to explore and identify reusable/reused components and to assess their suitability for their building projects in comparing with other new products. This can enable reclaiming, reusing and exchanging components for multiple cycles on the same site or at different locations.

4.1. Interoperability of the IFC Data Format in Different BIM Tools

The capability of the IFC data format in different BIM tools—ArchiCAD and Revit—is tested to confirm the universal data exchange between different BIM tools as well as seamless information exchange between a service provider and the potential buyer(s) or renter(s). As shown in Figure 5, information of a building component, such as a Framed Glazed Wall System, can be embedded within a BIM object. The information includes years of life expectancy, location, ownership, service period, and classification (Uniclass). Once the information is embedded, IFC data can be extracted from Revit or ArchiCAD to transfer the information to each other. As a result, all the embedded information can be transferred identically between two different BIM tools, while all the geometry of a BIM model (in this case, a simple house) is congruent.

Figure 5. Data exchange between different BIM tools via IFC (Industry Foundation Classes) data format.
4.2. Vertical Slice of Cyber-Physical System: Digital and Physical Transactions

Once the information of the reusable building components is available to access on the Cloud platform, various suppliers or service providers can start uploading their product data, contributing input to populate a mock-up Cloud-based library of reusable objects. By having this Cloud-based library connected to a purpose-built web platform for data accessibility, other users, such as potential buyers or renters, can use the search function on the web interface to explore the data library for reusable objects (elements, components and systems) that meet their criteria.

After suitable building components are identified, users can initiate a query to reveal the life-cycle data related to the respective components. For a building component, the complete dataset is not stored in its RFID tag due to limited storage space. Instead, more detailed information (e.g., descriptions of the object, graphics, dimensions and manufacture specifications, material properties, ownership, etc.) is accommodated in the Cloud-based object library and can be interrogated, together with other specific performance-relevant information. For example, exposure to weather could affect the quality and suitability of the object for another application. The search examines the initial BIM model by accessing the IFC data, Cloud-based viewing applications, or the graphic user interface to perform multi-parameter interrogations for suitable building components offered by different vendors, including their availability, current locations and distances for transport. Upon identifying an interested building component, such as a framed glazed module, the user can obtain the IFC data of the objects and import them into the BIM model of their own project to evaluate whether the component is a fit for the intended application. Such a process represents a “Digital Inter-Party Transaction”, which confirms and selects the component for reuse.

Following the “Digital Transaction”, the process proceeds to the stage of “Physical Transaction”. To enable interactions, a demonstration website is set up to connect with the Cloud-based data platform. This provides functions akin to an “e-market”, where potential clients (e.g., architects, builders, and developers) can seek available stock of used building components as well as check where they are currently located, their origins and histories of use, when they can be accessed, and at what prices they are offered. For the purpose of demonstration, some demountable glazed partitions, framed door units and other internal glazed modules, which are all affixed with RFID tags, are added to the website for users to explore. Additionally, suppliers or service providers can use the website to interact with potential buyers or renters and to manage provision and transaction processes.

Upon a reusable building component being retrieved by the client and incorporated in the new building, the information stored in its RFID tag will be updated and then regularly maintained over the extended life-cycle to retain the service record of the component. Such updates, including any change of ownership, will be relayed to the BIM model linked with the Cloud-based data platform to enable the supplier or a service provider to track and use the recorded information to provide real-time support.

As discussed above, the interplays among different stakeholders for identifying and retrieving reusable building components in this Cloud-enabled CPS take place at multiple layers. Figure 6 illustrates a “vertical slice” of the flows of information and transaction via the Cloud-BIM platform and the procurement website, which illustrates the interactions between providers and clients throughout the digital transaction and the physical transaction processes.
4.3. Web Interface and Life-Cycle Data Management: An Example

To establish a prototype for testing, BIM Viewer is adapted to construct a software tool on a Cloud platform to support data exchange with the hardware to read and record the IFC-format data files. When the data repository is established, users can explore the IFC dataset and select a suitable building component. Figure 7 presents an example of identifying a glazed door assembly through the Cloud-BIM Viewer.

![Figure 7. Illustration of Cloud-BIM Viewer (BIM 360) interface for component selection.](image-url)
Once the component is selected for reuse in a new project, the software extracts the critical information (e.g., component type, geometrical specifications, material properties, in situ operational condition, installation and maintenance methods, logistics record and ownership) from the IFC dataset and transmits it to update the data in the respective RFID tag. Meanwhile, when interrogated, the Cloud-BIM Viewer provides a brief description of both the component details and the associated RFID tag’s unique identifier from the database, as shown in Figure 8.

![Figure 8. Component and RFID Information in the Cloud-BIM Viewer.](image)

To use this cyber-physical data exchange to support digital and physical transactions, a mock-up web platform is further constructed and linked with the Cloud-BIM system to enable self-populating and updating the reusable objects library, akin to the UK-based National Building Specification (NBS) object library of new products, with information of building products listed by building product suppliers or service providers as available for reuse. Potential renters or buyers can access this web platform to search for reusable objects, components or systems, together with exploring options for product-service offerings. Responding to the search criteria set by users, the web platform brings up available options for exploring and selecting (Figure 9).

Interacting with the Cloud-BIM database, the web interface displays details of the chosen building products to inform potential clients about the product specifications, availability, supplier, and location, as well as physical condition and reusability (Figure 10a). The condition and suitability for reuse are suggested based on the data logic for building product reuse proposed in [55] and the data obtained from RFID tags in relation to history and in situ condition of use, installation and disassembly methods, manufacturer’s information and other logistics data captured during various supply chain processes over the life-cycle. Such information serves as a general guide for users to appraise in conjunction with economic and environmental parameters.
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Additionally, illustrated in Figure 10b, the web interface provides an embedded map function, drawing upon Google Map® applications, to allow users to choose the expected destination of delivery or new location of use to estimate the carbon expended, or “carbon cost”, for logistics. By further factoring in manufacturing and supply chain contributions to carbon signature of related products and services, the embodied carbon of a building product can also be calculated and considered as “benefits” or “credits” salvaged through reuse. For demonstration, the embodied carbon intensity data derived from the Australian Industrial Ecology Virtual Laboratory [56] based on the economic input-output life-cycle inventory data is applied in this mock-up web platform to support the carbon analysis for materials and products used/reused in local building projects. While the provider can indicate a nominal base price for the reusable component, the web platform allows potential clients to make a bidding offer (as shown in Figure 10b) or to explore more sophisticated procurement alternatives corresponding to the data and the service logics supporting reuse, as depicted in Figure 2.

A framed glazed partition module is selected as a preliminary example for potential product-service offerings, assisted by a local supplier of framed glazed systems in South Australia. The module consists of a 2700 × 1200 mm glass panel with aluminum frame and fixings. Drawing upon the data from the Cloud-BIM database and the web interface, a conventional “buy-and-sell” procurement without take-back and reuse (i.e., Option 1) and a “lease with reuse” service contract, covered by a 2-year lease arrangement, including delivery, installation, extended warranty and retrieval to reuse for a new project or client (i.e., Option 2), are compared with regard to both economic and environmental measures. The environmental comparison between the two options is based on their embodied carbon performance. The embodied carbon intensity data, i.e., kgCO₂e/$, of the components and operations in relation to a framed glazed module for the analysis are presented in Table 1.
(a) Figure 10. Cont.
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Figure 10. Web view of search results for internal glazed partition.

| Item                  | Embodied Carbon Intensity (kgCO₂e/$) * |
|-----------------------|----------------------------------------|
| Glass Panel           | 0.485                                  |
| Frame                 | 0.397                                  |
| Fixings               | 0.247                                  |
| Installation          | 0.193                                  |
| Recover and Reinstall | 0.193                                  |
| Handling and Logistics| 0.694                                  |

* Based on the embodied carbon explorer database of IELab (Australian Industrial Ecology Virtual Laboratory) [53].
For the economic comparison, the Net Present Value (NPV) approach is employed to examine the associated costs, as expressed by the following Equation (1):

\[
\text{NPV}(C_{\text{TTL}}) = \sum_{j=1}^{N} \left[ C_{j}^P (1 + r_j) + C_{j}^I \right] + \sum_{k=1}^{m} \sum_{j=1}^{N} \left[ C_{j}^P (1 + r_j) + C_{j}^I \right] \left(1 - a_j\right) + \left[ C_{j}^R (1 + r_j) + C_{j}^H \right] a_j \right] \frac{1}{(1+i)^k} \quad (1)
\]

- \( C_{\text{TTL}} \): total cost
- \( C_{j}^P \): cost of the \( j \)-th product
- \( C_{j}^I \): installation cost of the \( j \)-th product
- \( C_{j}^R \): replacement cost of the \( j \)-th product
- \( C_{j}^H \): handling and logistics cost for retrieval of the \( j \)-th product
- \( a_j \): reuse factor for the \( j \)-th product, where \( a_j = 1 \) for reuse and \( a_j = 0 \) for no reuse
- \( r_j \): the overhead rate of the \( j \)-th product
- \( i \): internal rate of return
- \( k \): number of use cycles, where \( k = 1, 2, \ldots, m \)
- \( t \): length of a use cycle

The parameters for and the results of the analysis on the two options are summarized in the table below (Table 2).

| Product Information       | Cost ($/Unit) | Procurement Option | NPV Cost ($/Unit) | Embodied Carbon (kgCO2e/Unit) | Total Carbon Intensity (kgCO2e/$) |
|---------------------------|---------------|-------------------|------------------|-----------------------------|----------------------------------|
| Glass Panel Supply        | 330           |                   |                  |                             |                                  |
| Install and Logistics     | 385           | Option 1          | 3300             | 1099                        | 0.33                             |
| Recover and Reinstall     | 825           | Option 2          | 3135             | 836                         | 0.27                             |
| Frame and Fixings Supply  | 660           |                   |                  |                             |                                  |
| Supply and Fabricate      |               |                   |                  |                             |                                  |

According to the results shown, it is evident that Option 2 ("lease with reuse") has advantages over Option 1, with a lower total cost and less embodied carbon per unit (by factoring in the supply chain carbon implications of products and services). By integrating both the environmental and economic impacts, this also translates to a lower overall embodied carbon signature per dollar of total NPV cost (i.e., total carbon intensity) for each unit of frame glazed module with Option 2 relative to Option 1 over the studied period, indicating a higher level of eco-efficiency (i.e., reduced environmental impact with each dollar value invested). Moreover, the reuse of the framed glazed partition modules for an extended life will also lead to decreased consumption of material resources, and reduced generation of waste from producing and supplying new units, adding to further environmental savings.

5. Discussion

The project has shown that reusing building components is technically feasible, especially when these are designed in modular and prefabricated form, able to be readily disassembled. Within the field of new building products, the NBS has created a BIM object library of new construction components. It may be possible to establish a complementary library and search engine related to identification and exchange of reused components. The increasing trend towards modularization and prefabrication within the building sector, as well as “refabricating architecture” along the lines of the manufacturing sector [57], opens up the opportunity for buildings to be planned for change, adaptability and
reuse—assisted by the Cloud-BIM platform. Although the mechanism is aimed initially at new buildings, it could be extended to existing structures in future.

Meanwhile, CPS has demonstrated its capability to improve efficiency, adaptability and productivity in operating assets and components as well as maintain required and reliable quality of operation outcomes in the industry such as manufacturing, healthcare and energy sectors as aforementioned [58]. However, the current building industry is limited in adopting a real-time CPS for asset management and reusing building components. Manufacturing factories, healthcare and power plants including smart grid must acquire real-time data of operation to monitor required outcomes in terms of product quality and quantity; patient’s condition and level of treatments; and energy generation and consumption. More importantly, professionals should be able to analyze real-time data acquired from operation and adaptively adjust inputs and processes to achieve the required outcomes. Increasingly, buildings utilize prefabricated modules and building components incorporate functional units for delivering value-added performance. Such a trend necessitates a constant monitoring and control over the life-cycle [11,57], as other industries do. As building components have various life expectancies and durability, real-time-based data acquisition can support well-planned operations and maintenance strategies for facility and asset management to sustain or improve their whole-of-life value. Furthermore, a building involves diverse stakeholders in decisions on operation and maintenance, as building components are interwoven and connected to render the expected building performance, while other sectors have relatively well-organized and standardized processes and workflows, which requires less complex information and stakeholders. Although other researchers are fully aware of the importance of a real-time-based asset information management platform, this research has aimed to achieve affordable and feasible bi-directional Cloud-BIM-based CPS as a solution for managing information on reusable building components. Based on the result of the Cloud-based BIM platform, this research proved that a Cloud-BIM system enables real-time monitoring of progress and coordination as well as data sharing amongst stakeholders regardless of data format, which cannot be achieved in traditional BIM software. Indeed, the finding is echoed by other researchers and construction professionals, who have acknowledged the identified benefits of adopting the Cloud-based BIM system in terms of enhanced data exchange communications as well as efficient design changes [59,60].

Whilst the cyber-physical exchange system developed in this research represents an important breakthrough towards reuse of building components, its integration with PSS enabled its full capabilities to be delivered. Reusable components could be managed at their optimum performance over their extended life, keeping them in closed loops for a much longer period. Currently, building component manufacturers mostly rely on up-front payments from their customers before they produce their product. Via the PSS model, the manufacturer’s bottom line may be improved by making a better product, providing an ongoing service to customers, while the environmental impact and embodied energy associated with manufacture of new building components is reduced, as shown in the case study. Indeed, embodied carbon is becoming increasingly important, with new buildings being required to be net zero carbon by 2050 based on government directives in various countries such as the US, UK, Australia and Singapore. Reusable materials and components with low embodied carbon should be considered for building construction and refurbishment to reduce carbon emissions and improve financial effectiveness. This opens up new business opportunities for fabricators/suppliers or additional third-party enterprises, to transition from sale of reusable products and components to a PSS mode. This is likely to require them to obtain financing to cover initial production costs, creating a new challenge [22,61]. Beyond the financing challenges of providing building components as a service, the real hurdle may be psychological as some customers may have an aversion to used products. As with most changes, there is some inertia in adopting a new business model; a marketplace and financing model with real incentives is required, as well as education about the benefits. Further investigation is also required on the legal responsibilities associated with reliability of data and components procured via the Cloud platform.
It is challenging to measure quantified benefits of adopting a Cloud-based BIM system over traditional stand-alone BIM software, since the level of BIM maturity, the purpose of BIM adoption and the size of organization can vary greatly in relation to the context of application. However, it is evident that the current trend of BIM development and usage is moving toward a Cloud-based system, which has been recommended in countries such as the UK and the US [62]. Furthermore, researchers and construction professionals also have recognized the benefits and potentials of a Cloud-based BIM system. Thus, this research serves to shed light on both potential and feasibility of a Cloud-BIM system, in conjunction with RFID and IFC-compatible data structure, to support life-cycle information management and reuse of building components.

For the next phase of this research, it is proposed that real-time-based CPS adopting Cloud-BIM and RFID systems will further expand the potential of the CE concept in the design and construction industry. Potential integration of the current rapid advancements in digital technologies, such as smart RFID sensors for strength, temperature and the like, embedded in building structures such as metal and concrete, with a real-time structural health monitoring system, will create significant synergy in further developing a real-time CPS based on Cloud-based BIM and RFID systems. As the essence of the Cloud-based information exchange system is its “Universal Accessibility”, a mobile-based Cloud-BIM platform, linked to Revit and the website, needs to be established, so that a potential buyer/renter can efficiently access the information about reusable components with their mobile devices. The mobile-based system can also be used to support the physical transaction between a service provider and a buyer/renter, aligned with the product-service provision. Meanwhile, the security and the integrity of data needs to be carefully planned and managed. This leads to the potential for the platform to utilize Distributed Ledger Technology, such as Blockchain, which requires further examination and exploration.

6. Conclusions

While the CE in the built environment is often viewed in terms of recycling, more value can be obtained from buildings and physical components by their reuse, aided by stewardship and remanufacture, to ensure optimum performance capability. However, the main challenges for exercising life-cycle management and improving circularity often involve lack of capability and a mechanism for online identification, examination and exchange of reusable components. To address such limitations, a bi-directional data exchange system is established between physical building components and their virtual BIM counterparts, so that their life-cycle information, including history of ownership, maintenance record, technical specifications and physical condition, can be tracked, monitored and managed. The resultant prototype Cloud-BIM data platform is then adapted to link with a web platform for a universal access, making it possible for reusable building components to be explored, recovered and reutilized, as well as supporting an ongoing product-service relationship between suppliers/providers and clients. A case study from a major new hospital, focusing upon an example of internal framed glazed systems, is presented for “proof of concept” and to demonstrate an application of the proposed method.

Although limited by low-cost equipment with short-range interrogation capability, coupled with low-capacity RFID tags and the use of a mock-up web platform, the research demonstrates the bi-directional exchange of data between physical components and their BIM “digital twins” within the Cloud. It also proves that, regardless of data format, the Cloud-BIM system enables real-time monitoring and tracking of components, which is an important factor in their reuse. Despite its preliminary nature, the study of an internal framed glazed system shows that a “lease with reuse” service contract has cost, carbon and other advantages over conventional “buy and sell” procurement. For full demonstration and application of the mechanism, it will be necessary to fully develop the web platform, to utilize real scenarios involving exchange and reuse of a range of component systems (beyond internal framed glazed systems), and to examine in more depth the cost, environmental and other implications.
Nevertheless, the research is expected to serve as a step forward in the era of Industry 4.0 and illuminates a more sophisticated way to manage building assets. While it is essential to capture, record, update and manage life-cycle information for reusing building components, the effectiveness of deploying this novel Cloud-based system for CE is also dependent on improved product modularity with design for disassembly and prefabrication, which requires more accommodating government policies, industry standards and business models. This necessitates further research on refined technological solutions, enabling regulatory frameworks and feasible financial measures in the building industry to evolve the model platforms from prototype into practice, whereby building assets are real-time monitored and automatically listed for possible reuse, supported by advanced services and life-cycle product stewardship.

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Abbreviations

BIM Building Information Modeling
CE Circular Economy
CPS Cyber-Physical System
IFC Industry Foundation Classes
IoT Internet of Things
PSS Product-service System
RFID Radio-frequency Identification
UHF Ultra-high Frequency

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