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► **To cite this version:**

Hang Wan, Michael David, William Derigent. Design of a multi-agent system for exploiting the communicating concrete in a SHM/BIM context. 4th IFAC Workshop on Advanced Maintenance Engineering, Services and Technologies, AMEST 2020, Sep 2020, Cambridge, United Kingdom. hal-02949522

HAL Id: hal-02949522

<https://hal.science/hal-02949522v1>

Submitted on 25 Sep 2020

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Design of a Multi-Agent System for exploiting the communicating concrete in a SHM/BIM context

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Abstract: Product Lifecycle Monitoring with new communication technologies is a huge challenge. Designing physical and digital architectures able to manage the monitoring is a critical step to achieve this goal. McBIM project consists in designing a communicating concrete and digital services that can be used by Building Information Modeling (BIM) applications throughout its lifecycle. A multi-agent system (MAS) is defined to structure and store the data produced by physical elements. The MAS is decomposed in two parts: one for the control of the communicating concrete materials and another one to make data available for BIM applications. First exploitation results and some perspectives are discussed.

Keywords: Communicating materials, Wireless Sensor Network, Digital Twin, Building Information Modeling, Multi-Agent System.

1. INTRODUCTION And PROBLEMATICS

The Internet of Things (IoT) is widely used in manufacturing, logistics or monitoring applications. The application of IoT makes the product more intelligent, its high flexibility brings new challenge to the Intelligent Manufacturing System (IMS). Numerous research works have pointed out the benefits gained by integrating technologies of the Internet of things (RFID, Wireless sensor networks – WSN) into concrete products. (Li & Becerik-Gerber, 2011) presents an extensive review of research works or industrial initiatives in the construction domain, using RFID technologies. It appears that RFID technologies have been tested and can bring important economic leverages in all the phases of the precast concrete lifecycle, e.g in precast quality management (Alonso-Calvo & Garcia-Remesal, 2016) or for construction supply chain (Ikonen et al., 2013), by bringing product information to stakeholders. Additionally, WSN are also seldom used when an active monitoring of the structure is needed as for example in manufacturing (for early-age concrete inspection as in (Barroca et al., 2013; Song, Gu, & Mo, 2008)) or for structure health monitoring (Jiang & Georgakopoulos, 2012; B. Quinn & Kelly, 2010; W. Quinn, Angove, Buckley, Barrett, & Kelly, 2011; Zain, Krishnamurthy, Sazonov, Jamil, & Taib, 2008). Industrial initiatives are also numerous as well, but most of the time RFID tags are used (Li & Becerik-Gerber, 2011). For example, in (Lafarge, 2013), Lafarge company (www.lafarge.com) integrated RFID tags directly into the concrete of the D2 tower¹ for traceability application.

¹ <https://skyscrapercenter.com/building/d2-tower/9831>

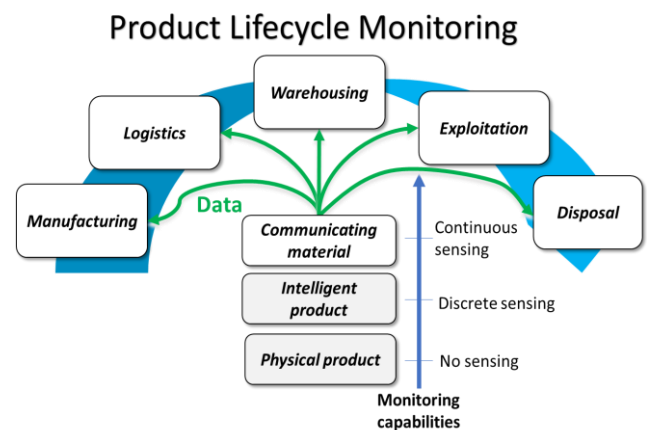


Fig. 1 Concept of Product Lifecycle Monitoring

In 2010, a new paradigm was proposed in (Sylvain Kubler, Derigent, Thomas, & Rondeau, 2010), introducing “**communicating materials**”, i.e materials able to communicate with their environment, process and exchange information, and store data in their own structure. Besides, they also have the capability to sense their environment and measure their own internal physical states. Diverse early prototypes were designed (or simulated) **for the needs of the construction industry**, either via the use of RFID tags (S. Kubler, Derigent, Rondeau, & Thomas, 2012; Mekki et al., 2015) or self-powered wireless sensor networks (WSNs) embedded into the material. The interests of such material are diverse: (a) because of their data storing capacity, they can convey all information related to design, manufacturing and logistics, useful during the BOL (Beginning Of Life – design, manufacturing and construction) and the EOL (End Of Life – dismantlement and recycling) of a building; (b) given their ability to sense their environment and process related

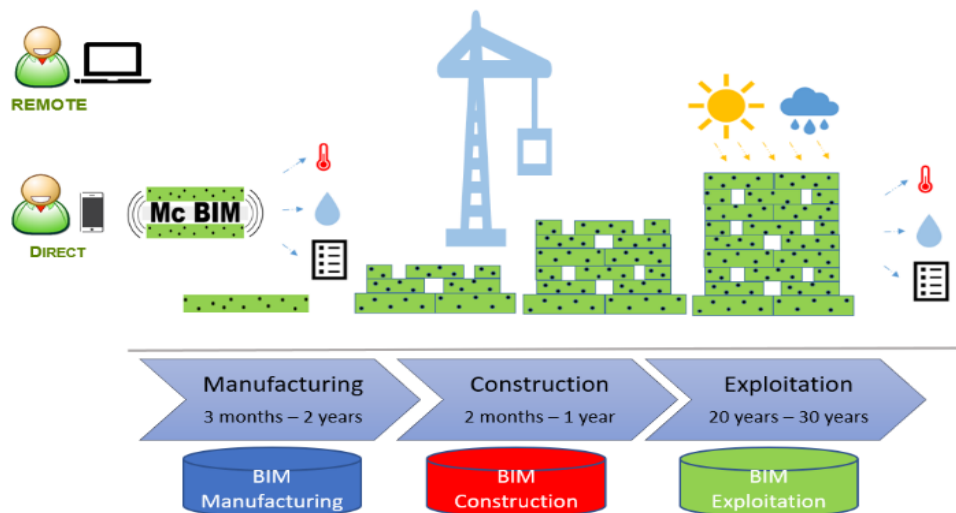


Fig. 2 McBIM communicating concrete lifecycle

information, they can also be used during the MOL (Middle Of Life – exploitation and maintenance) as intelligent building sensors, mainly to perform structural health monitoring. Since communicating materials give the opportunity to monitor and trace the product all along its lifecycle, we thus defined the notion of “**Product Lifecycle Monitoring**”.

Some issues must still be solved at different levels to concretize the concept of communicating materials. First, a deep study on how to correctly integrate such wireless sensors into materials is still needed, to optimize transmissions and energy consumption. Data management related to communicating materials is not a resolved issue as well. Furthermore, **BIM (Building Information Modelling)** platforms are now used to define and manage integrated and augmented 3D building models (and will become **mandatory** for French public tenders). According to (Eastman, 1975), BIM is a technology that allows one or more accurate virtual models of a building to be constructed digitally. When completed, a BIM model contains geometry and data needed to support the building lifecycle. In the framework of the McBIM project, BIM must allow generating, storing and exchanging information about building elements and sensors (Roxin et al., 2019). Since the McBIM solution could be used all over the concrete lifecycle and for multiple situations, the aim of the project is to develop semantic interoperability based on the IFC standard (ISO16739-1, 2018). ²(2018) underline the interest to reuse the models defined in the design phase across other building lifecycle phases (construction, exploitation or recycling) by connecting these virtual BIM models with data coming from the real infrastructure (produced by different intelligent building systems). The resulting cyber-physical system could then be used for (but not limited to) construction monitoring during

the construction phase, or structure health monitoring during the exploitation phase. The link between BIM, data models and communicating materials has not been addressed in past studies.

In order to solve these issues, the McBIM Project (Material communicating with the BIM - Building Information Modelling) (Derigent et al., 2019; McBIM Consortium, 2018) has been proposed and aims to design a “communicating concrete”. This project is funded by the French National Research Agency and is coordinated by the CRAN with 2 other French laboratories (LAAS, LIB) and one company (360 SmartConnect/FINAO SAS). In this project, different partners focus on different areas. Where the CRAN works on the network and information management, the LAAS designs the sensing and communicating nodes, the LIB studies data interoperability and all these works are then implemented by 360 SmartConnect/FINAO SAS.

Section 2 introduces the McBIM project and the concept of communicating concrete, detailing its main constraints and behaviours for each phase of its lifecycle. As will be described later, a communicating concrete is composed of physical components (i.e. the concrete structure, embedded WSN) and virtual components (i.e. database, applications). This paper mainly focuses on the virtual parts and more specifically on the information system controlling the concrete. However, to get a complete understanding of the structure of a communicating concrete, section 3 briefly presents the structure a wireless and battery-free sensor node prototype and the first tests/results in the air. Section 4 introduces some existing solutions of data management architectures in the framework of cyber-physical systems. A synthesis of those solutions and their use in our application case are then discussed. Last section concludes and gives some perspectives for the development of this work.

² <https://autodeskresearch.com/projects/dasher>

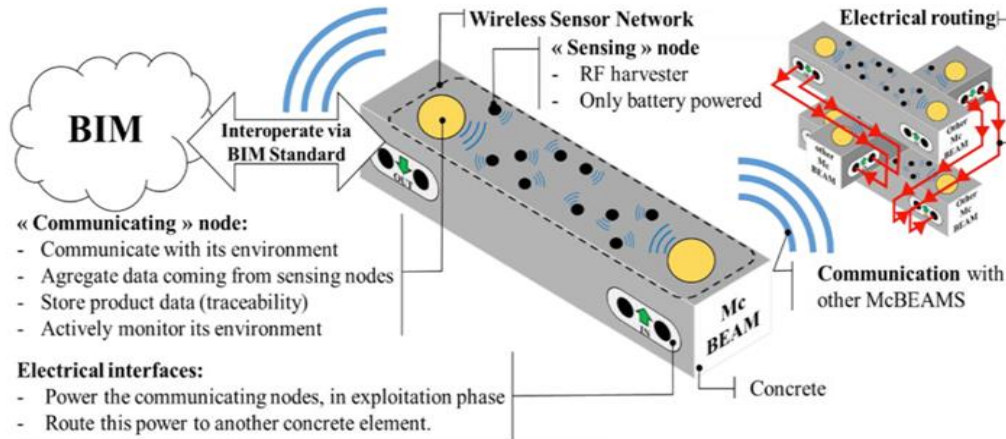


Fig. 3 Description of the ANR McBIM Project

2. DESCRIPTION OF THE McBIM PROJECT

The communicating concrete (see Figure 3) consists of a concrete structure where many sensing and communicating nodes are spread. The sensing nodes will periodically monitor the physical parameters (like temperature, humidity ...) of the concrete. Communicating nodes aggregate received data and transmit them to remote servers thanks to BIM standards. Besides, manufacturing data (like physical properties or information related to manufacturing actors) may also be considered. The communicating concrete element must last several decades from the manufacturing phase to the latest of the exploitation phase.

The communicating concretes behaviours may be different along its lifecycle (see section 1). During the manufacturing phase, the WSN nodes are inserted and initialized. The communicating concretes periodically (by example every hour) monitor their physical status, store the physical propriety information and manufacturing actor information. Those data are accessible directly via a reader device or remotely via the internet. During the construction phase, communicating concretes will be assembled. In this case, as communicating concretes arrive, auto-organization is then needed to dynamically define a 3D network to achieve energy savings. Due to the high flexibility in this step, concrete must report its status frequently (such as every half-hour) to ensure the safety of construction and updates the network information. When the construction is completed, the large 3D static WSN will regularly (by example every half-day) monitor structure health data (such as cracks, temperature, corrosion, etc.) to ensure the safety of the building. These data are then sent to an external specific information system. Indeed, the whole McBIM system is composed of a physical part (the embedded WSN) and a virtual part (the information system) linked together thanks to data flows (figure 4).

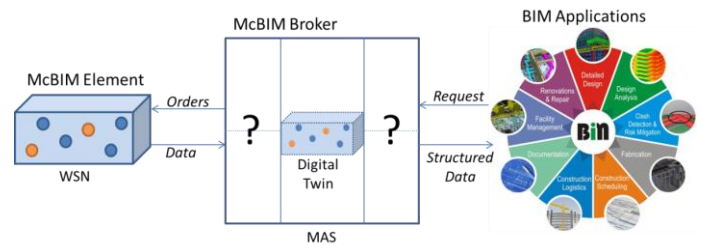


Fig. 4 Multi-agent System parts

2.1 Network infrastructure

According to the diverse targeted use cases and applications - especially for structural health monitoring (SHM) of concrete structure- a wireless mesh network architecture was proposed to design the communicating concrete. The proposed hardware implementation of the communicating reinforced concrete is based on the deployment of a two-level wireless mesh network as presented in Figure 5. This network consists of the interconnection of two kinds of node: the

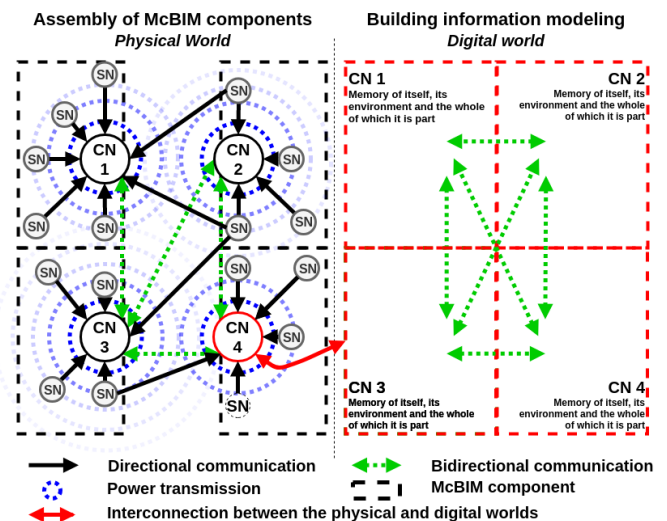


Fig. 5 Schematic the architecture of the proposed network

communicating nodes (CN) and the sensing nodes (SN). The sensing nodes must sense relevant parameters from the monitored structure and transmit through a unidirectional communication the measured data to the communicating nodes. They become inaccessible once deployed in the concrete. Thus, they must be fully wireless, low power, simple, robust and autonomous for the entire lifespan of the structure (i.e., for decades). The communicating nodes must recover the data transmitted by the sensing nodes in their neighbourhood, process, store and exchange with the other communicating nodes -though a bidirectional communication- this data, as well as connect the physical and digital worlds through the Internet to update the BIM.

The first implementations and tests in the air were performed regarding wireless measurements. The main obtained results are available in (Gael Loubet, Takacs, & Dragomirescu, 2018; Gaël Loubet et al., 2019) Data gathering and optimization of the CNs network was proposed in (Wan, David, & Derigent, 2019, 2020). These studies proposed models to evaluate the energetic dispersion of each communicating node of the WSN.

2.2 Digital environment

In this paper, we addressed another challenge of the project, which is the realization of the link between physical and digital elements contained in a structure called “Broker”.

(Basselot, Berger, & Sallez, 2019) presented a study of different several research projects related to the exploitation of Product Usage Data (PUD) all along its lifecycle for multiple purposes (maintenance, reuse, recycling, customer feedback ...). It shows that these research projects always have 3 key elements: an augmentation module that increase the product informational capabilities, an infrastructure for storing and enriching the data and the data promotion by different stakeholders. In our case, the augmentation module is provided by the WSN already in place in the concrete element from its manufacturing. The data promotion can consider proprioceptive or exteroceptive data. Proprioceptive

data are related to signals received by the sensors embedded in the material (temperature, humidity, stresses ...) whereas exteroceptive data corresponds to information coming from its environment (product ID, product owner, material properties ...). However, the different data consumers may not be known when the product lifecycle begins. As a result, data should be accessible via standard interfaces.

The question of the needed infrastructure is more complex. The design of the different parts of this digital world is thus the main object of this work. We have drawn inspiration from several works, notably on holonic systems (Le Mortellec, Clarhaut, Sallez, Berger, & Trentesaux, 2013) and on intelligent products (Sallez, Berger, Deneux, & Trentesaux, 2010) dedicated to product/system monitoring architectures.

Indeed, in the holonic community, real products are often linked to agents in the virtual world, the combination of both making a holon (Derigent, Cardin, & Trentesaux, 2020). Each holon can then monitor and control the behaviour of its corresponding physical part. Moreover, holons can also communicate to for networks of holons called hierarchies. (Basselot et al., 2019) consider a holonic architecture where each holon has access to a Dynamic Informational Structure (DIS) and a Static Information Structure (SIS). The SIS contains static data, information and knowledge related to the product (e.g. technical description, model behaviour and prescribed task). The DIS is an information system collecting all the PUD generated during the product lifecycle. Based on the DIS and SIS information, each holon evaluates the performances of its physical part and can react if deviations are detected.

This generic holonic architecture is used in this paper. Indeed, each concrete element (physical part) is thus linked to its corresponding virtual representation (virtual part) to form a holon. As a result, specific agents called “concrete agents” manage the information related to their real product. All these agents are gathered in a Multi-Agent System (MAS), each of them representing a communicating concrete element in the digital world. Concrete agents are monitoring concrete

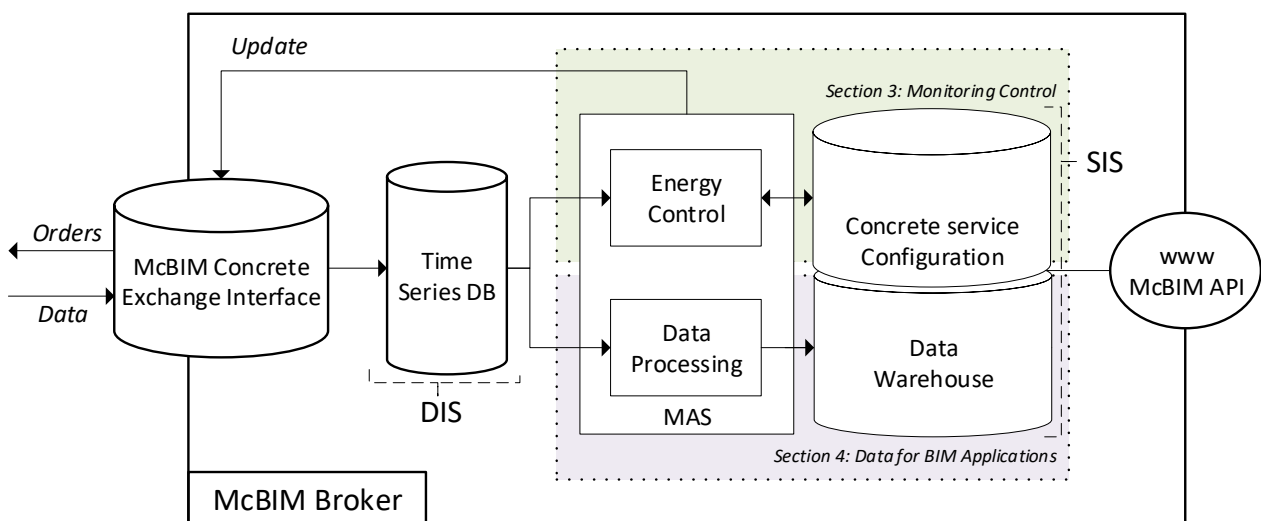


Fig. 6 MacBIM broker overview

elements thanks to the data coming from the WSN. As the WSN is an embedded monitoring system, the concrete agent also monitors its energy consumption of the embedded WSN and can decide to rearrange the WSN to extend its lifetime. Indeed, given the typology of (Meyer, Främling, Holmström, Främling, & Holmström, 2009) the level of intelligence of these agents are between 2 and 3 (problem notification and decision making). As a result, agents in the digital world can be considered as low-level twins of the real concrete elements. These agents are stored in a distant server where they can have access to more computation power and memory.

Data coming from the real communicating concrete elements are gathered in a DIS, which is the repository of all the measures made by the sensors. These sensor data are used and processed by the MAS to control the correct functioning of the monitoring system and to monitor the internal parameters of the real concrete elements. The processed data are then gathered in a SIS, containing also other non-sensor data (product ID, owner, manufacturing date...) and data related to the concrete service configuration. External BIM applications can then access the McBIM broker via a BIM-based standard interface. The Figure 6 describes the main parts of the information system architecture involved in the McBIM broker. The data coming from physical concrete are first treated in the McBIM Exchange Interface (Data acquisition). The concrete's ID is identified, and data are serialized to be stored in a Time Series Database Server. At this step, the information can be used by the MAS either for monitoring the behaviour of the McBIM physical element (section 3) or for the processing of the sensor data for BIM applications (section 4).

3. MAS for MONITORING CONTROL

This part concerns the interactions of the broker with the physical McBIM elements. As described in section 2.1, because McBIM elements will pass through different phases (manufacturing, construction, exploitation), the frequencies which communicating concretes produce data have to evolve over time. Because McBIM elements can interoperate each other, and in order to control the lifetime of the services provided by a McBIM element, the WSN have also to be reorganized. As depicted on Figure 7, these control orders are expressed when the "Concrete Service Configuration" is updated. Configuration changes can come either from BIM applications (via the McBIM API) or directly from the McBIM broker controller (via Energy control). We focus on the energy control in the following of the section.

To illustrate this kind of control and because energy management of the WSN embedded in the material is critical for our application, we designed a 3D-energy estimation software on Netlogo platform. Netlogo is a multi-agent programmable modelling environment developed by Northwestern University (Wilensky, 1999). This software allows integrating and storing sensor's values in order to be exploited by BIM applications. It can also in real time model energetic states of communicating nodes on a mock-up representation. Figure 7 gives a view of the produced

software for the different lifecycle phases of a McBIM concrete. In order to anticipate energy problems and to avoid stopping the services of a concrete McBIM element, this tool is able to simulate the number of messages spent in each lifecycle phase.

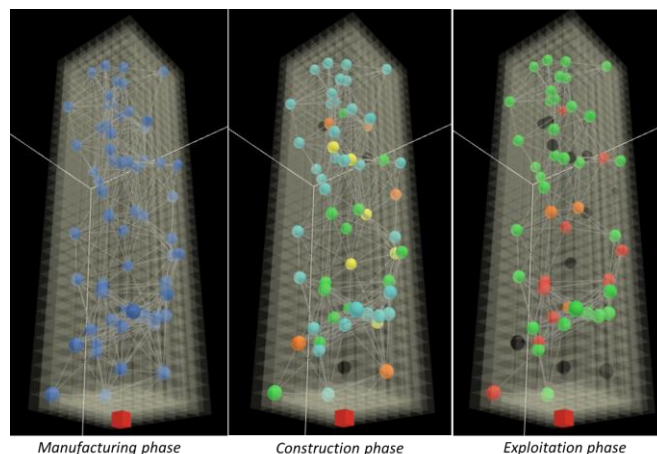


Fig. 7 Energy control and visualization of a concrete McBIM piece

First, in the manufacturing phase, the WSN representation is constructed by an analysis of the messages produced by the physical concrete element. Blue color on a CN represent an energy level between 90 and 100%. In construction or in exploitation phases, we can follow remaining energy of nodes represented by a colour gradient. If too many nodes die (black color) or if BIM applications need to change the measurement frequency, the Energy Controller can define another configuration for the monitored McBIM element.

4. MAS for BIM APPLICATIONS

The main objective of the McBIM project is to report information about a given concrete element. Data collected via WSN are first processed and then gathered in the data warehouse (SIS). These data can be proprioceptive or exteroceptive. Proprioceptive data are related to signals received by the sensors embedded in the material (temperature, humidity, ...) whereas exteroceptive data corresponds to information coming from its environment (product ID, product owner, material properties, ...). All these different types of information should be stored in the data warehouse. For a better understanding, a tentative data model is given in figure 8. Indeed, the future SIS will be mainly composed of entities related to the monitoring system and its configuration (*CommunicatingNode*, *SensorNode*, *MonitoringSpecifation*) and entities related to the measure and its context described by the measure itself (*ConcreteProcessMeasure*) the related concrete element (*ConcreteElement*) and the actor that demanded the measurement (*Actor*). In parallel, the DIS contains the raw data, represented in the data model by the *MonitoredSensorMeasure* entity. In this aspect, the role of the MAS is to process this raw data to transform them into *ConcreteProcessMeasure*. Indeed, the measure demanded by

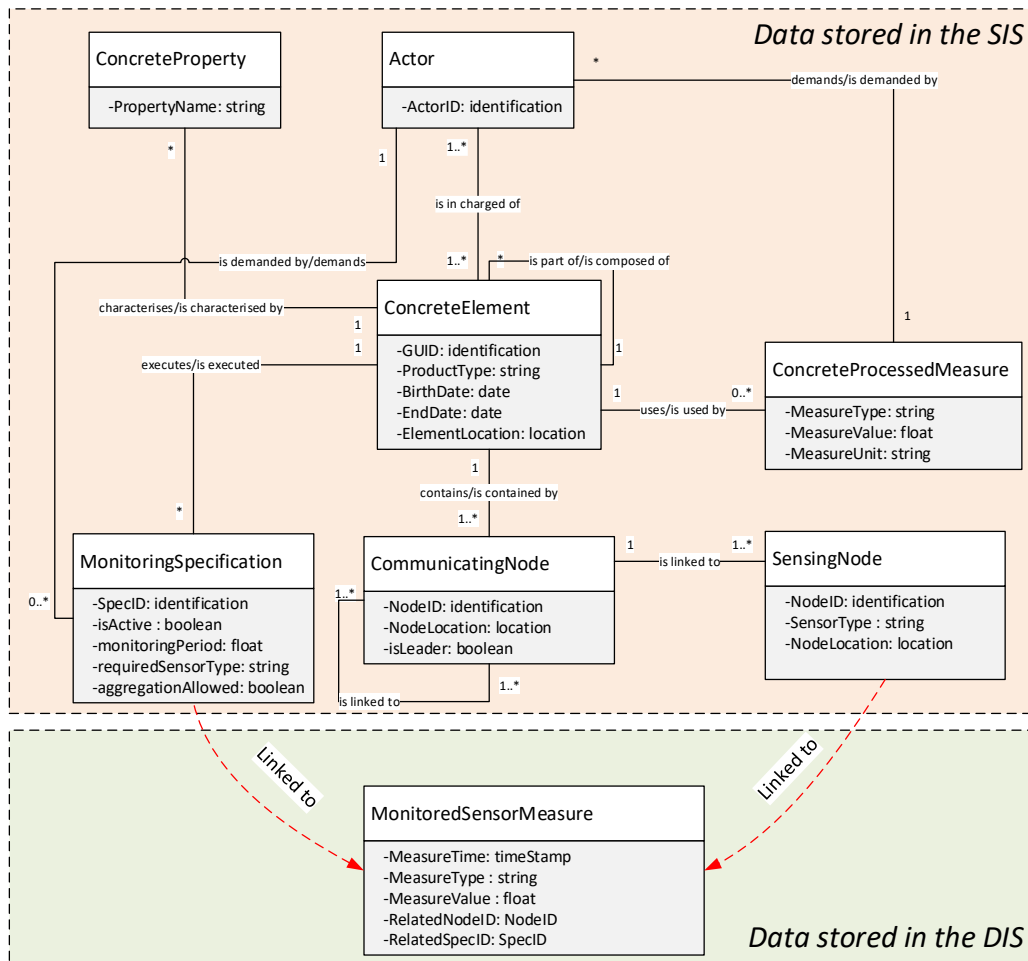


Fig. 8 Tentative data model for SIS and DIS

the actor could be the raw data itself (e.g. the temperature of a node in the concrete element) but also aggregated information (e.g. the minimum, maximum, average temperature in the concrete element). Once generated, this information should be made available to external applications and actors. To do so, the McBIM project proposes to use BIM standard interfaces.

To do so, two major problems still needs to be solved: first, the actual implementation of the IFC standard does not provide enough support for SHM. Recent solutions have been proposed but need to be evaluated in our context (Theiler & Smarsly, 2018). Moreover, in the context of BIM, resources are identified by means of so-called GUIDs (Globally Unique Identifiers) that usually contain UUID data. However, these GUIDs are not unique from one IFC file to the other.

5. CONCLUSION And PERSPECTIVES

New wireless technologies inserted in material bring a new way to manage the “Product Lifecycle Monitoring” issue. This work is about the design of physical and digital architectures able to address this issue. Main digital challenges relative to MAS design are discussed and some models are proposed to address these challenges.

To illustrate this problematic, the McBIM research project is described and some advances on it are used as examples.

Main project’s objective is the design of communicating concretes interacting during the overall lifecycle with BIM applications. In the first step of the project, the physical WSN architecture was defined and tested with the constraint to optimize the consumed energy by nodes in the network. As a second step, this project also includes digital challenges. We proposed to treat these kinds of challenges with a MAS and decomposed it in two parts:

1. MAS for controlling the physical and communicating part of the product: as example, an emulation 3D tool was developed in McBIM context to control the energy of the WSN
2. MAS for BIM applications: our proposal is a data multi-agent system based model for the exploitation by BIM applications. This architecture will produce knowledge organized in repositories based on specific ontologies. Each of these repositories will be tested in interaction with its corresponding BIM application. The digital architecture is still in development. Considering the exploitation phase of a building, the future McBIM broker could successfully interact with any kind of monitoring application, especially Structural Health Monitoring.

ACKNOWLEDGMENTS

Authors thank financial support from the French National Research Agency (ANR) under the McBIM project, grant number ANR-17-CE10-0014.

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