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A Quarter Century of Work to Revolutionize Architecture, Engineering and Construction Enterprise Information Systems

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Abstract: More than two decades ago, object-oriented representation of AEC (architecture engineering and construction) projects started to offer the promise of seamless communication of semantic data models between computer-based systems used from the design stage to the operation of the facilities. BIM (building information modelling) emerged and appeared as a means to store all relevant data generated during the life-cycle of the facilities. But this upstream view of the built environment, arising from the design and construction stages, extended to the downstream operations where building and industrial facilities appeared more and more as huge dynamic data producers and concentrators while being operated. This created new challenges leading to what is referred to as ISCs (intelligent and smart constructions). The current state of the art is that final constructions still contain various and increasingly versatile control and service systems, which are hardly standardised, and not interconnected among themselves. Monitoring, maintenance and services are done by specialised companies, each responsible of different systems, which are relying on customised software and techniques to meet specific user needs and are based on monolithic applications that require manual configuration for specific uses, maintenance and support. We demonstrate in this paper that the early promises of integration across the actors and along the life-time of facilities have gone a long way but will only be delivered through enhanced standardisation of computerized models, representations, services and operations still not yet fully accomplished 25 years after work started.

Key words: Architecture engineering and construction, building information models, semantic interoperability, intelligent and smart built environment, information systems and sensors for new services.

1. Introduction

This paper will review how progressive changes over a quarter century have led to a revolution in all stages of so-called EIS (enterprise information systems) used in the AEC/FM (architecture, engineering, construction and facility management) sectors. The emergence of product model data (having started in the early 1990s), somehow limited implementation by software companies and their slow adoption by industry will be addressed. Strength and weaknesses of the corresponding technologies will be considered and perspectives drawn. We will highlight how this slow introduction of a semantic digital artefact down to the construction and delivery of the facilities, together with the introduction of new technologies like integrated automation and control, remote diagnostics, context-aware seamless configurability, smart embedded systems and devices for monitoring and control have nevertheless slowly but steadily enabled the emergence of ISCs (intelligent and smart constructions) and RFs (responsive facilities). From thereon, the built environment is becoming a big data provider and collector and opens the road to new usages and services, completely changing the relationships between what used to be passive constructions and inhabitants or occupants into living symbioses

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between high tech hosting facilities and new services consumers.

2. Emergence and Rise of Semantic Data Models

During the late eighties and early nineties, it appeared obvious that the evolution of the performance of computer hardware and the emergence of object-orientation [1] and non-numerical software capacities would open the road to a new era of data modelling, representation and processing. Until then, computers had been mainly used to perform calculations and the emergence of AAI (applied artificial intelligence) as a disciplinary field of its own has opened the door to new ways of thinking especially with respect to what computers could be used for [2]. In the AEC sector, the first research projects having the objective to support through a common data model [3, 4] various design functions were initiated [5], often with an emphasis on HVAC (heating, ventilation and air-conditioning) performance simulations. The design stage was considered at the time as the main area where ICT (information and communication technologies) would bring value [6] for the simple reason that computer where already widely solicited for CAD (computer aided-design), structural engineering and thermal performance modelling and also because early choices have important economic consequences, e.g., up to 70% of the total life cycle cost of a product is committed by decisions made in the early stages of design [7]. Effective implementations of these SDM (semantic data models) proved possible by means of symbolic representation techniques which enabled the deployment of the first integrated systems [8-10]. Wide scale implementations of SDMs supporting data exchange mechanisms between design tools became possible and took place during the course of the COMBINE[1] project [11, 12]. Beyond simple design functions, appeared the possibility to offer additional services, prefiguring what would later be known as SOA (service oriented architectures) with code checking services for example with respect to anti-seismic design [13] or connections to documentary databases linked to the projects, e.g., building codes, project documents, etc. [14]. At that stage the development of BIM (Building Information Models), simply called SDMs at the time, became a major objective and though still confined to research projects and activities were clearly considered as representing a future major industrial stake, so as to submit them to international standardization activities with the building construction core model [15, 16].

Other projects (e.g., ATLAS EP7280) extended the objective to cover more if not all stages of the construction process leading to extended data models [17], new integration tools [18] and new software environments including knowledge base systems [19]. The IAI (International Alliance for Interoperability) was established in 1995 and quickly delivered two major IFC (Industry Foundation Classes) releases: IFC 1.0 in January 1997 [20] and IFC 1.5 in November 1997 [21], including the technical corrigenda published as IFC Release 1.5.1 in August 1998 [22] together with a methodology guide, i.e., Methodology for the Development of Industry Foundation Classes [23]. The objective of the IFC was to create a neutral environment for interoperability by providing a comprehensive specification of the information throughout the AEC/FM project lifecycle, globally, across disciplines and software applications [24]. Relationships with the ISO (International Organization for Standardization) working groups and especially ISO/STEP 10303—i.e., Standard for the Exchange of Product Model Data—were strong from the beginning of the IFC project and lead to the usage of some parts of the ISO standard published in late 1994 as basic technologies including the EXPRESS language, STEP physical file format (SPFF) exchange and the SDAI (standard data access interface) for implementation purposes and the IFC2x format was

[1] COMputer Models for the Building INdustry in Europe.

finally registered by ISO as a PAS (publicly available specification), i.e., ISO/PAS 16739 in October 2005, and since 2008, the status of this specification has remained "international standard to be revised" but harmonization with the latest IFC release 4.0 (March 2013) remains an open question.

Beyond the exchange of 2D and 3D models relying on file-based data exchange methods such as DXF (drawing exchange format), IGES (initial graphics exchange specification), and SAT (standard ACIS text) which were early developed to exchange geometric entities between one CAD system and another, parametric representations involving rules and constraints that define how shapes are to be generated or modified in various conditions [25-28] lead to new challenges that were no different from those arising from the promise that BIM models conveyed, i.e., exchange computer representations—numerical artefacts—based on construction objects and their attributes and relationships, geometry only being one of their relevant aspects. The road leading there was long as in the mid to late eighties there was no standard way of representing these aspects with existing geometry exchange standards, and the increasing presence in such models of semantic information concerning different aspects of the intended functionality or manufacturing requirements of the modelled artefact required the emergence of new methods, new tools and new standards. In some way, the requirements evolved from basic CAD to parametric modelling where the intention is to allow the design of a product for which certain dimensions are not fixed (e.g., to support families of products), to constraint-based modelling—sharing some similarities with AI based systems offering techniques of rule-based or constraint-based programming [19, 29]—where the design intent or integrity is in some way captured through the elicitation of the constraints ruling the objects [30, 31], to feature–based modelling, where in the mechanical engineering context, a feature (or more fully a form feature) is a local geometric configuration on the surface of a manufactured part which has some engineering significance and where design features are related to the intended functionality of the product [27, 28]. Therefore, these complex interoperability issues first arose in manufacturing and it is no surprise that this sector played a leading role in the development of product model exchange technologies in ISO-STEP. The standard beyond the data modelling and representation tools already mentioned, used to provide scenarios, i.e., AAM (application activity models), in which the data had to be used and exchanged, e.g., by means of activity diagrams [32], giving therefore a technical and or business context to the interchange and information flows. Furthermore, common resources were grouped under what was referred to as IR (integrated resources), and were made available to AP (application protocol) developers, producing in the latest release of STEP object-based data schemas in more than 20 different areas of manufacturing and electronics [33]. As such, the development of APs was focused on producing standardized data specifications that satisfied industry needs clearly identified [34].

As far as the AEC industry was concerned, some lead in these research areas came for Europe [35] and R&D funded activities by the European Commission Esprit programs, but apart from AP225 dealing with "building elements using explicit shape representation", aimed at representing buildings as assemblies of elements (e.g., beams, columns, windows, etc.) along with their explicit 3D representation (i.e., non parametric) plus some additional information as material properties, building element classification or versions which reached committee draft stage in January 1996, and a tentative AP228 in the HVAC sector, the AEC industry appeared insufficiently involved in STEP. A liaison status was proposed for the "Building Core Model", i.e., Part 106 [15, 16], but soon energies were organized by the IAI international industry group, somehow outside of STEP.

Unfortunately, and even though there has been some widespread adoption of BIM in the early 2000s in the AEC and FM (facility management) sectors, the early deployment of IFC has been rather disappointing, and Tolman [36] acknowledged that the AEC/FM industry's efforts to standardize product modelling generated fairly pessimistic outlooks: STEP, for being fragmented and burdened by democracy and lacking real drive behind it, and IFC, for generating weak support among industry actors and having few resources available to make substantial progress. IFC 2x2 was released in May 2003 and brought with it a considerable increase in scope, featuring 2D model space geometry, presentation, extension of the building service component breakdown, structural analysis structural detailing, support for building code verification and facility management [37]. Unfortunately, as described by Howard and Björk [38], IFCs have suffered some limitations, e.g., the lack of unified robust certification process could lead to unreliable data exchange between software applications in real projects [39], IFCs have been difficult to implement and utilize because the use cases in which exchanges are to be made have not yet been clearly defined [40]—as was required for the AP development process in STEP—and have faced a slow uptake by the industry [41]. To be honest, some of these drawbacks were anticipated and as stated by Wix as early as 2007, the case for a comprehensive reference to processes in building construction was made clear and some solutions proposed to provide the integrated reference for process and data required by BIM, by identifying the discrete processes undertaken, the information required for their execution and the results of these activities, by means of the IDMs (information delivery manuals) to define information content for data exchange based on the industry process [42] and MVDs (model view definitions) to document data exchange content based on the software and IFC properties. Model views had already been acknowledged as a requirement, though with a slightly different understanding, for some time [43-46]. Eastman et al. [40] propose an analysis of why the IFCs have to the best met a mitigated success in practice and of why other industry standards developed contemporaneously like the CIMSteel integration standard (i.e., second release CIS/2), of more limited scope and better defined usage scenarios [47] have ended up with a limited number of specific exchanges between relevant software applications but having a decisive impact on daily production. Furthermore, even if CIS/2 documentation is clearly on the pre-construction processes of design, analysis, detailing, and shop fabrication, the applicability of CIS/2 to on-site construction processes, focusing on automating the erection and surveying of structural steelwork and integrating these two processes into the overall project delivery system is feasible as reported by Reed [48]. Of course, one could also claim that the endorsement in 2001 by the AISC (American Institute of Steel Construction) of CIS/2 as the standard for the electronic exchange of structural steel project information for the North American steel design and construction industry has been a definite push forward factor, favouring this industrial success.

The NIBS (National Institute of Building Sciences) in the US, through its BuildingSMART Alliance council, provides industry-wide, public, and private leadership and support for the development, standardization, and integration of building information modeling technologies to provide for full automation of the entire life cycle of buildings. As for the AISC for the CIS/2 standards, the support of the NIBS granted to the national BIM standard and latest delivery of the NBIMS-US™ V2, might be a decisive move forward in bringing technical adjustments and wider acceptance of the IFCs. In the NBIMS approach, groups of people that are expert in some domain of AEC specify "use cases", i.e., IDMs for their domain, after which information experts prepare implementation-oriented MVDs to provide the information specifications needed to enable software developers to write appropriate export and import translators. This will solve most problems explored by Gielingh [49], whereby the lack of or insufficient definition of specific task-oriented exchange content had led to implementations conveying potentially ambiguities in how data structures could be defined while still conforming to standards, and presenting variations in domain scope between software applications. Furthermore, this IDMs / MVDs mechanism is supplemented with an International Framework for Dictionaries (IFD) as the IFDLibrary,[2] i.e. a consistent semantic library acting as a dictionary or ontology where concepts and terms are semantically described and given a unique identification number, a Globally Unique IDs (GUID), libraries of building products which can support designers to efficiently select those products that best match design constraints and criteria pertaining to specific projects as reported by Shayeganfar et al. [50]. Somehow similar approaches based on semantics supplemented by ontologies have been followed to ensure proper operation of high added-value applications, e.g., in the area of conformance checking of buildings to regulations [51, 52].

One should notice that the successful deployment of CIS/2 demonstrate that there is no technological hindrance to putting BIM at work for the AEC/FM industry, even though relationships across participants are short-lived and more volatile than for other industries, e.g., mechanical, aerospace, automotive, where similar technologies have been deployed with great success for some time. Finally, and as summarized in Ref. [53], BIM is finally expected to enable efficient collaboration, improved data integrity, distributed and flexible data sharing, intelligent documentation, and high-quality outcome, through enhanced performance analysis, and fast-track multi-disciplinary planning and coordination. After 25 years of work, the advent of the standards needed to foster innovation in processes, construction and infrastructure projects so that end-users throughout all facets of the industry can efficiently access the information needed to create and operate optimized facilities, is becoming a reality. We will now consider what it can mean for ICs (intelligent construction) as a primary area of application of these new EISs, but similar studies should be envisaged for other facilities, e.g., commercial, offices or industrial properties.

3. Intelligent Constructions

3.1 Background

The advent and availability of BIM artefacts, representing lifecycle repositories of building model components and libraries, down to the residential, commercial or industrial operating site open a new era of intelligent constructions acting as dynamic systems and collecting seamlessly operating data. These constructions contain various and increasingly versatile control and service systems, which are not (or very few and in scarce cases) standardised, and seldom interconnected among themselves. Moreover, they are currently based on vendor-specific technologies using “dumb” devices, proprietary software platforms and wired connections and protocols. Monitoring, maintenance and services are done by specialised companies, each responsible of different systems, which are relying on customised ICT (to meet specific needs of users) and are based on monolithic applications that require manual configuration for specific uses, maintenance, and support.

3.2 Vision

The vision that we develop here is that in the future, all objects[3] within the home, the office or potentially

[2] IFDLibrary™ is a new standard from a consortium including IAI, the CSI (Construction Specifications Institute) www.csinet.org, and the National BIM Standard, which will publish encodings to be incorporated by software vendors into a wide variety of applications.

[3] Including objects as simple as doors, windows, etc. potentially communicating with furniture like chairs, ovens…

any building will communicate and provide information ubiquitously, and will be able to "understand" people circulating or living in the built environment so as to answer to their needs at any time. To achieve such a desired state, it is required that:

Ambient intelligence is kept and managed within chips, sensors, actuators… embedded in objects that are able to dialog thanks to wireless communication techniques;

All systems in constructions share common platform, network, and protocols, with secure external connectivity via the internet enabling remote and mobile monitoring, diagnostics, operation and self-reporting, and provision of innovative interactive services to people at home or in their working environments.

Typical fields of applications of these R&D developments are for instance solutions related to AAL (ambient assisted living), especially for disabled and ageing people, or in another field, PEB (positive energy buildings)—and also energy self-sufficient buildings—with a new vision for tomorrow building energy performance to solve the global problem on sustainable energy uses at world-wide scale. Typically, this should be supported, among others, by technologies for ambient access [4] to all building information that should be made available to all stakeholders anytime and anywhere, and regardless of physical location: office, construction site, home, etc. ICT systems have to be intimately integrated with everyday environments and supporting people in their activities or their daily life (see Fig. 1) [54]. Wireless and powerless sensors should support interactive spaces providing personalised, location and context aware services,[5] and in an ultimate visionary future of the "smart, self-configuring and self-adapting home/building", users needs and requirements (including evolution of users' profiling) will require special attention, based on advanced technology like pattern recognition and uncertain reasoning (e.g., fuzzy or probabilistic logic, or neural nets).

We will now review what the deployment of these new EISs will bring for two specific domains, namely AAL for the elderly and for PEBs for energy efficient constructions. Assisting elderly people to remain in their familiar home surroundings, prolonging independent living and postponing their need to move into institutional care has become a societal objective. Age is beginning to affect wider society in very challenging ways. According to the UN report "World Population Ageing: 1950-2050", on-going demographic change is unprecedented and profound. It may lead to a restructuring of society, as social and economic forces compel us to find new ways of living, working and caring for one another. Everybody will be affected—young or old—and it is likely that never again will societies be shaped demographically as in the past with more young than old. In 2002, the number of persons aged 60 years or older in the world was estimated by UN to be 629 million. That number is projected to triple to 2,000 million by 2050, when the population of older persons is larger than that of children (0-14 years) for the first time in human history.

Old age is usually accompanied by physical and/or mental impairment (e.g., Alzheimer, Parkinson, etc.), observable in limitations and behaviours particular to each person. Assistance must therefore take account of individuality in terms of ameliorating the impairment and enhancing capability whilst ensuring safety, comfort, autonomy, and due privacy. So, the issue is very important to individual elderly people but also to family members and social agencies that have a responsibility for arranging care for them, especially in a context where, in many parts of the world, including Europe, family structures are becoming much looser because, for instance, of higher mobility

[4] Ambient access stems from the convergence of 3 key technologies: (1) ubiquitous computing; (2) ubiquitous and secure communication; and (3) intelligent user-friendly interfaces.

[5] It is worth noticing that the previous comments are also applicable to the "tools" and systems used during the construction process itself.

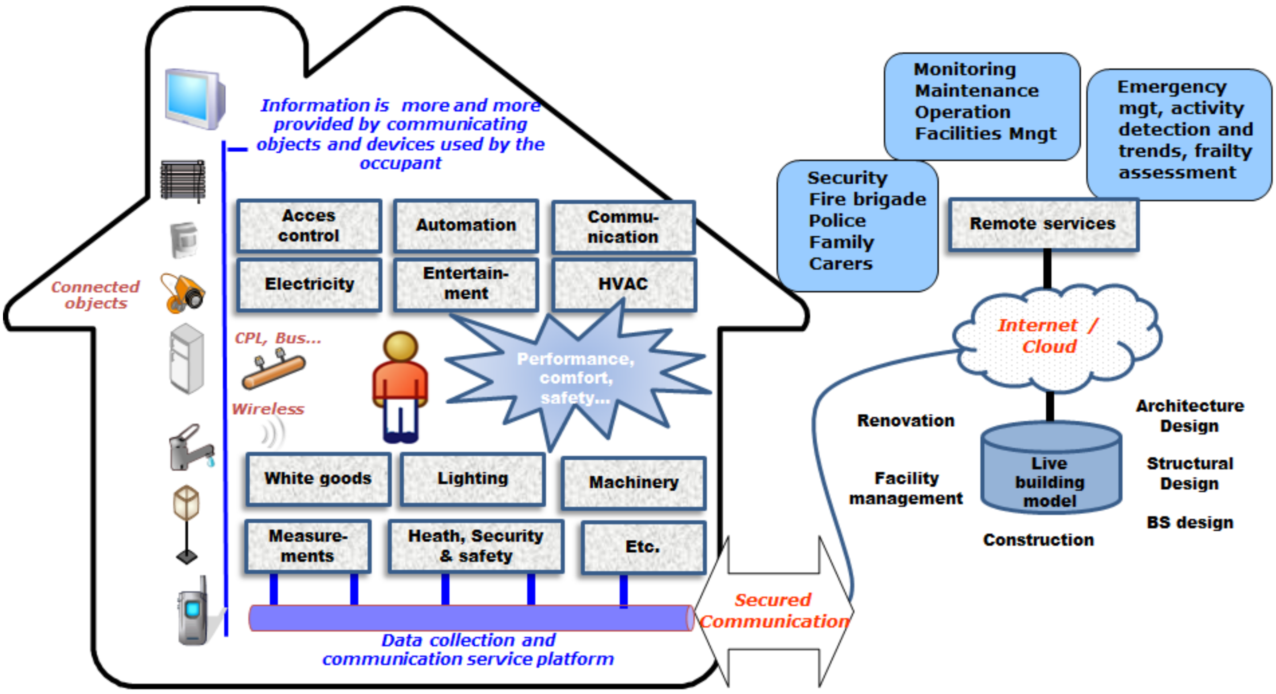

Fig. 1 A potential (non exhaustive) view on "intelligent constructions" services.

in the workforce. Often there is a stark choice between an elderly person moving to a new location with, or close to, their family or being placed in institutional care. The costs of care are high both in the commitment of family effort or for institutional care paid for by public agencies, relatives and the elderly themselves. The question is: "Is there a viable, ethical 'care at home' middle way?" Note that the question includes the role of national instances in charge of privacy (i.e., data and life), to be key in future scenarios so as to avoid negative reactions of people (and public in general) towards deployment of such innovations in the future.

ICT in such a scenario should play a major role to help address these new challenges (e.g., demographic) and in satisfying personal needs for quality care provided in a viable manner. Objectives and targets are numerous and diverse, but one key problem domain largely deals with healthcare, as exhibited in Fig. 2. It may allow dealing with "preventative care" (portrayed in red in the figure) that takes account of medical, physical and mental states to safeguard an individual and intervene or warn before "crisis intervention" is required, as well as to deal with "reactive care" and crisis management.

Another aspect that these new EISs deal with is PEBs as global climate change and risks of shortage of fossil energies put the AEC/FM sector in first line as it appears to be a big energy consumer, the housing sector alone being responsible for +40% of the power consumption. With a regular increase in the requirements in energy, stimulated by an always increasing demand of comfort within the individual residences even more roomy, the building industry must implement corrective actions, as regards to consumption, without degrading the levels of comfort, quality and safety desired by the end users.

Precursors on that matter, e.g., countries like Germany, Switzerland and the United States, [6] developed new models of sparing homes in energy, even self-sufficient and net producers of energy. These models, called Passivhaus® [7] in Germany, Minergie® [8] in Switzerland or Zero Energy Homes® in

[6] The United States did not sign the agreements of Kyoto.
[7] www.passiv.de.
[8] www.minergie.ch.

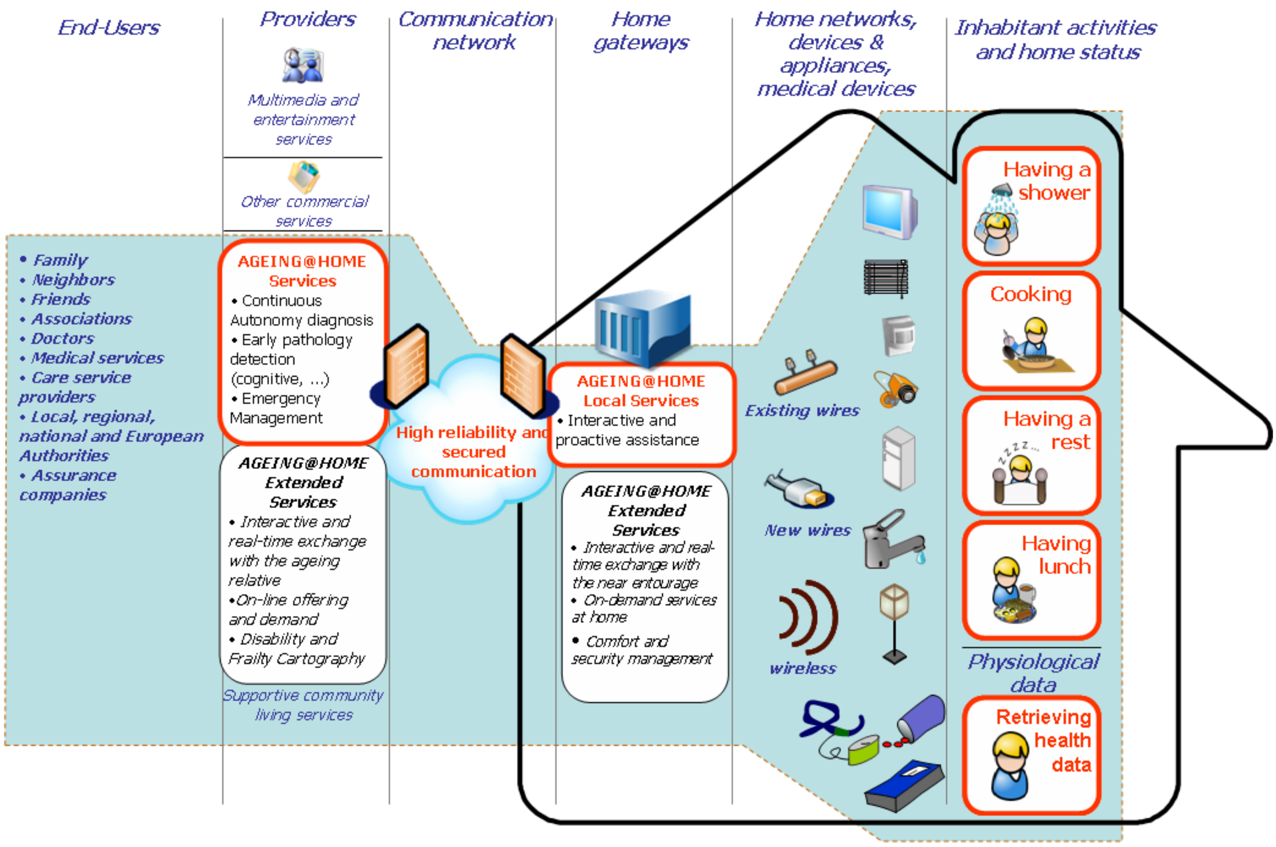

Fig. 2 Innovative ambient services targeting the elderly in the smart house of the future.

the United States, use renewable energies (e.g., wind, sun, geothermic, biomass...) for the needs for the house, and restore the energy not consumed on a network which becomes a wide energy co-operative store. These models allow, for example, to use only 1/3 of the power usually consumed by a traditional house. They recommend to improve in priority the insulation of the building (windows with double/triple glazings, reinforced insulation of the walls, phase change material...) before optimizing the treatment (production, ventilation…) of the calories in the winter, or the air cooling in the summer thanks to active thermal solutions (more efficient heat pumps, thermal solar collectors, Canadian wells...). As soon as the house becomes sparing in thermal energy, it can become producer of electrical power using photovoltaic solar panels first of all for the needs for the house, before reselling on the network, the surplus of electrical production.

But the improvement can also progress while equipping the house with "intelligent" solutions (environment sensors, dedicated software...) issued from ICT. Indeed, in addition to the fact that the owner of a positive energy building will have to run more and more complicated active equipment, it will be able to activate advanced devices, that will reduce or remove automatically useless consumption of energy, in real time, programmed or by anticipation of the evolutions of the weather (automatic release of solar blinds, screening of glazing electro chromes...). Conversely, when the user is outside, these automatisms will allow, without manual intervention, to benefit from favourable weather conditions, by storing electric or thermal energy.

Of course, the user will have to operate the same switching/control interface usually run for other applications as for example safety units, or comfort (quality of air, acoustics, infotainment services...) and be in relation with remote automatic or manual hotline for maintenance assistance. Integrated dashboards will permit soon to manage consumption and the storage of energy at home. Thanks to such equipment, it will be easy to decide, according to the instantaneous cost of energy, to sell or purchase electricity and to select different levels or strategy of consumption (economic, normal, forced, stand-by...) in real time or in anticipation.

3.3 Roadmap

The roadmap hereinafter [55-59] now aims to identify the various R&D axes required to transform the living and working environments as of today (houses, offices, buildings, etc.) in future smart environments and their innovative services, with a focus on all ICT artefacts that may support such an evolution.

This includes:

- Developing integrated system architectures, innovative sensors and sensor networks, and models sustaining solutions for communication, operation and control, including ambient user interfaces, context awareness and embedded support for virtual working environments;
- Developing monitoring and assistance of the home, buildings and public spaces, with seamless interoperability and use of all devices taking account of cost efficiency, affordability, usability and safety;
- Developing new services and new forms of interactive digital content and services including entertainment, access to information and management of knowledge. Such services should allow, for instance, the control and optimisation of energy fluxes and production over a full life-cycle operation of the building, or provide continuous support to people living or working in the building (e.g., elderly/disabled people);
- In parallel, consolidating international experiences from intelligent constructions and suggesting best practice, improved regulations and standards covering new constructions and retrofitting, and developing dissemination, experimentations, evaluations, training and certification around products and services for the smart houses.

Additional considerations are related to, on one hand, the acceptance of such ambient ubiquitous interactive services (which seems highly connected to the levels of both security and pervasiveness that such communicating objects and services may provide), on the other hand, the economic viability of services that could be imagined and further deployed (see Fig. 3).

3.4 Main Research Areas

The R&D targeting the intelligent and smart constructions (i.e., residential, commercial, offices, industrial) is to be developed around three fundamental pillars:

The ***"intelligent" objects***: these objects must have embedded electronic chips, as well as the appropriate resources to achieve local computing and interact with the outside, therefore being able to manage appropriate protocol(s) so as to acquire and supply information.

The ***communications***: these must allow sensors, actuators, indeed all intelligent objects to communicate among them and with services over the network. They have to be based on protocols that are standardised and open.

The ***multimodal interactive interfaces***: the ultimate objective of those interfaces is to make the in-house network as simple to use as possible, thanks to a right combination of intelligent and interoperable services, new techniques of man-machine interactions (wearable computing, robots…), and learning technologies for all communicating objects. These interfaces should also be means to share ambient information spaces or ambient working environments thanks to personal advanced communication devices.

On this basis, the main research areas are decomposed as represented in Fig. 4:

Putting these R&D efforts in perspective, one can

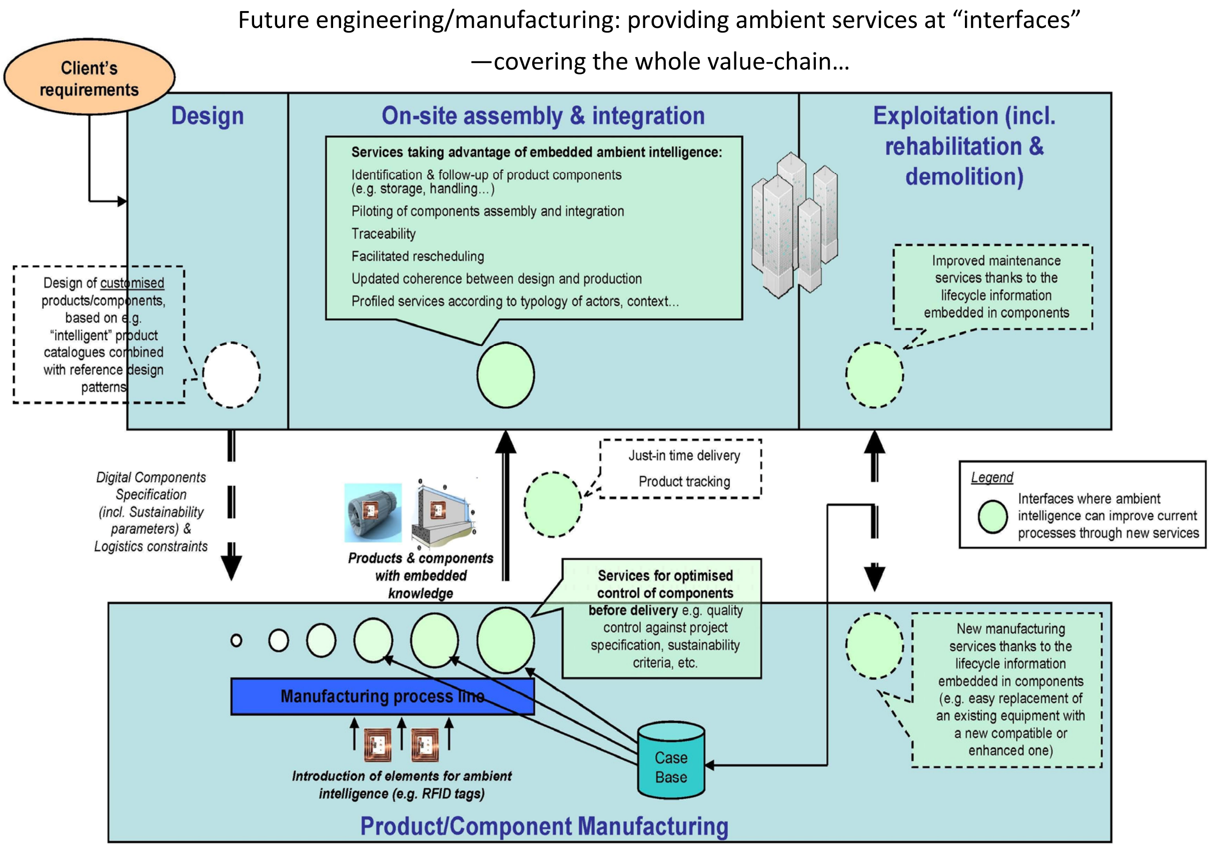

Fig. 3 **Ambient services along the whole value chain and the complete AEC/FM lifecycle.**

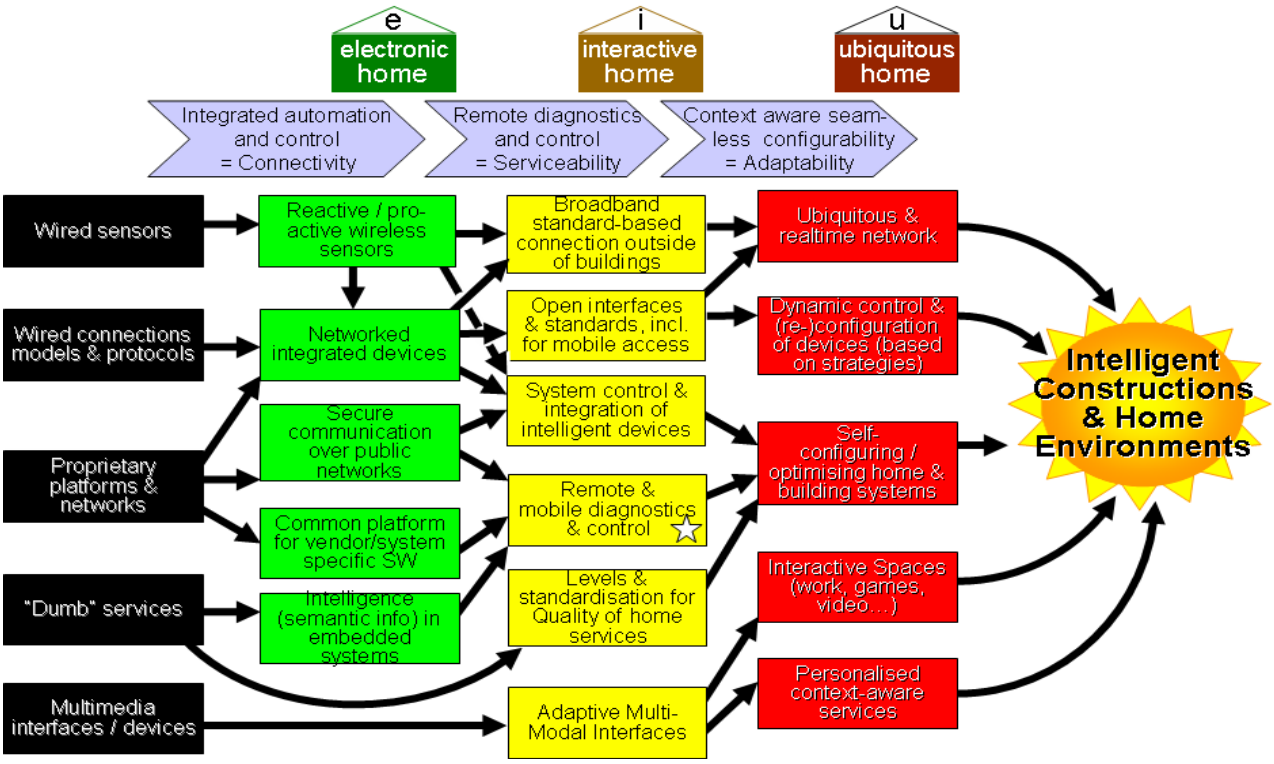

Fig. 4 **Roadmap for intelligent constructions.**

identify short, medium and long term challenges:

• Short term, the R&D is devoted to achieving full integrated automation and control, leading to the ***e-HOME***—the "electronic HOME". This is mainly about:

(1) All objects and components in the built environment integrating elements for a given degree of intelligence: RFID (radio frequency identification) tags, chipsets, embedded micro-systems, etc., including the opportunity for humans to wear such devices or chips with embedded intelligence;

(2) Application of sensor technologies for distributed monitoring, control, end-user support and services, thanks to all "intelligent" communicating objects being able to mutually identify in the network, connect and interact with each other according to various communication models and channels;

• Medium term, the R&D is devoted to the generalisation of network-based services accessible from home, leading to the ***i-HOME***—the "interactive HOME". This is about considering the built environment being naturally considered as a node (or set of nodes) of the Internet backbone, therefore providing and requesting services over the network:

(1) Smart products and systems with embedded devices, and embedded learning support to users, operators and maintenance staff;

(2) Software tools for tracking, logistics, diagnostics, monitoring and control;

(3) Modular integrated automation, monitoring and control of all subsystems with holistic optimisation and support to service provision;

• *Long term*, the R&D eventually is targeting a full understanding and adaptability of the home as regards to people living in it, leading to the ***u-HOME***—the "ubiquitous HOME". This includes:

User and context aware, self-optimising intelligent built environments, with potential for dynamic re-configuration, and providing access to interactive spaces and personalised services.

Let's make a short overview of where we stand in terms of current state of the art in various critical areas to deliver the vision that we have exposed in the roadmap:

• Wired sensors: lots of various remote controlled devices, with the use of such devices in various domains (e.g., HVAC, lighting, audio-video equipment…) being currently investigated in the built environment through preliminary deployment and experimentations;

• Wired connection models and protocols: still under development and even more looking for harmonisation and standardisation (NFC—near field communication, Bluetooth, Wi-Fi, RFID, ZigBee, etc.), they aim at establishing and managing communication between objects;

• Proprietary platforms and networks: current platforms implementing connected objects are mainly experimental platforms, with no standardisation of management of and communication between any kinds of "intelligent" objects;

• "Dumb" services: all services provided by the industry so far are specialised/dedicated services that ensure one given function, without providing interoperability, and no capacity to "talk" with other services or to take into account the full environment;

• Multimedia interfaces and devices: still few intelligent objects that are not intrusive and offer appropriate interfaces to allow the final user to seamlessly integrate the ubiquitous network.

Now let's consider for some of these key technologies what could be the expected time to industry or deployment, again identifying short, medium and long term challenges:

• Short term:

(1) Reactive/proactive wireless sensors: sensors able to integrate a set of contextual data and compute them before providing information corresponding to any specific request. As a potential chain in an overall process, they should also integrate behaviour patterns to proactively fill in a given mission;

(2) Networked integrated devices: the achievement

of such network integrated devices (such as home appliances and site equipments) should allow the development of new applications seamlessly and dynamically integrating through the network any autonomous device, based on its universal ID, its dedicated API, and its capacity of active/reactive behaviour;

(3) Secure communication over public networks: this should allow exchanging any type of information, including private information whenever required, between smart components and/or houses, and e-services over any type of networks, including the Internet. This means both in terms of reliability of the transport (i.e., no loss of alteration of the data), than in terms of privacy and security of conveyed information;

(4) Common platform for vendor/system specific software: must allow the integration of any devices/components (sensors, actuators, transmitters, chips in building components and furniture…) so that these objects can collect data, compute them, and send them, thanks to standardised operating systems and platforms. This is also related to specifying format of objects for distributing the middleware. Such systems/platforms must form the ground for "spatial information systems" able to link objects in a physical space;

(5) Intelligence in embedded systems: embedded systems should make their (construction) containers "smart" by being able to deal with semantic information (query and get) and to manage it (locally analyse, compute, and provide output—in case according to pre-defined or dynamic strategies) so as to integrate a network of smart sub-systems that form the smart house/building;

- Medium term:

(1) Broadband standard-based connection outside of buildings: need for environments subject to automation to be integrated in networks and systems that provide proved and reliable communicating channels, including for large in and out data streams;

(2) Open interfaces & standards, including for mobile access: coherency between information managed by the "intelligent" ambient objects…. They are a key angular stone to the software interoperability which still remains an issue in a context where all the intelligent objects have to organise themselves and communicate spontaneously over the network;

(3) System control & integration of intelligent devices: specify and develop enhanced products characterised not only by improved features (e.g., optimising the equation quality/duration/cost) and capabilities (e.g., smart buildings), but also shipping with, e.g., fully digitalised, unique and personalised, universal electronic cards or digital mock-ups, that could manage the information structuring and integration for the product, allowing traceability of all parts of the final end product (so as to provide all guarantees of quality and safety to the client), and long-term memory of end products for maintenance, enhancement, refurbishment, and even the demolition process (in terms of potential reuse of parts of the building). Such products/devices will communicate by embedding appropriate tags (RFID, etc.), and will allow to improve global monitoring of complex systems in the built environment;

(4) Remote & mobile diagnostic & control: achieving diagnostic/control and indeed leading to decision-making systems will require semantic based content integration (including data fusion), i.e., specify and develop algorithms and solutions that will achieve syndication of information from a semantic point of view leading to a seamless integration of data from disparate and multiple data sources. This will especially rely on BIM[9] in the context of the built information;

(5) Levels & standardisation for quality of home services: identify and classify different levels (defined by some sets of indicators and parameters) for quality of services in smart homes and buildings. Such levels should provide quality repositories for service

[9] Such as the IFC model mention in Section 2.

developers and providers to target a given level (as a level of service ensured to the end user), as well as to achieve tests and evaluation and deliver certification for new home services;

(6) Adaptive multi-modal interfaces: this is about the achievement of intelligent user-friendly interfaces, i.e., identify, specify and develop systems allowing context-based multiple modes of interaction, augmenting human to computer and human to human interaction (including potential interaction with robots), adapting to the devices, user preferences and contextual conditions, and available/accessible to all. One step is the evaluation, adaptation to the construction processes, and integration of such systems (currently developed in research centres and laboratories), including speech recognition interfaces, roll-able and foldable displays, head-mounted display devices, and holographic applications.

- Long term:

(1) Ubiquitous and real-time network: develop solutions and systems exploiting the 4th generation broadband mobile network that will provide the best interactive and intuitive collaboration and communication services than any alternative networks, including high-level security, better QoS, mobile and audio/video conferencing enabled, improved wireless data protocols, etc., enabling the achievement of ubiquitous and secure communication;

(2) Dynamic control and (re-)configuration of devices (based on strategies): develop algorithms and architectures for any configuration of smart devices (i.e., any set of such devices being inter-connected) to be able to dynamically evolve according to the environment or change in a choice of a global strategy. This includes as well individual “roaming” profiling, allowing configurations to follow users, related to a wide variety of applications;

(3) Self-configuring home & building systems: develop architectures where component-based in-house systems learn from their own use and user behaviour, and are able to adapt to new situations, locating and incorporating new functionality as required. Situations are automatically tracked and significant events flagged up. Intelligent assistant maintains a view of the users responsibilities, finds needed resources as required and priorities events and tasks, making relevant services available as needed. This included use of pattern recognition to identify and prioritise key issues to be addressed, and to identify relevant information;

(4) Interactive spaces: develop architectures and systems that offer smart audio, video, leisure and working environments that must be adaptive and “immersive”. This includes agent-based user interfaces adaptation to suit user preferences and profile inferred from usage habits, and advanced identity management (based on a follow-up of the progress in current research in this field, e.g., biometrics), to identify and assess the potential of integration of these technologies in services dedicated to construction;

(5) Personalised context-aware services: identify, specify and develop smart systems that easily integrate or connect to the house or building, and that are context aware systems providing services to support personalisation and context data processing, and interpretation of information on the user and his environment in order to provide seamless information access and gathering for each stakeholder, as well as value-added information dependent on the context.

3.4 Impacts

These solutions shall increase comfort, security, and safety in the built environment, at working and living place and reduce energy consumption, and needs for travelling and transports. Considering the case of PEB, there are of course evident social impact: reducing and, in a longer term view, reversing buildings consumptions by making them net producers of energy, reducing buildings emissions (e.g., small particle matters as $PM < 2.5$ microns released by heating systems), contributing to the overall reduction of petrol/fossil consumption, etc. But impact is expected at the level of the AEC industry, with control and optimisation of energy fluxes and production over the full life-cycle operation of the building and facilities. The technologies developed at the level of each component should also allow zero-default "knowledge-embedded" building components to be immediately assembled on construction sites—with assembly easily done, even with limited skilled labour. Indeed, emergence of new concepts like energy self-sufficient buildings or energy positive buildings connected to energy distribution networks might become a common practice in a sustainable economy. A local market of energy exchanges between buildings in micro urban area should become a common situation. Developing technologies and practices will not only improve sustainability and competitiveness of the industry, but also offer possibilities of transferring technologies to developing countries, contributing to solve the global problem on sustainable energy usage. Experimental and demonstration buildings in the last two decades proved the technical feasibility of such concepts. Some European countries or regions of these countries entered the process of progressively generalizing such practices.

4. Road to the Future

4.1 Starting Point

The next great revolution to come in the AEC-FM sector after 25 years of patient development of BIM based technologies (since the emergence of the ISO-STEP standard up to its wide acceptance today), is the drastic change of the built environment into sets of interconnected, responsive and interoperable objects as building blocks of the intelligent cities of tomorrow. Gartner [60], one of the world's leading information technology research and advisory company, consider that smart homes already resort to 294 million "connected things" in use right now and forecast that smart cities will use close to 10 billion "connected things" in 2020. Residential housing and intelligent buildings should represent 45% of that figure and up to 81% of the 2020 estimated target, with promising market revenue for technology and service providers, though most of it would favour service providers and information and data analytics of IoTs (Internet of things) operators even though hardware investments are a prerequisite for the deployment of IoTs. New offerings, delivering innovative economic or social added value services, proposed on wide scale (e.g., smart cities) will enable a better usage of scarce resources (e.g., transports, infrastructure usage, parking lots, electric mobility and charging stations availability, etc.) and will be based on dynamically geo-localised data. Beyond the emergence of BDA (big data analytics) in the AEC-FM sector with exponential volumes of information to collect and process, this revolution to come will leverage on the new but tight interconnection of the built environment with various technologies such as widespread sensors and ubiquitous information gathering, IoTs, cloud computing, BDAs, robotics and collaborative robotics, i.e., cobotics.

These technologies are expected to play various roles in the four key phases of the life-cycle of built facilities: design stage, industrial manufacturing and delivery of an increasing number of components straight from factories and their later assembly and incorporation into the built project on site, running and operating the building or facilities with monitoring, control, end-users services and maintenance ending with the dismantling (end of life). New open components, equipment and systems offering standardized interoperable functions and capacities will be the building blocks of the future services and economic models essentially user and human-centred, whereas previous approaches favoured equipment and systems, in their unique function, with little or no interconnection capacity.

4.2 Vision and Future

BIM models delivered from design/construction phases to the operating site plus wireless sensors enabling AmIn (ambient intelligence) and cloud monitoring of constructions connected to trading energy networks should enable the emergence of new sorts of constructions in all domains (i.e., residential, commercial, industrial, offices). The built environment must integrate emerging non-intrusive devices and systems (e.g., sensors, actuators, intelligent components, etc.) which should be able to generate and communicate data and information and potentially interact among them and with the users. Therefore, there is the need to develop standardized communication channels that will manage all the collected and distributed data flows, along with new methods and tools to analyse ambient data in the building, but also behaviours leading to the emergence of a new form of engineering based on embedded services for the built environment, deploying new forms of extended enterprise information systems, as for virtual enterprises [61, 62] and achieving coherence between strategies in these extended enterprise systems [63]. As an example of these types of new open platforms to plug-in software and hardware, the CSTBox, i.e., CSTB sensing and tele monitoring box [64], is a global solution designed by CSTB, which targets embedded applications based on ambient instrumentations and allows using at the same time various devices, including sensors, actuators and user interaction devices, which are provided by different makers and make use of different communication protocols. This makes possible to assemble a configuration by taking advantage of the most suited components, whatever they are. In addition, information collected from sensors or sent to actuators is defined using a neutral model, fully decoupled from the involved hardware; this feature is based on the concept of drivers, which role is to translate proprietary communications to and from neutral ones. A number of low-level services (i.e., infrastructure) are provided such as local data storage, common internet protocol support (HTTP (hyper text transport protocol), FTP (file transfer protocol)…) for communication with external servers, scheduled data upload mechanism, plugin architecture for data format converters used to interface with external servers, system parameter monitoring (e.g., devices battery level, radio link quality for wireless devices, etc.), automation scenarios engine allowing the definition of complex tasks using interaction with installed devices, web based administration console providing interactive tools [65] opening the road to SOA architectures and extended EIS.

The emergence of theIoT is going to create a world where physical objects are integrated into information networks in order to provide advanced and intelligent services for human beings. Indeed, the IoT now increasingly includes electronic devices operating in our homes. The interconnected "things" such as sensors or mobile devices sense, monitor and collect all kinds of data about human social life [66]. The IoT aims to extend the benefits of the regular Internet—constant connectivity, remote control ability, and data sharing, etc. —to goods in the physical world [67]. The capability to integrate the sensing element with electronic circuits that support the data storage, computation and communication software at the chip level (smart sensors) is clearly a goal for future devices, as for the aim to provide widespread computing and sensing capabilities. The techniques of micro fabrication will be largely adopted to produce mechanical, optical, magnetic and chemical micro system-based sensors (MEMs), but with the additional challenge to integrate also micro-actuators, microelectronics and other technologies on a single microchip. A host of new sensors will also be deployed to continuously deliver data related to the operation of the built facilities and their occupants, for instance, environmental sensors measuring and controlling several fields of the building (e.g., centralized control of lighting, heating and ventilation air conditioning appliances, security locks of gates and doors, gas and fire, energy efficiency, in/on body sensors, biosensors, vision sensors, etc.). These interconnected objects will even bring more value if they remain independent from the one another and capable of self-behavioral capacities. Furthermore, platforms ensuring the interconnection between these self-sufficient objects should offer proper security and confidentiality levels.

Intelligent buildings and smart cities of tomorrow will heavily rely on ubiquitous sensors and data collecting devices which will represent the heart of new urban operating systems, able to make work together as relatively independent agents, these billions of devices providing each sensible data to be gathered and put into a broader perspective by the proper level of service able to organize the collecting and processing of these vast amount of information according to specific needs arising along the daily operation of the facilities. Undoubtedly, the notions of CC (cloud computing) and BDA (big data analytics) will play a leading role in that respect especially as they are intimately related to the previous technological changes and breakthrough based on widespread intelligent sensors, AmIn and ubiquitous IoTs.

CC offers an access to services via a virtual electronic space with ad-hoc billing mechanisms, on a pay per use model without the requirement to purchase software licenses. The design stages, resorting to intense numerical modelling including dimensioning and simulation of the systems (e.g., structural, HVAC, etc.), have already started benefiting from CC by means of an access known as Saas (service as a software). CC will enable the deployment of intellectual ecosystems where services will collaborate in a transparent manner for the user according to an appropriate configuration of his/her electronic desk and the cloud will support collaborative works among various project contributors ensuring synchronization of their actions and enabling work on documents, models and applications with simultaneous sharing and real-time updating mechanisms.

BDA can be viewed as a new phase in data management techniques, kind of an industrialization stage whereby due to the exponential increase in data production and its extraordinary diversity, their structuring and appropriate exploitation by data-mining techniques will enable their reliable and resilient usage to inevitable disruptions created by defective sensors or devices. Therefore, flexible systems should cope with diverse data for complex and interconnected services and more importantly their reliability, this assessment being performed according to several techniques including plausible data ranges, temporal plausibility, interrelated values according to network of constraints of data to be maintained, etc. (see Fig. 5). Deployment of BDA in the built environment will have major outcomes favouring renewable energies deployment, usage and sharing, optimizing cogeneration with traditional energy sources, enabling reactive and even predictive maintenance, all that serving the wise deployment of new energy consumption strategies including managing intermittence, self-production and storage, all leveraged across several buildings or neighbourhood.

Finally, robotics and its sister cobotics (collaborative robotics) which associates robotics to humans in various collaboration schemes will play a major role at various levels in the built environment, starting from the construction site itself, the later usage and operation of the built facilities especially for aging inhabitants requiring various forms of help to overcome their dependencies, or for maintenance purposes whereby robots will contribute to implement some of the routine operations. Beyond exoskeletons that will eventually increase on site worker's strength, on site cobots will benefit from the BIM information servers to drive them execute processes including but not limited to assembly, assistance, control, maintenance,

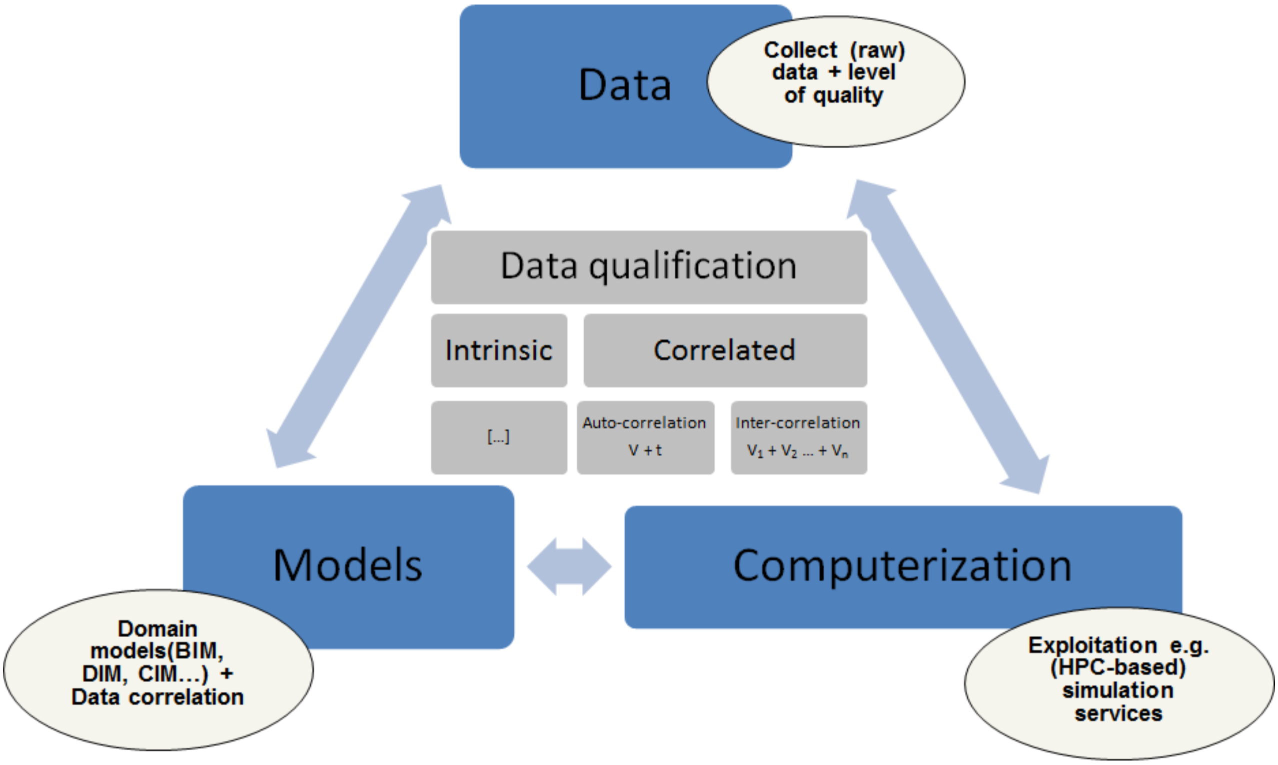

Fig. 5 Data, models and "big data" computerization.

etc., as it appears natural that the BIM will more and more extend the knowledge represented into its electronic artefacts beyond design to construction and later operation and maintenance. These cobots will of course be granted of a vast set of sensors that will make then interoperable with human workers on site ensuring security for both, with increased mobility, vision, communication, and self-learning capacities to make possible the deployment of application and services based on interconnected and intelligent software objects and embedded in these machines.

But undoubtedly, the major deployment of cobots will address one of the challenges arising from an aging population requiring ever more assistance, be it at home, senior residences or hospitals [68]. Cobots will interact with the IoTs to deliver contextualized assistance according to ambient information collected directly from sensors or from robotics' nodes and will assist old persons often requiring some sort of "mechanical" help and not only smartphones of web-type based interfaces. Recent technological breakthroughs and sensible pricing made possible by mass market industrialization will lead to significant added value at an affordable price in new roles for cobots, these new machines emulating furthermore some sorts of emotions making the interaction with humans more satisfactory. In that respect, behavioural studies have demonstrated the benefits of such interactions with individuals showing cognitive or relational hindrances.

5. Conclusions

BIM models delivered from design/construction phases to the operating sites of various sort, plus wireless sensors enabling ambient intelligence and cloud monitoring of constructions connected to trading and monitoring networks, appear as massive data producing hardware/software environments feeding new enterprise information systems in the AEC sector. With the rise of micro-electric mechanical devices, smart-phones, and wearable Wi-Fi enabled devices, occupants will be surrounded with a cloud of information to be shared, and have access to relevant information for a better usage of the facilities of various types (e.g., residential, commercial, industrial). These data in turn can be fed into intelligent agents providing feedback to the users. The main aspects to be underlined are the importance of integration, standardization, and interoperability of several sensors within the same environment. An interesting development in this direction is the CSTBox that allows a variety of sensors to talk together and offers most of the frequently needed services through standard protocols. The early promises of integration across the actors and along the life-time of facilities have gone a long way after a quarter century of work but full scale benefits will only be delivered through enhanced integration, standardization and interoperability of computerized models, representations, services and operations still not yet fully accomplished.

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