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# INFORMATION AND COMMUNICATION TECHNOLOGIES APPLIED TO INTELLIGENT BUILDINGS: A REVIEW

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***Fabio Parisi, Ph.D. Candidate,***
***University Polytechnic of Bari - Department of Electrical and Information Engineering;***
***fabio.parisi@poliba.it***

***Maria Pia Fanti, Professor,***
***University Polytechnic of Bari - Department of Electrical and Information Engineering;***
***mariapia.fanti@poliba.it***

***Agostino Marcello Mangini, Professor,***
***University Polytechnic of Bari - Department of Electrical and Information Engineering;***
***agostinomarcello.mangini@poliba.it***

***SUMMARY:*** *In this paper an insight on innovative implementation strategies and operative Information and Communication Technologies (ICT) regarding Intelligent Buildings (IBs) is provided. Data-driven knowledge extraction and re-usage can be a valid source of information to study the whole building life-cycle as a process to optimize. Today, new challenges can be provided thanks to ICT and Internet of Things (IoT) paradigms that allow big data to be stored, processed and analysed. This approach is still not deeply applied in construction engineering fields. In order to analyse the related literature, first a framework to describe the IB technological environment is proposed. Second, the literature is reviewed according to this framework and focusing on ICT tools and implementation aspects for the whole building life-cycle. To the best of our knowledge, there isn't yet a survey focusing on innovative operative tools adopted in the development of the ICT technological layer of IB. The reviewed literature is discussed by identifying implemented technologies and related ICT tools and classifying applications in building life-cycle. Finally, critical aspects are singled out and opportunities for future developments in the field of IBs are outlined.*

***KEYWORDS:*** *Intelligent Building, Building Information Modelling, Big Data, Internet of Things, Semantic Technologies, Building Life-cycle, Natural Language Processing*

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# 1. INTRODUCTION

The recent development of Information and Communication Technologies (ICT) favored the intelligent modelling and management of many application areas.

Also in architecture, engineering and construction industry (AEC) the availability of ICT fosters a deep transformation of the approaches for modelling, designing and managing Intelligent Buildings (IBs).

This paper reviews the ICT tools and strategies presented in the related literature and implemented in IBs, by considering the specific applications in the different building life-cycle phases. There are many different definitions of IBs and each of them points out some aspects of the IBs. Some first definitions pointed attention mainly on performance aspects, such as for example the definition of the Intelligent Building Institute of U.S.: an IB "provides a productive and cost-effective environment through optimization of its four basic elements including structures, systems, services and management and the interrelationships between them" (Wigginton & Harris, 2002).

With the evolution of the IB concept, different topics and factors are taken into account and the importance of users and environments become central.

In (Ghaffarianhoseini et al, 2016), the authors identify four Key Performance Indicators (KPIs) to assess and classify the IB main features considering two levels as shown in Fig. 1: i) smartness and technological-driven awareness, ii) economical and cost efficiency, iii) social sensitivity, iv) environmental responsiveness. More in details, the KPI-1 of the top-level focuses on technological aspects that are specified in different contexts in the bottom level by considering KPIs that evaluate economical and cost efficiency (KPI-2), social sensitivity (KPI-3) and environmental responsiveness (KPI-4).

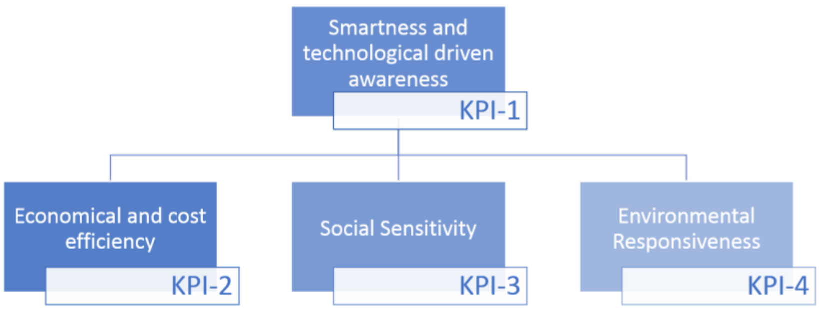


*Fig. 1. KPIs in Intelligent Building definition (Ghaffarianhoseini, et al., 2016)*

The novelty of the presented review is twofold.

First, starting from the specification of the KPIs, this paper performs a IB literature review on the basis of a defined framework. More precisely, the literature review performed in this work involves the usage of a hierarchical two-layer framework for specifying the IB technological contexts. The first top layer of the considered conceptual framework is constituted by the evaluation layer inspired by the KPIs reported in Fig. 1 and including the performance areas of the IB construction. The second layer consists of the ICT construction-related technologies and is divided in two sub-layers: the ICT construction sub-layer and the generic ICT tools sub-layer.

Second, the main operative technological tools to be investigated in the second layer are not determined a priori but they derive from a text analysis of the IB review papers. Such text analysis performed on the large amount of the literature related to the application of the ICT allows identifying the main technological tools employed in the IB paradigm and not sufficiently discussed in the related literature.

By a Natural Language Processing approach (Chowdhary, 2020), we automatically retrieve and analyse the review papers from the most important scientific archives. By using such approach, the results of the analysis point out that in the review papers about the IB field, innovative technologies such as Big Data (BD), Internet of Things (IoT) and Semantic Technologies (ST) are worthy of further study.

Hence, on the basis of such outcome, the paper performs a review analysis about the application of BD, IoT, ST in the context of the IB by locating them in the building life-cycle. Moreover, considering the basic importance of the implementation of the Building Information Modelling (BIM) in the IB design and management, the proposed review also deals with the possible integration of such ICT tools in the BIM environment.

The paper is structured as follows: Section II introduces the IB review framework; Section III presents the main investigated ICT technologies; Section IV recalls the IB applications; Section V discusses the results and Section V draws the conclusions.

## 2. INTELLIGENT BUILDINGS REVIEW FRAMEWORK

In this section we specify in detail the components of the ICT construction-related technological layer, named IB ICT layer in the following, in order to perform the review analysis about the use of the modern ICT tools in the IB modelling, designing and managing.

We start by considering the two layers of the hierarchical technological framework adopted to perform the review: the evaluation layer and the IB ICT layer.

The evaluation layer includes the technological KPI's areas reported in Fig. 1 characterizing the different aspects of the IB construction and maintenance.

The IB ICT layer describes the specific ICT construction tools devoted to model, design and manage IBs during the complete building life-cycle. We consider this layer divided in two sub-layers: the ICT construction sub-layer including the information tools adopted in the construction industry and the generic ICT tools sub-layer including the ICT tools that are relevant for supporting the construction sub-layer tools development.

The following sub-sections specify the components of the two technological sub-layers on basis of the analysis of the contributions in the related literature.

### 2.1 The ICT construction sub-layer components

In order to identify the components of the ICT construction sub-layer, it is necessary to consider the performance areas and the relative domains characterizing the building life-cycle.

The phases of the building life-cycle are the following: planning/ design, construction, operation/maintenance and improvement/disposal. Fig. 2 shows the four phases of the building life-cycle and the relative sub-areas (Tang et al, 2019), (Solihin & Eastman, 2016). Note that the sub-areas are depicted on the rays labels and specify the phase preceding them.

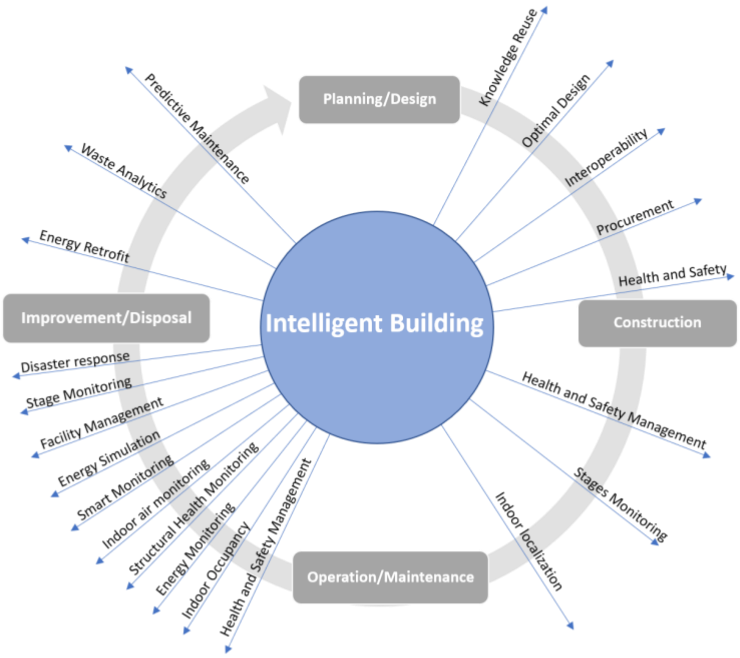


*Fig. 2. Building life-cycle phases and sub-domains.*

The four phases of the building life-cycle are supported by dedicated ICT construction tools that can be characterized by the following main three systems: Building Management System (BMS), Facility Management System (FMS) and Building Information Modelling (BIM).

#### 2.1.1 Building Management System

The BMS is aiming at the computerized control and management of building, characterized by a distributed infrastructure (Domingues et al, 2016). The usual architecture of this distributed system is typically structured into three levels: (i) the field level that includes the interaction with sensors and actuators (field devices); (ii) the automation level, where processing activities are performed, like measurements processing, control loops execution and alarms activation; (iii) the management level where data elaboration activities are performed, such as system data presentation, forwarding, trending, logging, and archival. As reported in (Shaikh et al, 2014), BMS includes some related systems such as building control systems and building automation systems.

#### 2.1.2 Facility Management System

FMS is an holistic term that covers topics ranging from financial management to facilities maintenance (Atkin & Brooks, 2009).

In (Nutt, 2004) different definitions presented in the related literature are provided. A definition that is consistent with this work is in (Nutt, 2004) where the author defines FMS as: "*a supporting tool to obtain sustainable and operational strategy for an organisation over time through management of infrastructure resources and services*". Moreover, an additional system named Energy Management System (EMS) includes tasks partially in common with the FMS and the BMS. In particular, the EMS involves strategies and methods aiming at the building performance, efficiency and energy utilization improvement (Bonilla et al, 2018). This sub-system is focused on key energy management tasks like the demand-response strategies, energy costs prediction, energy use anomalies detection, and management of energy use information (Mariano-Hernández et al, 2020).

#### 2.1.3 Building Information Modelling

Depending on the literature and context, BIM can be defined in a *narrow sense* or in a *broad sense* (Volk et al, 2014).

- BIM in *Narrow Sense*: it is seen as a "tool" strictly used for building model creation process, i.e., a technology to manage different information related to the building design. The great content visualization and representation capabilities are strong features for the management process: a building description is strongly geometric-driven, hence three-dimensional visualization models gain more and more attention. In BIM, visualization models are enriched by interdisciplinary design information: these models become a visual representation and integration of cross-fields time-dependent data (Chen et al, 2015).

  BIM historical role allowed a large interoperability among different stakeholders involved in design, construction and management process (Eastman et al, 2008). Despite of this, there are still limitations in BIM usage (Pauwels, 2014): i) proprietary platforms are strongly pushing towards the development of further features in their own software environment, and this implies an high dependency on proprietary data format; ii) even if information exchange open data format is used (like Industry Foundation Classes), the flows of information suffers consequences; iii) even if official Application Programming Interfaces (API) and scripting environments are largely diffused, custom features integration remains tricky.

- BIM in *Broad Sense*: the National Building Information Model Standard (National Institute of Building Science, 2021) defines BIM as a *"digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward*". In this case, BIM technology has a wide perspective of usage, and does not focus only on the first stages of the building process (design and construction phases), but it has a key role also in the management stage.

  The gradual evolution of the BIM concept from the *Narrow Sense* to the *Broad Sense* is observable in the progressive introduction of features and functionalities in BIM software. This BIM evolution is also described by the growing number of "dimensions" considered in the model (Guillen et al, 2016):

  - 2D models: 2D CAD model application;

- 3D models: modelling and visualization of the third dimension, also with parametric modelling, object-oriented approach and automated digitalization;
- 4D models: scheduling and sequencing of operations to plan project and construction execution;
- 5D models: cost estimation, i.e., the budget estimation and control of the construction phase;
- 6D models: sustainability, i.e., impact control of construction and operation;
- 7D models: facilities management, including operation, maintenance, planning and execution of building life-cycle.

In this "n-dimensions" BIM applications it is clear the trend to the integration of BIM with the BMS and the FMS. The main evolution of BIM in broad sense has led to the modern concept of digital twin in construction, which promises greater potential at the intersection of IoT and AI through semantic models (Boje et al, 2020).

The new challenge for the future development of the potentialities of the BIM in broad sense is represented by cloud-BIM supported by Common Data Environments (CDE's). Indeed, as in other industrial fields where the cloud-based software and platforms boost applications potential, also BIM environments are being developed towards web services and cloud-based applications. In (Afsari, et al., 2016) some examples of cloud-based applications and services are mentioned, like GRAPHISOFT BIM Explorer, ONUMA System, BIMServer.org, Autodesk BIM360, Trimble Connect and xBIM.

## 2.2 Generic ICT sub-layer components identification

In order to identify the technological components of the generic ICT sub-layer, a preliminary analysis of existing review papers on the topic "Intelligent" and "smart" "buildings" is performed, following a methodology proposed in (Yang et al, 2018).

This preliminary study has two objectives: i) determining the research fields already deeply analysed, and the most prominent topics already speculated in the field of the IB literature; ii) identifying the emerging technology that are applied in the IB research areas but are not still deeply reviewed in the related literature.

### 2.2.1 Preliminary review papers analysis methodology

An in-depth research of the review papers about the IB and smart building concepts is performed in order to single out the most reviewed research fields.

The database used in this analysis and the related results are shown in Tab. 1.

*Tab. 1. Intelligent and Smart Buildings Review papers*

| Journal / Database | Searching | References |
|---|---|---|
| Elsevier | 15 | (Zhou, et al., 2020), (Khajenasiri, et al., 2017), (Ralegaonkar & Gupta, 2010), (Wong, et al., 2005), (Dai, et al., 2020), (Al Dakheel, et al., 2020), (Lee & Karava, 2020), (Panteli, et al., 2020), (Ahmad, et al., 2020), (Dong, et al., 2019), (Jia, et al., 2019), (Daissaoui, et al., 2020), (Younus, et al., 2019), (Nguyen & Aiello, 2013), (Alvarez-Alvarado, et al., 2015) |
| IEEEXplore | 10 | (Boyes, 2013), (Kumar, et al., 2018), (Vergini & Groumpos, 2015), (Osisiogu, 2019), (Jia & Srinivasan, 2015), (Bashir & Gill, 2017), (Kuzlu, et al., 2015), (Verma, et al., 2019), (Chinchero & Alonso, 2020), (Joench, et al., 2019) |
| Taylor&Francis Online | 5 | (Clements-Croome, 2011), (Kerr, 2013), (Kolokotsa, 2007), (Panchalingam & Chan, 2019), (Morales-Beltran & Teuffel, 2013) |
| ResearchGate | 12 | (Chen, et al., 2006), (Saad, et al., 2020), (Ralegaonkar & Gupta, 2010) (Alvarez-Alvarado, et al., 2015), (Cardinale, 2020), (Ciholas, et al., 2019), (Djenouri, et al., 2019), (Petroșanu, et al., 2019), (Huang, 2018), (Shah, et al., 2019), (Patil & Jain, 2017), (Chaizara, et al., 2019) |
| Emerald | 1 | (Ghansah, et al., 2020) |

The research is performed by an automatic procedure consisting in the following steps:

- Research: both Application Programming Interfaces (APIs) provided by databases maintainers and *Web-Scraping* techniques (Glez-Peña et al, 2014) are applied. The research is performed by searching for all paper titles in which the words "intelligent" or "smart" together with "buildings" and "review" or "survey" are present.
  APIs allow us to obtain response from the APIs server directly in form of analysable text data (JSON or XML format). If APIs are not provided, a web-scraping approach is used. This methodology implies the analysis and the parsing of web pages in order to detect automatically desired information. This approach requires a large processing activity in order to make the research directly usable to retrieve papers.
- Collection: once papers corresponding to the research are identified, full texts are automatically retrieved and stored locally, in order to create the corpus on which to perform the preliminary analysis.
  By the APIs approach, the full texts are retrieved by Digital Object Identifier directly as text data and stored locally in the software script in order to be analysed.
  By the web-scraping approach, the texts are retrieved in PDF file form, and stored locally. A subsequent phase is necessary to read the content of this file and put this text data in the text obtained by the APIs approach by obtaining only one "corpus".
- Analysis: raw text data are not directly analysable. The entire corpus obtained in the previous collection phase is pre-processed and analyzed in Python development environment. The preliminary pre-process is necessary to put the corpus in a form usable as input for natural language processing or machine learning algorithms. In this stage the Python library Natural Language ToolKit (NLTK) is used. The following steps are applied to the corpus:
  - tokenization is the process of dividing the corpus on the elementary unit (Jurish & Würzner, 2013 ); in the present work, the used token units are the words. In particular, the Treebank tokenizer (NLTK, 2020) implementation in NLTK is applied;
  - stopwords removal allows removing tokens that bring no informative content about the text from the corpus. Example of stopwords to delete are articles and prepositions (Ghag & Shah, 2015);
  - lemmatization aims at expressing tokens into their dictionary form, by using vocabulary and morphological analysis to remove inflectional endings. It also helps in matching synonyms by the use of a relational thesaurus (Balakrishnan & Lloyd-Yemoh, 2014);
  - the corpus is then re-built in the form of a continuous text composed by the pre-processed tokens;
  - after the text is pre-processed and re-built, analytical methodologies are applied to extract the frequency (the number of occurrences) of the concepts the corpus contains. The concept is expressed by an *n-gram*, i.e., a sequence of *n* words that appear with a specific order in the corpus. The analysis method assumes that important concepts are more often present in the text (Yang et al, 2018). In this work, the n-grams composed of two and three words are analysed.

### 2.2.2 Results of the review papers analysis

In Fig. 3 the presented procedure are shown in a "Word Cloud" representation. In the used "BagOfWords" approach bi-grams and tri-grams are considered because of their capacity to be more consistent in content representation in the text corpus (Miao et al, 2005).

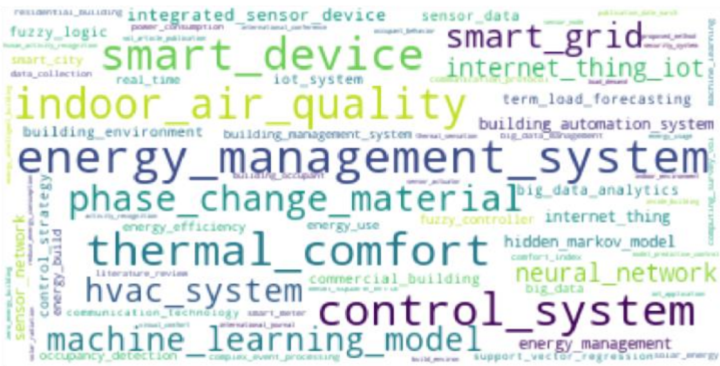


*Fig. 3. Bi-grams and Tri-grams reviews Word Cloud*

The metric that supports the generation of Fig. 3 and Fig. 4 is the frequency distribution of bi-grams and tri-grams in the whole corpus text, defined as the number of times that each bi-grams or tri-grams appears in the considered corpus text.

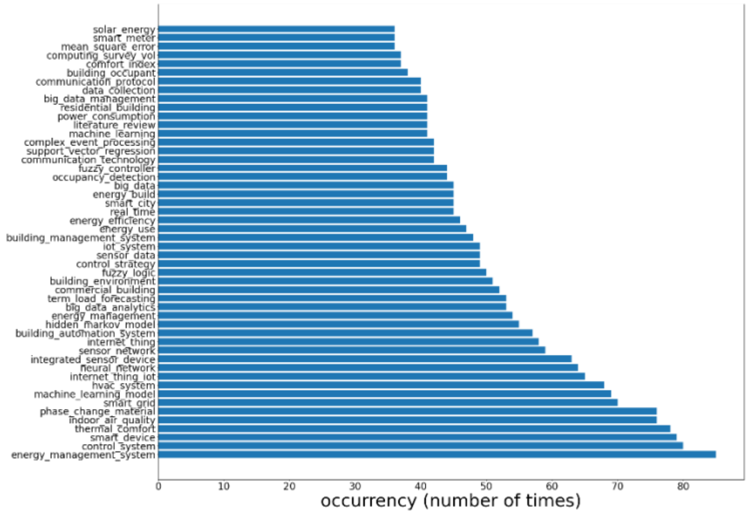


*Fig. 4. Bi-grams and Tri-grams Word Cloud Occurrency (first 50)*

The first evident outcome of the analysis is that the most investigated field concerns the energy efficiency and indoor comfort management supported by automatic control systems. Indeed, in Fig. 4 the bi-grams and tri-grams "indoor air quality", "termal comfort", "hvac system", "control system" and "energy management system" are the most frequent in the corpus text.

After these main topics, the most relevant ICT technologies determined by the analysis are the tools that support such systems: Internet of Things (keywords highlighted by "smart device", "Internet Of Thing", "Sensor Network" and "IoT System"), Big Data ("Big Data Analytics", "Big Data") and Artificial Intelligence ("Neural Network, "Artificial Neural Network", "Machine Learning").

By the presented analysis results, it is possible to specify the generic ICT sub-layer as it is shown in Fig. 5: the new emerging technologies that are changing design and management of IBs are BD including the semantic concepts of "Big Data Analytics", "Big Data Management", "Neural Network, "Artificial Neural Network", "Machine Learning Model" and "Machine Learning"; IoT including the semantic concepts of "Sensor network", "IoT system".

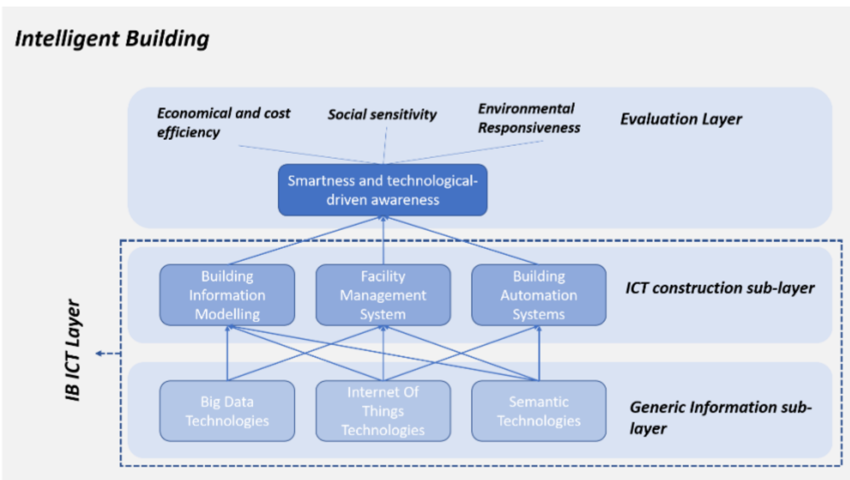


*Fig. 5. Intelligent Buildings General Conceptual Framework*

Moreover, considering the basic importance of BIM in the IB applications, in this paper we also investigate about one of the main ICT strategies recently used in BIM: the ST.

# 3. INVESTIGATED ICT TECHNOLOGIES

In this section the technologies composing the ICT IB layer are described, pointing the attention mainly on the aspects analysed and reviewed in the related literature.

First the importance and the roles of such technologies is outlined by describing their integration in a typical cloud-based architecture. Then they are individually described highlighting the reviewed features.

## 3.1 The integration of the ICT technologies in the BIM

Common architectures to develop cloud-based computing systems for IoT and BD in BIM are designed by implementing the following layers:

- *Sensing layer*: IoT sensors and devices aiming at collecting data from the environment. This sensing layer is devoted to the implementation of the connections between the physical world and the IBs (Dou & Nan, 2017).
- *Network layer*: the configuration of the network infrastructure for allowing transmission of data. In particular, data can flow both from and to the sensing/physical layer. Important requirements regard communication and security issues.
- *Cloud-based Big Data Management layer*: internally divided in sub-modules, is devoted to the BD-related tasks, such as data acquisition, integration, storage and mining (Cai et al, 2017).
- *Cloud-based service layer*: the services available to the users.

BIM, with its evolution in the Digital Twin for construction, is a huge source of information about the building process during the IB life-cycle, since it allows the collection of data and information regarding geometric description, material composition, but also procedural information for construction process. In a cloud-based architecture, BIM can acquire data also from remote sources and repositories such as weather data, Geographical Information Systems data and seismic data, as well as from IoT infrastructure. Semantic and ontology technologies can offer a strong support for formalizing and reusing acquired knowledge about building life-cycle processes. Moreover, BD infrastructure are improving their support for STs, that are also playing a relevant role in IoT data semantic enrichment and in BIM platform exchange information capabilities.

## 3.2 Big Data

Multi-source data are effective information sources for knowledge extraction. As firstly specified in the Doug Laney 3V model (Laney, 2001), BD are characterized by specific features as "Volume", i.e., huge data size, "Velocity", i.e., data speed of generation and "Variety", i.e., different formats. Further feature like "Veracity" considers the authenticity and trustworthiness, "Value" is the "*added-value that the collected data can bring to the intended process*" (Demchenko et al, 2013). In addition, BD analytics involves the processes of searching a database, mining, and analysing data (Marjani et al, 2017). More precisely, different BD analytics can be applied according to the time requirements:

- Streaming or Real-time analytics is performed on data collected from sensors. Due to memory constraints, small data portions of the stream are stored and examined to determine potential knowledge from the approximated patterns. Some examples of platforms supporting streaming analytics (Silva et al, 2016) are Spark, Storm, and Kafka.
- Batch/off-line analytics is used when a real-time response is not required (Chen & Zhang, 2014), and differently from real-time data analytics, it analyses data after storing. MapReduce is the most widely used batch processing method (Silva et al, 2016) and Hadoop, Kafka and are examples of off-line analytics architectures (Marjani et al, 2017).

Distributed storage, distributed and parallel computing are with the data analysis processes involved in the BD implementation. There are different open-source frameworks for BD-based software development (Silva, et al., 2016) (Chintapalli et al, 2016): for instance Apache Hadoop, Apache Spark, Apache Storm, Apache Kafka and Apache Flink.

## 3.3 Internet of Things

Different IoT definitions are present in literature (Dhumane et al, 2016). As reported in (Enterprise, et al., 2008), "*the semantic origin of the expression is composed of two words and concepts: Internet and Thing, where Internet can be defined as the world-wide network of interconnected computer networks, based on standard communication protocol, the Internet suite (Transfer Control Protocol/Internet Protocol TCP/IP), while Thing is an object not precisely identifiable. Therefore semantically, Internet of Things means the worldwide network of interconnected objects uniquely addressable, based on standard communication protocols.*"}

The IoT network can be specified with regard to communications area dimensions (Lin et al, 2017):

- *Low Power Wide Area Network* is a communication scheme that can achieve the long-range *machine to machine* communication by using low power energy with low data transmission rate (Gu et al, 2020). The main technologies for Low Power Wide Area Network are: *SigFox*, *Low Range WAN*, *Long Term Evolution-Modified*, *NarrowBand IoT*.
- *Short Range Network* is used for medium and short-range *machine to machine* communication. The main technologies adopted for Short Range Network are: *IPv6 over low-power wireless personal networks*, *ZigBee*, *Bluetooth Low Energy*, *Radio-frequency Identification*, *Near Field Communication*, *Z-Wave*, *Message Queuing Telemetry Transport Protocol*, *The Constrained Application Protocol*, *Advance Message Queuing Protocol*.

## 3.4 Semantic Technologies

### 3.4.1 Ontologies in Construction Industry

The ontology is fundamental concept in dealing with knowledge usage applications, together with formalization and representation concepts. In (Gruber, 1993) the ontology is defined as "*a formal, explicit specification of a shared conceptualization*", i.e., "*simplified view of the world to represent*". In some cases, the conceptualization aims at organizing concepts into a hierarchical tree structure. The entities of the structure are characterized by super-classes, sub classes and relationships, and their semantic descriptions enable automated query and reasoning.

In the construction-related literature, these concepts are applied mainly in information extraction by BIM software (Ismail et al, 2018) (Pauwels et al, 2017) and in automated flows of data in cloud computing environment (Lee et al, 2016).

In particular, Industry Foundation Classes (IFC) is a data model widely applied in semantic-oriented description in the construction industry. IFC data model is defined as "*a standardized, digital description of the built environment, including buildings and civil infrastructure. It is an open, international standard (ISO 16739-1:2018), meant to be vendor-neutral, or agnostic, and usable across a wide range of hardware devices, software platforms, and interfaces for many different use cases*" (buildingSMART International, 2018). The data model language EXPRESS (Schenck & Wilson, 1994) is formally used in IFC format and proprietary platform owners are implementing it in BIM models.

Even if IFC has prominent role in the BIM model description, it is cannot be defined as an ontology in the architecture, engineering and construction industry domain, due to the problems in its practical applications. In (Pauwels et al, 2011) and (Beetz et al, 2009) authors identify the main limitations of IFC approach: limited expression range, difficulty in partitioning information, ambiguity deriving from the multiple possible descriptions of the same information, limited reuse and interoperability.

Hence, ST can be considered valid tools to integrate and model information in an ontology-based environment in order to overcome the IFC limitations.

### 3.4.2 Semantic Web Technologies in constructions

The semantic web is an information space able to integrate different knowledge, expressed in compatible meanings/forms and expand isolated source of knowledge (Decker & Hauswirth, 2008). According to the W3C (Barners-Lee, 2009), the "*semantic web is a web of data to provide a common framework that allows data to be shared and reused across applications, enterprises, and community boundaries*".

In particular, Semantic Web Technologies are devoted to the exploitation of the semantic web potential, and the translation of the ontology-based knowledge representation paradigm, in order to allow the reuse of formalized knowledge.

The World Wide Web Consortium identifies (W3C, 2012) some core technologies of the Semantic Web environment:

- *Resource Description Framework (RDF)* is "*a framework for representing information in the Web*" (W3C, 2014). In RDF, data and information are expressed as directed labelled graphs, that allow to describe information in Semantic Web as a set of "triple", composed by subject, predicate and object.
- *Web Ontology Language (OWL)* is a semantic web language designed to represent ontologies in the web. "*It is a computational logic-based language such that knowledge expressed in OWL can be exploited by computer programs, e.g., to verify the consistency of that knowledge or to make implicit knowledge explicit*" (W3C, 2012).
- *SPARQL query language for RDF* is a language used to query data stored as RDF graph across different data sources (W3C, 2013).

Other important data web technologies are the linked data, introduced in (Berners-Lee, 2006), defined as "*a set of best practices for publishing structured data on the Web*" (Barners-Lee, 2009). A vision that underlines their important role asserts that they are "*to spreadsheets and databases what the Web of hypertext documents is to word processor files*" (Barners-Lee, 2009).

#### 3.4.3 Semantic Sensor Web

Also for sensors data there is a strong effort to enhance web automation capabilities, by replicating the data approach of configuring a common web information infrastructure to improve their reachability (Sheth et al., 2008).

The two main organizations that are leading the standardization process are the Open Geospatial Consortium (OGC) and the World Wide Web Consortium: the sensor web is described by the OCG as a "*Web-accessible sensor networks and archived sensor data that can be discovered and accessed using standard protocols and application program interfaces*". Sensor Web Enablement is acting to reduce the poor standardization aiming at reaching deeper automated data exploitation by adopting these technologies.

There are many ontologies developed to semantic enrichment and formalization of sensors and sensors data (Bermudez-Edo et al, 2016): semantic sensor web ontology from W3C Group (W3C, 2017), IoT-A model and IoT.est (Wang et al, 2012), Sensor Model Language and OneM2M (One2M2, 2014).

## 4. APPLICATIONS OF ICT TO THE INTELLIGENT BUILDINGS

In this section, the literature is reviewed by adopting the hierarchical framework introduced in Section 2. In particular, the ICT technologies adopted for the implementation of the IB ICT layer inner components are analysed.

The analysis is conducted by considering the building life-cycle phases and the related performance sub-areas shown in Fig. 2.

The results of the review are summarized in Tab. 2, Tab. 3, Tab. 4, Tab. 5, Tab. 6.

In each table, the following information is reported: the first column shows the reference of the considered paper; the second column shows the BIM-related technologies that characterize the ICT construction sub-layer (denoted Middle Layer) of the framework in Fig. 5; the third, fourth and fifth columns describe technologies related to the generic information sub-layer (denoted Low Level) consisting of BD, IoT and ST; the last column reports the domain of application in the building life-cycle (Fig. 2).

### 4.1 Planning / Design

Tab. 2 summarizes the ICT technologies that are mentioned in the reviewed papers according to the proposed framework and focusing on the "planning/design" stage.

In (Lee et al, 2016) the authors propose a framework based on linked data for BIM defects detection. The aim of the system is to convert defect data to an ontology-based linked data format in order to link and search defect data between different data sources. In (Wu & Issa, 2012) a cloud-BIM approach is proposed in order to achieve an optimized leadership in energy and environmental design project delivery and certification. In (Costa & Madrazo, 2015) ST have been applied for building component descriptions by using linked data from different sources available on the Web. Moreover, the data sources are made available and accessible in product catalogue to end-users working with BIM models via web services.

In (Zhang et al, 2013) the authors propose an automated approach to identify and prevent potential safety hazards by using a rule-based checking system integrated with BIM. The hazard identification is implemented in the early design stage. In (Jeong, 2018) an evaluation, analytics and prediction platform is presented for BIM in order to collect, store, process, and analyse BIM data in an integrated approach. BIM is used as an "entry point" for user information that are automatically converted into ontology, characterized by a web-scale expandability.

*Tab. 2. Adoption of the analysed technologies in planning/design stage*

| | **Middle Layer** | **Low Layer** | | | |
|---|---|---|---|---|---|
| **Ref.** | **BIM** | **BD** | **IoT** | **ST** | **Sub-Areas** |
| (Lee, et al., 2016) | Autodesk Revit | - | - | RDF Converter, SPARQL, Protege, Linked Data | Knowledge reuse |
| (Wu & Issa, 2012) | Autodesk Revit, Stratus | - | - | - | Optimal Design |
| (Costa & Madrazo, 2015) | Autodesk Revit | - | - | D2RQ | Knowledge reuse |
| (Zhang, et al., 2013) | Tekla | | | | Health & Safety |
| (Jeong, 2018) | WebGL, General BIM | Hadoop, Spark, MapReduce | - | OWL | Interoperability |

## 4.2 Construction

Tab. 3 summarizes the ICT technologies that are mentioned in the reviewed papers focusing on the "Construction" phase.

In (Ding et al, 2016) the authors introduce an organized, stored and reusable construction risk knowledge, by combining the strength of BIM, ontology and semantic web in an ontology-based methodology. More precisely, a risk map representing this risk knowledge allows capturing and semantically inferring interdependence between risk and risk paths. A tool is implemented to allow the reuse of the knowledge. In (Li et al, 2018) a centralized BIM platform powered with IoT applications provides features both for integrating information from previous construction stages and for real-time locating prefabricated components by improving decision making among stakeholders. In (Teizer et al, 2017) an application of IoT together with the lean and injury-free construction management approach is presented. Firstly, a framework to integrate in existing system the proposed application and then a prototypical example is described with a validation in field-like work setting. In (Riaz et al, 2014) the authors propose *CoSMoS*, i.e., a system that aims at improving health and safety of workers in construction work-site by integrating real-time sensors monitoring in a BIM environment. The solution is applicable in construction and maintenance stages. Paper (Fang et al, 2016) proposes a solution for monitoring the construction site, on the basis of RFID protocols by locating construction workers and providing real-time visualization with a cloud server architecture. The visualization capability is based on BIM technology. In (Matthews et al, 2015) authors apply BIM360 Field technology to a real-case scenario in order to extend BIM potentiality of the progress monitoring from the design phase to the construction site. In (Jiao et al, 2013) authors aim at solving the full life-cycle data management by implementing a cloud architecture.

*Tab. 3. Adoption of analysed technologies in construction stage*

| | Middle Layer | Low Layer | | | |
|---|---|---|---|---|---|
| **Ref.** | **BIM** | **BD** | **IoT** | **ST** | **Sub-Areas** |
| (Ding, et al., 2016) | Autodesk Revit, Naviswork | - | | SWRL, OWL, Protege | Health & Safety |
| (Li, et al., 2018) | WebGL | - | RFID | - | Stage Monitoring |
| (Teizer, et al., 2017) | Autodeks Revit, Dynamo | Azure | BLE, RFID | BIMtoIFC | Indoor Localization |
| (Riaz, et al., 2014) | Autodesk Revit | - | TelosB | - | Health & Safety |
| (Fang, et al., 2016) | General BIM, Unity | - | RFID | - | Indoor Localization |
| (Matthews, et al., 2015) | Autodesk Revit, Naviswork, BIM360 Field | - | | - | Stage Monitoring |
| (Jiao, et al., 2013) | Autodesk Revit, Naviswork | SQL Database, MongoDB | | - | Stage Monitoring |

## 4.3 Operation / Maintenance

Tab. 4 summarizes the ICT technologies that are mentioned in the reviewed papers focusing on the "Operation/Maintenance" phase.

In (Arslan et al, 2017) the authors develop a tool to reduce building hazards in facility management stage. BIM technologies, sensors and Hadoop architecture are integrated to gather real-time data about temperature, activities in the facilities and water monitoring. The data are then aggregated and exposed by cloud services. Paper (Bashir & Gill, 2016) presents an IoT BD analytics framework for storing and analysing real time data generated by IoT sensors inside the IB. A real-case scenario that analyses by the automatic management of the oxygen level, luminosity and smoke/hazardous gases in wide areas is conducted.

In (Dave et al, 2015) a platform named *Otaniemi3D* is proposed in order to provide information about energy usage, occupancy and user comfort by integrating BIM, IoT devices, IFC and open messaging standards. An implementation of Bluetooth devices for indoor location and customizable pathfinding solutions for building modelled by BIM technologies is described in (Ferreira et al, 2018). A framework for managing information in the operational stage of buildings is implemented in (Pasini et al, 2016).

In (Bottaccioli et al, 2017) an IoT software infrastructure integrating heterogeneous data from IoT devices into BIM and geographical information systems is presented. The validation of building energy model with real data and the simulation of building energy behaviour is strengthened by the usage of real weather data from third-part services. The system can be employed to check near-real-time bad usage of building resources. In (Yu, 2016) the integration of information between BIM and sensor data is obtained by a linked data approach. The work aims at the performance analysis of the energy demand of the facility manager's building. Linked data for implementing cloud-based data services are proposed in (Curry et al, 2013). In (Degha et al, 2019) an intelligent context-awareness building energy management system aiming at identifying particular energy waste causes is presented. In (O'Flynn et al, 2010) authors develop a wireless sensor network by ZigBee technology to efficiently monitor energy consumption in integrated BIM environment.

In (Sternal, 2016) authors integrate a semantic sensor network with the IFC standard in a prototypical wireless structural health monitoring system.

A real-time energy awareness system and an audit-style energy tracking system are implemented using the merged data. A middleware for ambient intelligence systems is presented in (Stavropoulos et al, 2013). It is based on the Service-Oriented Architecture, and the work includes a real-scenario application in a smart university system, a prototype board server, and a sample client application. In (Linder et al, 2017) the authors present an architecture named *Building Big Data*, i.e., a distributed system for storing and processing building data. In the platform, ICT tools for data analytics and software applications development are implemented; also, an insight on scalability is given in order to aggregate data from different smart buildings. The support of intelligent water management is the topic in (Howell et al, 2017), where sensing, analytics, services and interfaces are implemented in order to optimize the water network at the homes scale. An innovation of the work is using a domain ontology on a web service to integrate heterogeneous data sources and analytics, and visualization components. The authors present a framework based on BIM and IoT technology for monitoring IB in (Kang et al, 2018). BIM is used to manage the 3D data and a prototype is developed and tested in an office building.

*Tab. 4. Adoption of analysed technologies in management stage*

| **Ref.** | **Middle Layer** | **Low Layer** | | | |
|---|---|---|---|---|---|
| | **BIM** | **BD** | **IoT** | **ST** | **Sub-Areas** |
| (Arslan, et al., 2017) | Autodesk Revit | Hortonworks Hadoop, Tableau | TelosB motes | - | Health & Safety |
| (Dave, et al., 2015) | WebGL, X3DOM | - | O-MI, O-DF | IFC OpenShell | Indoor Occupancy |
| (Bottaccioli, et al., 2017) | Autodesk Revit | - | ZigBee | - | Energy Monitoring |
| (Yu, 2016) | Autodesk Revit | - | - | Apache JENA RDF API, IfcOWL, SAREF, SPARQL, IFCtoRDF | Energy Monitoring |
| (Sternal, 2016) | - | - | 802.15.4 / ZigBee | IFC, SSN | Structural Health Monitoring |
| (Bashir & Gill, 2016) | - | Flume, HDFS, Spark | TCP | | Health & Safety, Indoor air monitoring |
| (Curry, et al., 2013) | - | - | | Linked Data, Semantic Sensor Network | Energy Monitoring |
| (Stavropoulos, et al., 2013) | - | - | ZigBee, Z-wave | - | Smart Monitoring |
| (Linder, et al., 2017) | - | Kafka, Flink, MySQL, Cassandra | - | - | Indoor Monitoring |
| (Howell, et al., 2017) | - | - | MQTT | Apache Jena | Water management |
| (Degha, et al., 2019) | Open Smart building Simulator | - | - | - | Energy Simulation, monitoring |
| (Quinn, et al., 2020) | Autodesk Revit, Dynamo | Kafka, Spark, Cassandra | TCP | - | Facility Management |
| (Pasini, et al., 2016) | Autodesk Revit | - | Z-wave | BIMtoIFC | Indoor Occupancy, Air Monitoring |
| (Kang, et al., 2018) | Autodesk Revit | MongoDB | MQTT | IFC Converter | Indoor Air Monitoring |
| (Rio, et al., 2013) | ArchiCAD, Solibri | - | - | IFC Converter | |
| (Fernbach, et al., 2016) | General BIM, gbXML | - | OPCUA, Obix, 6LoWPAM | OWL, SPARQL | Indoor air monitoring, Energy monitoring |
| (Chen, et al., 2014) | Autodesk Revit API | - | - | IFC Converter | Automatic As-built details updating and performance monitoring |
| (Chen, et al., 2018) | Autodesk Revit | MySQL | BLE | - | Disaster And emergency response |
| (Park, et al., 2018) | Unity | - | ZigBee | - | Disaster And emergency response |
| (Bottaccioli, et al., 2017) | Autodesk Revit, gbXML | - | ZigBee | - | Energy Monitoring, simulation |
| (Ferreira, et al., 2018) | Autodesk Dynamo | - | BLE | - | Indoor Localization |
| (O'Flynn, et al., 2010) | General BIM | - | ZigBee | IFC Converter | Energy Monitoring |
| (Lee, et al., 2016) | Unity | - | - | - | Facility Management |
| (Mohamed, et al., 2020) | Autodesk Naviswork | - | - | Apache Jena, SPARQL | Facility Management |

In (Quinn et al, 2020) a foundation study for the development of a cloud-based platform for the integration of BIM and FMS platforms is presented. A tool is implemented for data analytics, and complex predictive and classification modelling. Also data visualization issue for managers is analysed. In this BIM-based system, the integration of different data sources is used to improve building conditions linked to user behaviours. In (Rio et al, 2013) authors integrate sensor data, BIM and structural analysis. In the paper they develop a prototypical data transfer model that integrates modelling, visualization and structural analysis tools. A first step in using semantic web technologies in building automation systems is presented in (Fernbach et al, 2016). A reference designation system is integrated in a BIM environment. A proof-of-concept prototype for embedded real time information from sensors in BIM is presented in (Chen et al, 2014). A software that allows real-time energy monitoring and simulation and integrates BIM and IoT sensors is developed in (Bottaccioli et al, 2017). A cloud-based BIM application for visualizing and managing facility tasks is developed in (Lee et al, 2016), while an automatic integration of BIM and FMS information is obtained with ST in (Mohamed et al, 2020).

In (Chen et al, 2018) authors develop a fire visualization and warning system by integrating BIM, fire simulation and IoT technology. In (Park et al, 2018) authors propose an augmented reality-based smart building that focuses on fire emergencies and integrates different sensors in a cloud-based environment.

## 4.4 Improvement / Disposal

Tab. 5 summarizes the ICT technologies that are mentioned in the reviewed papers focusing on the "Improvement/Disposal" phase.

A "cognitive" concept applied to building is elaborated in (Desogus et al, 2017), where a monitoring framework is used for energy retrofit in a real-case application. In (Bilal et al, 2016) the authors propose a BD architecture for construction waste data analytics based on a waste analytics life-cycle. The authors in (Cheng et al, 2020) focus on BIM and IoT integration for improving predictive and long-term dynamic maintenance strategy. Finally, (Tsai et al, 2019) presents an approach to manage and predict corrosion in mechanical and electrical plumbing BIM by integrating RFID and cloud-based tool in Autodesk environment.

*Tab. 5. Adoption of analysed technologies in improvement/disposal stage*

| | Middle Layer | Low Layer | | | |
|---|---|---|---|---|---|
| **Ref.** | **BIM** | **BD** | **IoT** | **ST** | **Sub-Areas** |
| (Desogus, et al., 2017) | Autodesk Revit | - | Z-wave | IFC Converter | Energy Retrofit |
| (Bilal, et al., 2016) | Autodesk Revti | Flume, Spark, HDFS, Neo4J | - | - | Waste Analytics |
| (Cheng, et al., 2020) | Autodesk Revit | Autodesk Forge | RFID | - | Predictive Maintenance |
| (Tsai, et al., 2019) | Autodesk Revit API | - | BACNet | IFC Converter SSN | Predictive Maintenance |

## 4.5 Full life-cycle phases

Tab. 6 summarizes the ICT technologies that share applications in all the IB life-cycle phases.

In (Chen et al, 2015), features as viewing, storing and analysing massive BIMs are implemented in a cloud-based system by using: i) Apache Hadoop as cloud computing technology, ii) WebGL 3D as display technology, iii) and HTML5 as web page technology. The on-line services provided by the systems allow to upload BIMs model to involve both the project and the visualization capability. In (Lv et al, 2020) authors propose an hybrid storage architecture including NoSQL database, distributed peer to peer storage, and spatial database engine to store remotely BIM geo-spatial data. An open-source BIM platform based on cloud computing technology to handle geo-spatial data is presented in (Logothetis et al, 2018). In (Das et al, 2014) a tool named *Social BIMCloud* facilitates the storage and the partial exchange of integrated BIM to study inefficiency in data transfer speed and inconsistency in a distributed environment. The result is achieved both by using IFC technology and cloud-based

NoSQL database. In (Zhou et al, 2019) authors deal with the visualization of geometrical BIM big data, and propose a novel scalable BIM triangulation service named *BIMTriSer*: the service is able to decompose the original IFC description into several IFC files. BIMTriSer enables scaling of IFC geometric triangulation thanks to a parallel computing framework. Also in (Johansson et al, 2015) complexity and challenges involved in visualizing large BIMs are addressed. The main contribution is the development and the validation of a prototypical BIM viewer to handle detailed and large building models. In (Dimyadi et al, 2016), a web service based on the Representation State Transfer (REST) protocol is used to integrate BIM Rule Language into an automated compliance audit framework named *ARCABIM*.

*Tab. 6. Adoption of analysed technologies in full-cycle stage*

| Ref. | Middle Layer | Low Layer | | | |
|---|---|---|---|---|---|
| | BIM | BD | IoT | ST | Sub-Areas |
| (Chen, et al., 2015) | CloudBIM (WebGL) | Apache Hadoop, Hbase | - | IFC Converter | Data Visualization |
| (Lv, et al., 2020) | WebVR | Apache Accumulo | - | - | Data Management |
| (Logothetis, et al., 2018) | BIMsurfer | BIMServer, Maria DB, Apache Tomcat | - | - | Data Visualization |
| (Das, et al., 2014) | Autodesk Revit | Cassandra | - | IFC Converter | Data Management |
| (Zhou, et al., 2019) | BIMTriSer | MPI, Spark | - | IFC Splitter | Data Management |
| (Johansson, et al., 2015) | Developed Visualizer | - | - | IFC Converter | Data Visualization |
| (Dimyadi, et al., 2016) | BIMSurfer | BIMServer | - | IFC Converter | Data Management |

# 5. DISCUSSION

## 5.1 Research findings

A synthesis about the distributions of the considered technologies in the reviewed papers is performed in the current subsection.

In particular Fig. 6 shows the number of times ST, IoT and BD are utilized in the 44 analysed papers employing the BIM in the different life cycle phases. The bar diagram shows that ST is the most used technology followed by IoT and BD.

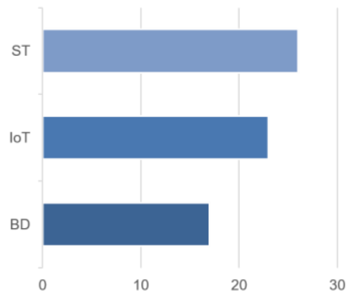


*Fig. 6. ICT IB components usage in references*

Moreover, Fig. 7 shows that most of the analysed papers adopt two (51%) or three (43%) of the components of the IB ICT layer in Fig. 5. Only few papers employ one component or all the components. More precisely, Fig. 8 specifies Fig. 7 by listing the number of papers that integrate the different technologies. As expected, the most diffused applications regard the BIM-IoT integrated usage. On the other hand, few papers consider IoT, BD and ST without integrating them in a BIM component.

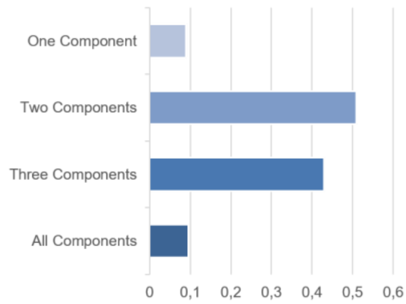


*Fig. 7. ICT IB components integration in references*

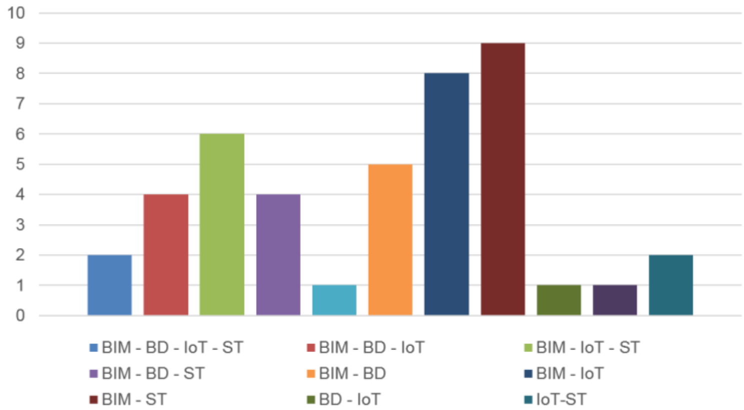


*Fig. 8. Framework components integration in references.*

In Tab. 7 the specific BIM-related technologies adopted in the researched papers are reported. In this context, BIM-related technologies refer strictly to BIM features that characterize proprietary software, but also to all cloud-based data visualization tools and software libraries.

Fig. 9 shows the number of times in which the mentioned BIM technologies are applied in the considered papers. It is evident that Autodesk Revit is the most used technology in the BIM integration strategies. Also other Autodesk-related technologies like Dynamo, Naviswork and Revit API are applied, because of their flexibility and potential in services and applications customization. Moreover, libraries for cloud visualization (like WebGL) are also applied in 4 papers.

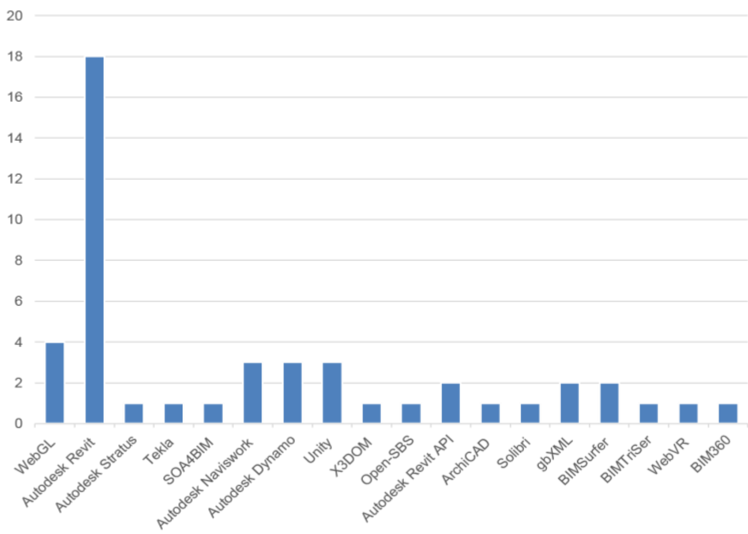


*Fig. 9. BIM-related technologies adoption*

*Tab. 7. BIM-based adopted technologies*

| Technology | Functionality | Description |
|---|---|---|
| WebGL | Cloud Visualization | Web standard for a low-level 3D graphics API based on OpenGL ES, exposed to ECMAScript via the HTML5 Canvas element. |
| Autodesk Revit | Design, visualization, management | Software for integrated BIM, also able to export to IFC4 format. |
| Autodesk Stratus | Design, visualization, management | Autodesk Revit add-on which leverage mechanical and electrical plumbing together with fabrication issue. |
| Tekla | Design, visualization, management | BIM software focused on structural construction activities. |
| Autodesk Naviswork | Management | Project review software that improve the BIM project obtained by integration of different projects coordination. |
| Autodesk Dynamo | Design | Parametric and generative modeling tools in Autodesk Revit environment. |
| Unity | Cloud visualization | Game engine to create web-based visual programming dynamic models. |
| X3DOM | Cloud visualization | open-source framework and run-time for 3D high-resolution graphics on the Web |
| Open Smart Building Simulato (Open-SBS) | Visualization, Simulation | A proposed platform integrating the possibility to simulate different scenarios for smart home. |
| Autodesk Revit API | Development | Software development kit to develop plug-in and software application in Revit environment. |
| ArchiCAD | Design, visualization, management | BIM software. |
| Solibri | Design, visualization, management | Modelling, coordination and validation software. |
| gbXML | Cloud Visualization | A standard supported from industry for sharing and storing building data. |
| WebVR | Cloud Visualization | Specification to allow experience of Virtual Reality in browsers. |
| BIM360 Field | Construction management | Platform for managing construction workflows. |

In Tab. 8 the specific BD-related technologies adopted in the considered papers are reported by focusing on BD architectures, BD technologies and widespread standard cloud-technologies. Fig. 10 points out that Apache Spark, Apache Cassandra and Apache Hadoop are the most mentioned technologies. In particular, Apache Hadoop environment still remains one standard and practically adopted tool because of its prior release. Relation database such as MySQL technologies have valuable applications.

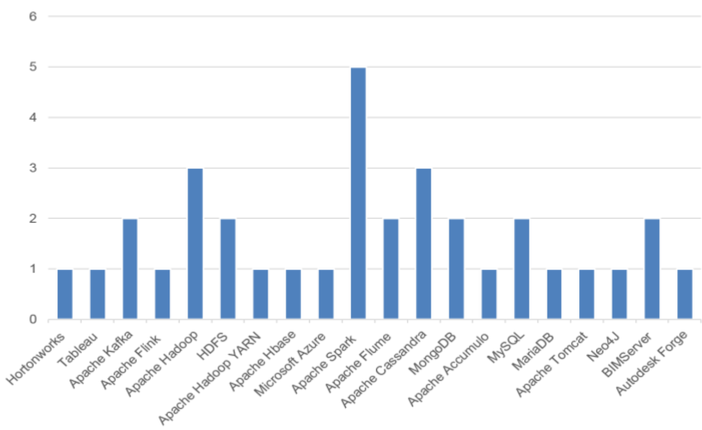


*Fig. 10. BD-related technologies adoption.*

*Tab. 8. Cloud computing-based adopted technologies*

| Technology | Functionality | Description |
|---|---|---|
| Hortonworks | distributed storage / distributed processing | Open source framework for cloud distributed storage and processing for Big Data. |
| Tableau | data visualization | A platform for visual analysis of data. |
| Apache Kafka | distributed storage / distributed processing | A distributed streaming framework used to build data pipelines for real-time data streaming among systems. |
| Apache Flink | distributed processing | A framework for data stream management. It can deal both with online and offline stream, state management, event-time processing semantics, and consistency guarantees for state. Like Spark, Flink can run on various resource providers such as YARN, Apache Mesos, and Kubernetes. Most common types of application developed by using Flink are event-driven application, data analytics applications and data pipeline applications |
| Apache Hadoop | distributed storage / distributed processing | A libraries collection that configure a framework for all Big Data-related tasks. |
| Hadoop Distributed File System (HDFS) | distributed storage | Distributed file system for storage in Hadoop environment. |
| Apache Hadoop YARN | resource provider | Hadoop environment resource manager and job scheduler. |
| Apache HBase | Distributed Storage | Open-source database for Big Data based on Google BigTable |
| Microsoft Azure | Cloud Computing | Platform that offers products and cloud services. |
| Apache Spark | distributed storage / distributed processing | General-purpose open-source distributed cluster-computing framework, supporting both stream data processing and batch processing. It integrates ApacheSparkSQL, GraphX, MLib, and Spark streaming components and can access data from various data sources and run on various platforms such as Hadoop, Mesos, and Yarn. It is considered cost effective compared to Storm even if Storm has shown superiority in terms of latency (Silva, et al., 2016). |
| Apache Flume | streaming data service | A framework for managing stream of large quantities of data, modelled as events. |
| Apache Cassandra | Distributed storage | Open-source distributed NoSQL database solution for Big Data. |
| MongoDB | Distributed storage | Document-based NoSQL distributed database. |
| Apache Accumulo | Distributed storage | Key/value NoSQL distributed database. |
| MariaDB | Storage | SQL Database technology. |
| Apache Tomcat | Web server | Open Source software for powering large-scale application over the web. |
| Neo4J | Distributed storage | A graph database technology to leverage also relationships between data. |
| Autodesk Forge | web-service API's | Environment to improve Autodesk data formats interoperability. |

Tab. 9 reports the specific IoT-related technologies adopted in the considered papers by referring to communication protocols and hardware devices.

Fig. 11 shows that ZigBee is the most used technology because of its double nature of hardware device integrated with specifically implemented communication protocol. RFID and Z-wave are also widespread.

*Tab. 9. IoT-base adopted technologies.*

| Technology | Functionality | Description |
|---|---|---|
| Crossbow TELOSB | Platform/device | Platform published to research community with IEEE 802.15.4/ZigBee compliant RF transceiver sensors. |
| O-MI/O-DF | communication protocols | A Messaging standard text-based protocol (Robert, et al., 2016). |
| ZigBee | communication protocols | Communication protocol & Protocol on top of IEEE 802.15.4 network standard. It allows the creation of personal area network application that requires a low data rate, longer battery life, and secure networking devices (Al-Sarawi, et al., 2017). |
| BACNet | Communication protocol | Standard data communication protocol for building automation and control networks (Park & Hong, 2009). |
| Z-wave | Communication protocol | Low speeds, network up to 50 nodes and small data packets characterize this technology. Masters and slaves nodes network, with only masters node able to initialize the communication and force slaves to execute commands. |
| Message Queuing Telemetry Transport Protocol (MQTT) | Communication protocol | A publish/subscribe, simple and lightweight messaging protocol, designed for constrained devices and low-bandwidth, high-latency or unreliable networks |
| Open Platform Communications Unified Architecture (OPCUA) | Service Oriented Architecture | An Interoperability platform-independent standard, for data exchange in industries |
| Open Building Information Xchange (oBIX) | Web service | XML web service-based mechanism for building control systems. |
| 6LoWPAN | Communication Protocol | Protocol in which every device is identified by a unique IPv6 address (Han, 2015) |
| Radio-Frequency Identification (RFID) | Technology | Characterized by a variety of standards, consists of a reader device and a small radio-frequency (from 3 to 30 GHz) transponder called RF tag. Main feature of RFID is the necessity of programming static information into the tag; since static nature of programmed data, possible application are restricted. |
| Bluetooth Low Energy (BLE) | Communication protocol | It aims at minimizing power consumption in low data rate application in power constrained IoT application (Jeon, et al., 2018). |
| Transfer Control Protocol (TCP) | Communication protocol | Data transfer protocol that belongs to the Internet Protocol Suite. |

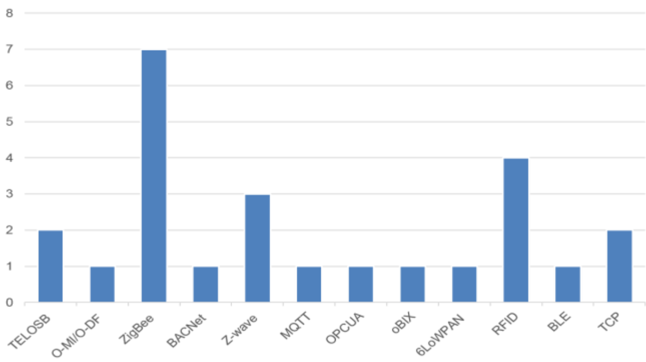


*Fig. 11. IoT-related technologies adoption.*

In Tab. 10 the specific ST-related technologies adopted in the reviewed papers are reported. More precisely, the considered ST applications deal with: i) the conversion issues from BIM proprietary format to a common IFC interoperable format; ii) the cloud-exploitation of converted format; iii) the semantic web technologies to deal with converted data; iv) the ontology-based reasoning basing on converted format and semantic web technologies; v) the semantic enrichment of IoT data from sensors.

In addition, Fig. 12 shows that the use of conversion tools from BIM to IFC format is the most widespread application, but also the ontology-based reasoning has numerous applications due to OWL usage.

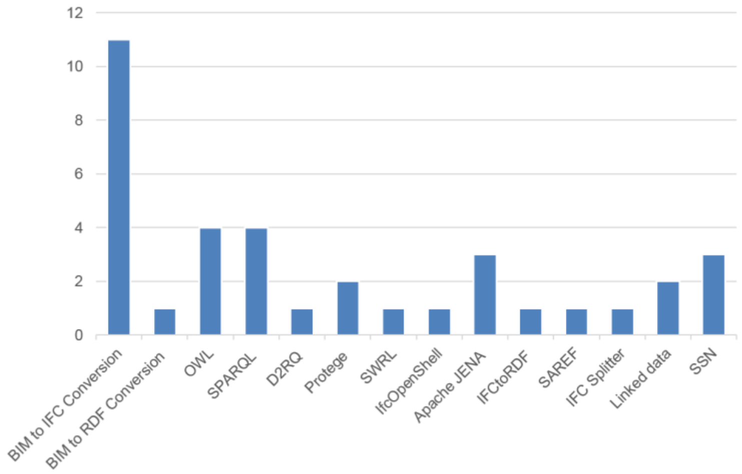


*Fig. 12. Semantic-related technologies adoption.*

*Tab. 10. Semantic-related adopted technologies*

| Technology | Functionality | Description |
|---|---|---|
| BIM to IFC Conversion | Conversion | IFC used as an exchange format to allow reusing of BIM data. |
| BIM to Resource Description Framework (RDF) | Conversion | RDF used for semantic query via SPARQL towards converted BIM data. |
| Ontology Web Language (OWL) | Knowledge formalization | Semantic Web language designed to represent ontologies over the web. |
| SPARQL | Query Language | Language used to query data in RDF format. |
| D2RQ | Platform | Solution to map and expose SQL databases as RDF/OWL ontologies |
| Protege | Platform | Open-source service and framework to build ontology on the Web, fully supporting OWL2 specification. |
| Semantic Web Rule Language | Language | A combination of sublanguages of the OWL Web Ontology Language with a sublanguage of the Rule Markup Language. |
| IfcOpenShell | Visualization | Open-source library to work with IFC files. |
| Apache JENA | Development framework | Open-source framework for Semantic Web and Linked data-oriented application development. |
| IFCtoRDF | Conversion | Development components written in JAVA to convert from IFC to RDF graphs. |
| Smart Applications REFerence (SAREF) | Knowledge formalization and sharing | An official ontology model for smart applications domains. |
| IFC Splitter | Conversion | Library for splitting IFC file in smaller parts. |

The distribution of the reviewed work in the analysed building life-cycle is also an important aspect to be investigated. To this aim Fig. 12 shows the distribution of the considered papers in the different cycle-life sub-areas reported in Fig. 2. Building life-cycle phases and sub-domains.. The analysis points out that about half of the reviewed works focus on the operation/maintenance stage. This result was expected since the most investigated topics in IBs related literature are about Energy Management, Building Automation Systems, etc. as it is pointed out in the review analysis performed in Section 2.

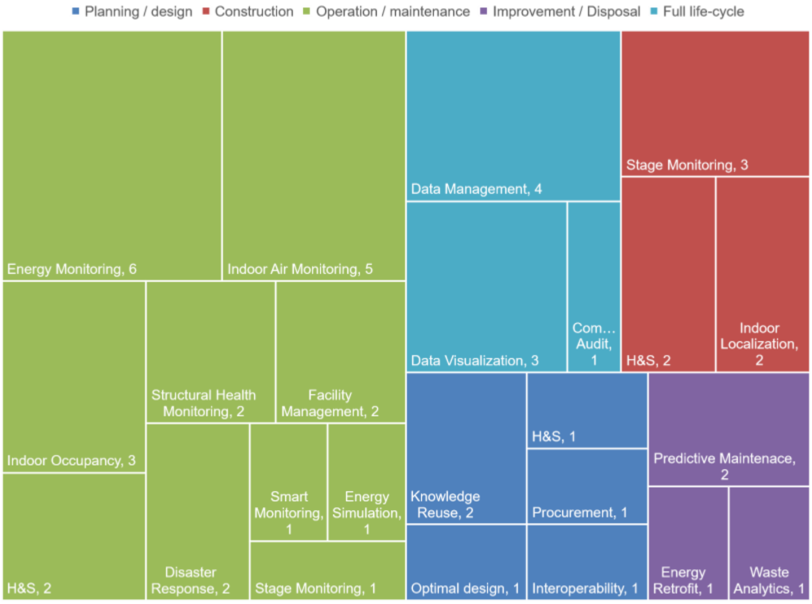


*Fig. 13. Life-cycle classification of applications.*

## 5.2 Future Challenges

This paper reviewed different implementation strategies and operative tools adopted for the IB ICT Layer by considering the whole building life-cycle. These strategies aim at optimizing the management of the building life-cycle sub-areas presented in Fig. 2.

The construction process during the whole life-cycle is a complex process, due to the countless technical and management aspects involved. Mainly, this process is still conducted with an anachronistic approach if it is compared with other application fields: operative tools allow to simulate many mandatory aspects in the design phase such as structural design, technological sub-system design and legal constraints in urban planning. After the design, the construction phase needs to strictly follow the design specifications; after the construction, a single time-defined testing step assures the correspondence between design and construction; the future development during operational stages usually is not investigated and monitored, and it is not compared with the pre-construction design simulations.

These observations lead to point out the following two challenges:

- engineers take decisions on the basis of simulations and their own personal experience, that are not formalized knowledge; being not formalized, it is difficult to reuse or transfer;
- the real construction performance during building life-cycle is not matched with the pre-construction designed one, so that there is no evaluation of effectiveness of design decisions.

Regarding the first consideration, the key to solve this drawback is the availability of systems capable of collecting data and enriching a formalized and reusable knowledge. Their application to multiple buildings allows the collection and the enrichment of a unified, shared and usable knowledge.

Examples of this kind of system, providing automatic generation of knowledge bases from data, are available in literature, such as (Bosselut et al, 2019), (Chen & Luo, 2019), (Bianchi, et al., 2020). These systems are introduced in general terms and applied in other research and engineering fields. Their application to the IB area would provide the possibility of creating and formalize a real-time, up-to-date and reusable knowledge on which to build software and services to support building life-cycle management.

Regarding the second consideration, it is important to consider that the starting point in building life-cycle performance evaluation is the collection of effective IB heterogeneous data. The actual flows and real-time event processing characterize activities of the emerging intelligent systems in other research and engineering fields. In an IB system, data are referred to BIM general data, IoT sensors data, and third part service data from remote repositories, e.g. weather data. Each data type has its own features, like different granularity, semantic enrichment, and BD characteristics reported in Section 3.2: the BD paradigm is the most suitable one for this kind of applications.

In the state-of-the-art, IFC format is the *de facto* standard to represent BIM models, and is largely used also in cloud-based visualization applications. The distributed storage and retrieval best technological strategy within the Built Environment is still to be investigated.

About the collection of heterogeneous data, a specific issue is related with interoperability and data format. The most used format for interoperability is still the IFC format, used to migrate from proprietary-specific platforms to common usable formats. Despite its effectiveness, the necessity of conversion between data formats creates issues on data management in life-cycle and between stakeholders. A change of a global unified environment in which to completely manage data ranging from BIM to IoT sensors data should be investigated, in order to understand how to organically integrate the independent proprietary platforms in this ecosystem.

To this aim, semantic web technologies considered in Section 3.4 may enhance the potential of IB systems, e.g. by improving non-technical stakeholders involvement in data management and monitoring.

## 6. CONCLUSIONS AND FUTURE WORKS

This paper reviews the ICT tools and strategies presented in architecture, engineering and construction (AEC) literature and implemented in the IBs, by considering the specific applications in the different building life-cycle phases. The review analysis is performed by using an original framework that consists of a hierarchical two-layer structure, of which the lowest layer, named IB ICT Layer, contains one construction-specific sub-layer and one ICT generic sub-layer. The components of the ICT generic sub-layer are identified by a procedure supported by natural language processing technique.

The defined methodology can be applied for a review analysis in different research contests where there is a huge number of aspects and documents to be considered. Indeed, the specification of the hierarchical framework helps to single out and rank the aspects to be analysed in the review process. Moreover, the automatic procedure for exploring the paper contents allows structuring the framework in an objective way and does not need any a-priori assumptions. Obviously, the proposed approach should be supported by the critical expert supervision in order to guide the obtained research outcomes. However, the analysis performed in this work has been very useful to determine the most applied ICT tools in the AEC field and the technologies that are not adequately exploited and need future consideration.

In particular, two main conclusions can be pointed out.

First, the authors in the considered literature develop their innovative results in the BIM environment and integrate the new findings in the BIM. This common approach is a limitation for a wide knowledge management and reuse and may hinder or slow the development of new ICT tools for construction. Indeed, focusing on the BIM implementation of the technical results may prevent from the evolution of the more innovative environments such as the digital twin. Such drawback could be overcome by foster the interoperability of the software currently employed for BIM systems.

Second, a roadmap for the large application of the analyzed technologies in the construction process is still far. Indeed, the solutions presented in the literature deal with very specific construction-related problems and do not propose general outcomes for wider purposes.

Despite the evidence of large amount of data generated from construction industry during the entire building life-cycle, it is possible to conclude that there are not yet consistent applications in this field that can effectively represent an "holistic" intelligent system.

Future research will focus on the challenge of implementing an IB ICT Layer by adopting the reviewed technologies such as BIM, BD, IoT and ST to the large amount of heterogeneous data that are involved in the construction industry.

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