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TOWARDS A CUSTOMIZABLE ARCHITECTURE FOR INDOOR MULTI-USAGES DRONES

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Abstract

Where the building industry already uses drones for outside inspection and digitization activities, this paper proposes the use of multi-usages drones able to perform various services inside buildings, ranging from inspection, digitization, monitoring health and evaluation of technical performances of the building. Related to four different operational environments (scenarios), such multi-usages drones, which can rely on the use of Unmanned Aerial Vehicles (UAVs) or Unmanned Ground Vehicles (UGVs), need to be able to be adapted for their specific use, raising specific design challenges that increase the complexity of the system. A Model-Based Systems Engineering approach is proposed and applied to address this complexity, so to develop a customizable architecture. First results of this work are presented in this paper, part of the 'Indoor Multi-Usages Drone Acquisition' (IMUDA) project.

Keywords: Drones, Functional Architecture, Logical Architecture, Systems Engineering (SE), Building Information Modeling (BIM)

1. Introduction

Over the past two decades, drones have increasingly been used for building inspection. Such activities have to be performed since the early life cycle stages of buildings. A literature survey indicates that drones have essentially been used for outdoor inspections of buildings or for digitizing the exterior of buildings [1]. By contrast, little work has been published on indoor inspection of buildings using drones. Inspection of construction sites allows to ensure that executed work corresponds to what is expected. Further, during the operation phase, inspections enable detection of disorders of the buildings [2]. Building industry is in the process of digitizing its processes thanks to the use of digital models of buildings, also called Building Information Modeling (BIM), that contain both geometric and semantic information about the building, and that are known to be an efficient tool to manage and operate buildings [3]. For example, semantic information encompasses descriptive characteristics of the air conditioning systems, which can be used for scheduling the maintenance activities to keep the building exploitable.

In this paper, discussion is focused on exploration of buildings using drones in a context where BIM is increasingly deployed. The objective is to design a new system of indoor multi-usages drones to perform various inspection services for the interior of buildings. These systems, which can rely on the use of Unmanned Aerial Vehicles (UAVs) or Unmanned Ground Vehicles (UGVs), are intended to inspect, digitize, monitor, and evaluate the technical performances of buildings. They are further expected to fulfil missions adapted to the following four operational environments, referred to as scenarios:

- a building during its operation phase *(Sc01)*,

- a construction site *(Sc02)*,
- a building in danger *(Sc03)*, and
- a post-incident inspection *(Sc04)*.

To cope with the complexity of the development of indoor multi-usages drones, the authors of this paper apply a Systems Engineering (SE) approach, and more precisely a model-based one. Model-Based Systems Engineering (MBSE) offers many benefits, for instance in terms of communication and collaborative work between different teams from different domains [4]. The authors of this paper further see MBSE as an enabler to cope with constraints from both the robotic systems and the building domains. The objective is to propose optimized solutions and to satisfy the needs and desires expressed by the stakeholders involved throughout the system life cycle.
This paper extends on the MBSE approach presented in [5]: from mission analysis to logical architecture of an indoor multi-usages system and shows its application and first results.
The paper is organized as follows. Section 2 surveys related work on system architecture for drones. Section 3 presents the Systems Engineering approach used in this paper. Section 4 presents the contributions of this paper. Section 5 concludes the paper and outlines the future work.

2. Related work

In [6], Tanzi, Apvrille and Roudier present a system architecture for an autonomous drone that collects data. The system is made up of four main subsystems. Different sensors and actuators are grouped within the *Environment Sensing (ES)* and *Payload Management (PM)*, which are respectively responsible for the mission and the situational awareness platform. The *Motion Controller (MC)* interacts with several components, such as the avionics and the engines which it controls through autonomous decisions under normal flight conditions. The *Emergency Controller (EC)* can trigger other components such as parachute in case of abnormal situations such as lost of user signal. The purpose of the current paper is to propose an architecture encompassing data processing in order to satisfy the multi-usages aspect of the system.
Similarly, in [7] Hussein, Nouacer, Corradi, *et al.* present a general architecture for drone systems which is composed by three layers. The *Control layer* is responsible for the low-level control modes of the drone, that are take-off, landing and trajectory following. The *Flight Management layer* is responsible for selecting a pre-defined plan in response to an environment situation that cannot be handled in the control layer. The *Planning layer* is responsible for high-level planning, that is generating the different plans enabling the drone to perform its intended missions in an optimized way. This architecture is intended for autonomous drones. The current paper proposes a generic functional architecture for drones expected to perform missions inside buildings, that can be evolved from manual to more automated or autonomous systems.
In [8] Gustave, Chahal and Bebachir present a functional architecture for autonomous fire localization UAVs using Robot Operationg System (ROS) [9]. This hierarchical architecture [10] is divided into three layers. The *Perception layer* contains exteroceptive sensing, including temperature sensing, forest-fire localization, and position tracking. The *Controller layer* is responsible for computing the control law from the UAV pose information provided by the perception layer. The *Decision layer* is responsible for the exploration strategy, depending on the temperature measurement. Developing the functional architecture using ROS offers flexibility for any kind of UAV and missions, and ensures to get a reliable system.
The system architectures for drones presented in [6], [7] and [8] provide drones with the ability to perform their intended missions in an autonomous or semi-automated ways.
On the other hand, the architecture of the indoor multi-usages drone proposed in this paper has to encompass features related to the building perspectives, and should be customizable enough to adapt the drone to the different scenarios that are presented in section 4.3. So far, the authors of this paper refer to the possibility of using UAVs or UGVs by meaning drones, since the objective of this paper is to build a customizable architecture for the whole indoor multi-usages drone system as presented in section 4.5.

The authors of the current paper have decided to adopt a Model-Based Systems Engineering approach to ensure that the constraints from both the robotic systems and building domains are taken into account while designing an architecture for such a system.

3. Systems Engineering approach for indoor multi-usages drones

Applying an MBSE approach requires a modeling language, one or several tools, and a well-defined method to drive the development of a given system [11]. Regarding the modeling language, the authors of this paper propose SysML [12], the Systems Modeling Language co-developed by OMG (Object Management Group) [13] and INCOSE (INternational COuncil on Systems Engineering) [14]. Regarding the tools, the authors of this paper use Papyrus [15], which is a free, open-source tool, and which enables SysML diagram edition.
The method used in this paper was presented in [5]. It is organized over seven main steps, as depicted by the activity diagram in Figure 1.

1. The *Mission Analysis* consists in defining precisely the purpose, the mission, and the objectives of the system of interest to tackle one or several problems that it is expected to solve.

2. The *Requirement Analysis* includes the elicitation of the needs and desires of the stakeholders that are involved throughout the life cycle of the system of interest. These needs and desires are further derived into requirements that will serve as inputs for the rest of the design process.

3. The *Operational Analysis* consists in studying the behavior of the system of interest inside its operational environment, while it is being used.

4. The *Functional Analysis* defines the functions and services provided by the system of interest that are derived from the functional requirements, in order to design a functional architecture of the system.

5. The *Logical Architecture Analysis* consists in allocating the previously defined functions to logical components which are composing the logical architecture of the system of interest. The later is a first decomposition of the system, shows how it is organized.

6. The *Physical Architecture Analysis* translates the functional and logical architectures into physical architecture which is composed of physical components with a given set of properties.

7. The *Verification & Validation* are transverse activities allowing to check that the solutions satisfy the requirements and the needs, respectively.

This method is iterative and recursive. Iterations (represented as red dashed arrows in Figure 1) mean the repeated application of and interaction between the main steps of the method at a given level in the system structure (*e.g.,* at the system level (n)), in order to accommodate stakeholder decisions and evolving understanding [16]. Recursions (represented as blue curved arrows in Figure1 mean the repeated application of and interaction of the main steps of the method at successive levels in the system structure (*e.g.,* at the subsystem level (n-1)), to define the requirements for each of the subsystems of the system of interest. The main steps, except the Mission Analysis which is proper to the system level, are expected to be recursively applied for each successive level of the system structure until the level is reached where the decision is made to make, buy, or reuse a system element [16].
Note: for simplification and space reasons, inputs and outputs are not represented on the diagram in Figure 1. Verification and validation are not also shown, although they are performed after each step identified by the activity diagram.
Section 4 shows an iteration of the application of this method at the system level in order to identify functional and logical architectures candidates for the indoor multi-usages drone.

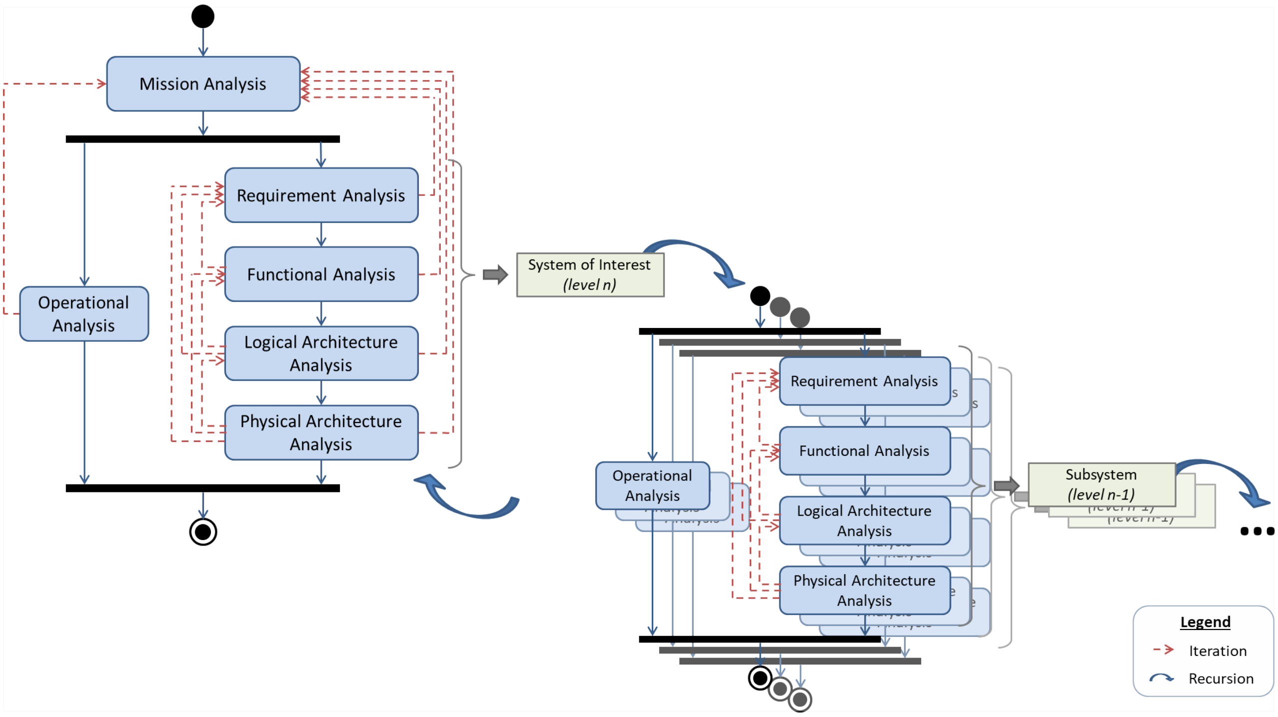

Figure 1 – The Systems Engineering method used in this paper.

4. Systems Engineering approach applied to an Indoor Multi-Usages Drone

In this section, the MBSE method presented in the previous section is applied to the indoor multi-usages drone in order to chose the suitable logical architecture for its system. In this section, “System of Interest” (SOI) refers to the overall system that is expected to explore the building of interest, as well as to provide the expected results, such as inspection results, digital models, or the technical performances of the building. This system of interest supports human operators for data gathering and processing in order to achieve the expected objectives, ranging from inspection, digitization, monitoring health and evaluation of technical performances of the building.

4.1 Mission Analysis

This section focuses on the definition of the mission which makes systems different from each others [5]. To do so, the *problems* that the system of interest is intended to solve are identified. First, the inspection of buildings during their construction and exploitation can be mentioned. The inspections of the interior of buildings with today’s solutions involve the use of considerable amount of resources, requiring time-consuming and costly operations [2]. Further, the evaluation of the technical performances of a building (*e.g.,* the *structural performance* to identify the load-bearing characteristics of the building elements; or the *energetic performance* to evaluate the thermal insulation and the energy consumption of the building), requires the mobilization of several tools and humans expertise to get the expected results [17]. Moreover, most of the existing tools for creating digital models of the interior of buildings are based on manual or semi-automated solutions requiring the presence of humans on the field, lead to costly and tedious operations, and presenting a safety risk for humans [18].
These are some of the problems that the system of interest proposed in this paper is intended to solve. The *purpose* of this system is to provide a cost efficient and time saving solution for the inspection and the creation of digital models of the interior of an existing building, and for the evaluation of the technical performances of the building.
The *mission* of the system is to explore the interior of an existing building, in order to gather the necessary amount of data and information that will be processed in order to achieve the expected mission objectives, and in the mean time to provide a visual feedback to humans.
As far as modeling the mission is concerned, one should keep in mind that SysML does not offer any specific diagram to express the mission, although requirement diagrams may be used as presented in [19].

4.2 Requirement Analysis

Before launching the Requirement Analysis, the needs and desires from the stakeholders that are involved throughout the life cycle of the system of interest should be elicited. Needs are what are mandatory for the system according to the stakeholder's perspective, whereas desires are what are nice to have to improve the experience of using the system.
To do so, interviews and brainstorming sessions with people from the building industry, especially BIM and building inspection experts have been held to dress up a list of their needs and desires for the indoor multi-usages drone. Mind maps are used to represent the needs and desires of the stakeholders in order to structure them according to the four operational environments in which the system of interest is intended to work (subsection 4.3) [20].
Figure 2 depicts an excerpt of the mind map representing the needs and desires that are expected from the stakeholders of the building perspective. These needs and desires are organized into four scenarios (Sc01, Sc02, Sc03 and Sc04 - see section 4.3) that regroup elementary services such as:

- creating BIM models of existing buildings,
- detecting disorders of the building elements and systems,
- ensuring the safety and comfort inside the building,
- performing the inventory of the building objects,
- evaluating the technical performances of the building,
- identifying the source of incidents,
- monitoring the construction work progress, and
- monitoring the supply networks, that are the power, gas, and hydraulic supplies.

The requirements are derived from these needs and desires, and are further classified into Functional, Behavioral, and Structural requirements, according to the taxonomy from Brazier et al. [21]. Functional requirements consist in the purpose of the system. Behavioral requirements describe the way the system acts. Structural requirements describe the components of the system and their relationships.
So far, covering the four scenarios, we have a list of 246 functional requirements which will be considered to design the functional architecture (subsection 4.4), 20 behavioral requirements that will allow to verify and validate the performance of the solutions, and 20 structural requirements implying constraints and partial imposed solutions, which will be considered and will be evolving during the logical and physical architectures analyses (subsection 4.5). Additional behavioral and structural requirements will be defined as much as we go deeper into the application of the MBSE method to better specify the system and its subsystems and elements.
The requirements are listed and prioritized using tables (see Figure 3). The applicability of the requirements to the four scenarios are spotted within the same table, as well as the traceability with the stakeholder requirements and with other aspects of the system (such as stakeholders and functions).

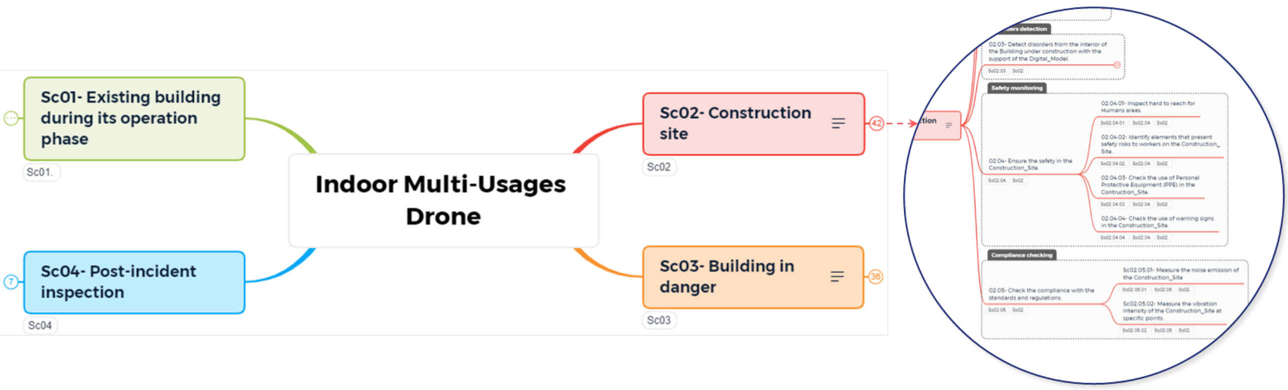

Figure 2 – Excerpt of the mind map representing the stakeholders needs and desires.

ID	System requirement	Type (FBSE)	Priority	Sc 01	Sc 02	Sc 03	Sc 04	Trace to stakeholder requirements	Trace to Functions	Trace to Stakeholders
Sys.R.04	**The system shall detect disorders of the interior of the Building.**	**Functional**	**High**	**x**	**x**	**x**	**x**	Stk.R.04	Perceive the operational environment	Building_Inspection_ Expert
Sys.R.04.01	The system shall detect Cracks.	Functional	High	x	x	x	x	Stk.R.04.01	Perceive the operational environment	Building_Inspection_ Expert
Sys.R.04.01.01	The system shall detect Cracks more than 1 mm of large.	Behavioral	High	x	x	x	x	Stk.R.04.01		Building_Inspection_ Expert
Sys.R.04.01.02	The system shall identify the Orientation of the Cracks.	Functional	Medium	x	x	x	x	Stk.R.04.01	Collect data	Building_Inspection_ Expert
Sys.R.04.01.03	The system shall measure the Large of the Cracks.	Functional	Medium	x	x	x	x	Stk.R.04.01	Collect data	Building_Inspection_ Expert
Sys.R.04.01.04	The system shall measure the Depth of the Cracks.	Functional	Medium	x	x	x	x	Stk.R.04.01	Collect data	Building_Inspection_ Expert
Sys.R.04.01.05	The system shall measure the Local_Placement of the Cracks.	Functional	High	x	x	x	x	Stk.R.04.01	Collect data	Building_Inspection_ Expert
Sys.R.04.01.06	The system shall monitor the evolution of the Cracks over time.	Functional	Medium	x	x	x		Stk.R.04.01	Process data	Building_Inspection_ Expert
Sys.R.05	**The system shall monitor the construction of the Building.**	**Functional**	**Medium**	**x**	**x**			Stk.R.05	Perceive the operational environment	Civil_Engineer
Sys.R.05.01	The system shall compare the progress of the construction work with the planned Digital_Model of the Building.	Functional	High	x	x			Stk.R.05.01	Perceive the operational environment & Process data	Civil_Engineer
Sys.R.05.01.01	The system shall compare the geometry of the Executed_Work against the Expected_Work.	Functional	High	x	x			Stk.R.05.01	Perceive the operational environment & Process data	Civil_Engineer
Sys.R.05.01.02	The system shall monitor the evolution of the Executed_Work according the Schedule.	Functional	Medium	x	x			Stk.R.05.01	Perceive the operational environment & Process data	Civil_Engineer
Sys.R.05.02	The system shall provide Building_Data of the Current_State of the Building to the File_of_Executed_Work of the Building.	Functional	Medium	x	x			Stk.R.05.02	Process data	Civil_Engineer
Sys.R.05.02.01	The system shall save the differences between the Executed_Work and the Expected_Work within the File_of_Executed_Work of the Building.	Functional	Medium	x	x			Stk.R.05.02	Process data	Civil_Engineer

Figure 3 – Excerpt of the requirement table for the indoor multi-usages drone.

Most of the requirements are applicable to all of the four scenarios: *e.g.,* the set of requirements regarding the detection of disorders (requirements ID: *Sys.R.04* - see the upper part of the table in Figure 3); although there are some that are specific to particular scenarios: *e.g.,* the set of requirements corresponding to the construction monitoring which are applicable to Sc01 and Sc02 (requirements ID: *Sys.R.05* - see the lower part of the table in Figure 3).
Note: a glossary table has been designed to define the specific expressions that are used in the requirement statements (capitalized and underscored words or expressions).
The Requirement Analysis helps to identify each competences and skills that will be necessary to design the system of interest, so that it can benefit from the aeronautical industry advances, and consider the constraints from the perspective of the building.
Once the Mission and the Requirement Analyses are performed, the Operational Analysis can begin thanks to the identification of the involved stakeholders that can include the actors interacting with the system while it is being used.

4.3 Operational Analysis

The Operational Analysis consists in considering the system of interest inside its operational environment to study its behavior, and to identify the different scenarios to which the SOI will be subject to. Since the SOI is intended to be multi-usages, it is expected to be adapted to the four scenarios corresponding to four different operational environments:

1. *Building during its exploitation phase (Sc01)*: this includes buildings in operation as well as buildings under renovation. Depending on the existence of a digital BIM model of the building or not, the system of interest will be used for three main operations:

   (a) to create a BIM model of the building or to update the existing BIM models;
   (b) to detect the disorders of the building, such as cracks, water damages, or defects of the building elements and systems; and
   (c) to evaluate the technical performances of the building, such as structural, energetic, architectural, hygrometric, and acoustic performances.

   In addition to the three aforementioned operations, we assume that the ones presented bellow for Sc02 concern Sc01 as well, since Sc01 encompasses the renovation of existing buildings which is a kind of construction site but being applied to buildings that are already existing.

2. *Construction site (Sc02)*: we assume that buildings under construction own digital BIM models that are followed during the construction process. In this case, the system of interest will be used for five main operations:
   (a) to monitor the progress of the construction;
   (b) to update the BIM model of the building under construction;
   (c) to detect the disorders such as cracks and water damages;
   (d) to ensure the safety of Humans inside the construction site; and
   (e) to check the compliance with the standards and regulations in terms of construction site management, and noise and vibration levels.
3. *Building in danger (Sc03)*: the system of interest will be used to inspect buildings that present a danger for Humans. The system of interest will support human operator for four main operations:
   (a) to evaluate the health of the building;
   (b) to perform in-situ diagnostics;
   (c) to identify the active supply networks, that are the power, gas, and hydraulic supplies; and
   (d) to create a BIM model of the Building or to update the existing BIM model.
4. *Post-incident inspection (Sc04)*: the system of interest will be used to perform indoor inspection inside buildings that have encountered incidents, such as fires, gas leaks or the spread of any other harmful products. Similarly to Sc03, the system of interest will be used for five main operations:
   (a) to evaluate the health of the building;
   (b) to perform in-situ diagnostics;
   (c) to identify the active supply networks, that are the power, gas, and hydraulic supplies;
   (d) to create a BIM model of the Building or to update the existing BIM model; and
   (e) to identify the sources of incidents.

SysML diagrams, especially context, use case, activity, and sequence diagrams, are being designed to complete the Operational Analysis in order to have a better global view on the whole system of interest.
The use case diagram in Figure 4 conveys a set of use cases that specify the required behavior of the system of interest in order to provide a measurable benefit to one or more external actors [22]. In SysML, a rectangle sets the boundary of the system of interest whereas use cases are represented by ovals. The set of functional requirements defined from the Requirement Analysis step are further refined by use cases titled “Explore the Building” which is the main function of the system, and is including “Move inside the Building”, “Detect Obstacle”, “Process Command”, “ Report”, “Collect Data”, and “Process Data”. Actors, which are represented by stickman (for human actors) and by rectangular blocks (for non-human actors), are connected to one or several uses cases as depicted in Figure 4. This use case diagram can be documented to further describe the operations thanks to activity and sequences diagrams.
Most of the aspects of robotics systems, such as the operational modes and states, will be considered and adapted to the system of interest, and taking the BIM models into consideration.

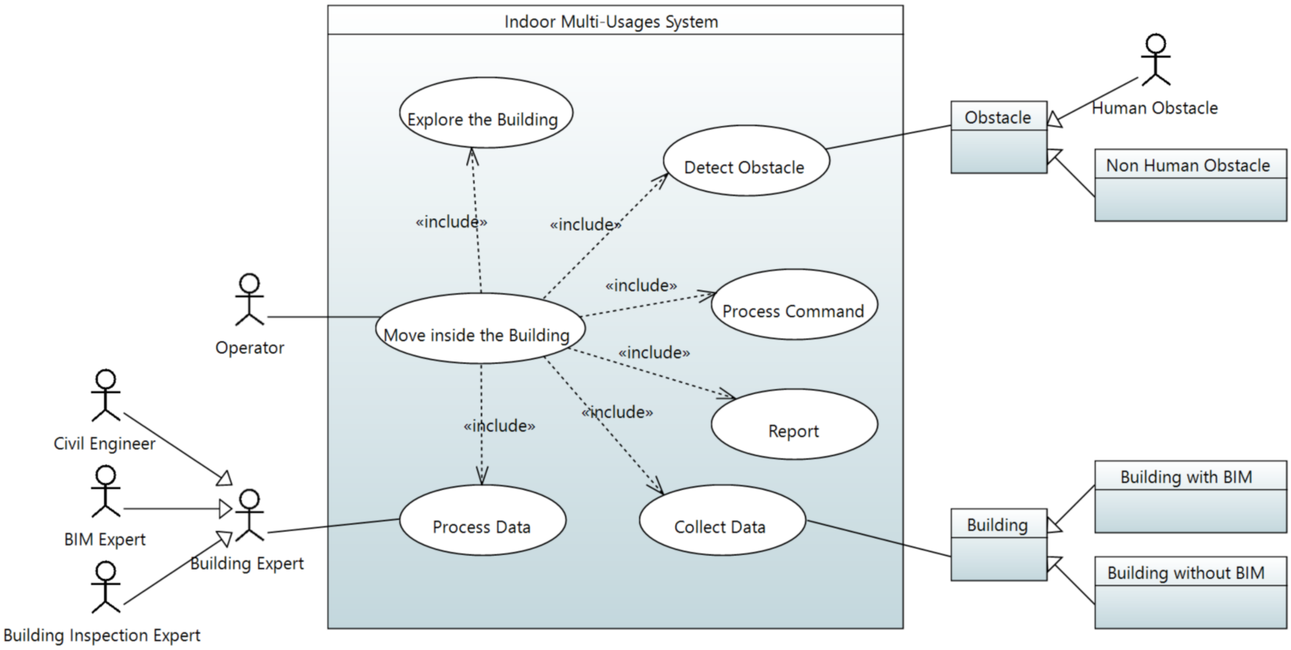

Figure 4 – Indoor multi-usages system use cases.

4.4 Functional Analysis

The Functional Analysis consists in identifying the functions that are provided by the system of interest, and the relationships between these functions. This allows to build a generic functional architecture for the system of interest, without any focus on any technical solutions nor on any technological choices. The functional requirements corresponding to each of the four above mentioned scenarios have been studied to identify seven main functions of the system of interest.
Figure 5 shows the functional decomposition of the system of interest in which the green rectangles with the «Function» stereotype represent the functions.

1. *Monitor the system (F1)* is responsible for monitoring the whole system, by managing the operator orders, and giving the operator access to the live feedback while performing the mission to keep her/him aware of the evolution of the mission.
2. *Plan the mission (F2)* is responsible for planning the mission, in order to generate the set of actions to be performed by the other functions, especially the “Perceive the operational environment” (F4) and the “Collect data” (F5) functions based on the operator orders.
3. *Manage the movement (F3)* is responsible for managing the motion of the system, to manage its state vector (position, speed, acceleration, and energy) in order to attend the targeted positions required to complete the mission objectives.
4. *Perceive the operational environment (F4)* is responsible for perceiving the operational environment while the system is performing its mission in order to model the external world as it is perceived by the system. This allows detecting Humans and objects such as building objects or any other obstacles inside the operational environment.
5. *Collect data (F5)* is responsible for collecting the data that are required to complete the mission objectives. These data can be collected from the direct interaction with the environment (to measure the temperatures or noise emission for example), or extracted from the world model perceived by the system.
6. *Exchange information (F6)* is responsible for ensuring the communication between the different subsystems and modules of the system of interest. It also includes the exchanges of the system of interest with the human operators, and with all the external systems, such as the facilities of the building like the Building Management System (BMS) or the Centralized Technical Management (CTM) [23].

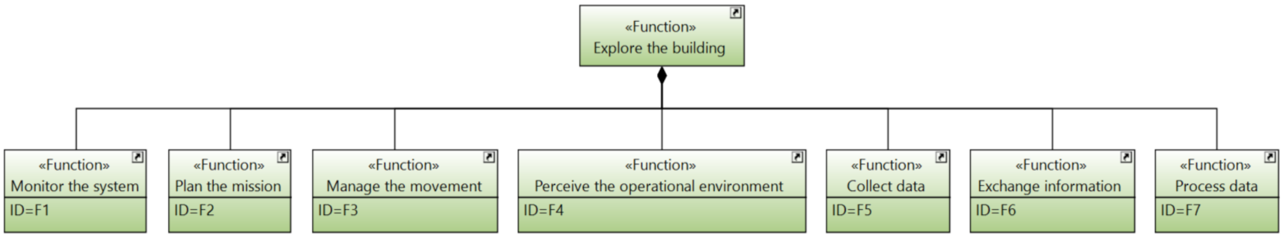

Figure 5 – Functional decomposition of the indoor multi-usages system.

7. *Process data (F7)* is responsible for processing the data that have been collected to get the expected results. It also processes the data that are provided by the building experts or the building owner, such as the existing 2D, 3D or BIM models of the building, that may be used as a support to perform the mission.

The functional architecture of the system of interest is depicted by the block diagram in Figure 6. It shows the functional exchanges between the seven functions defined above thanks to the association links represented by the black solid arrows.
The F1 function *(Manage the system)* provides the "Operator_Order" to the F2 *(Plan the mission)* and the F3 *(Manage the movement)* functions which will allow converting the orders provided by the operator into a motion of the system and a set of actions that are necessary to perform the intended mission respectively.
The F4 function *(Perceive the operational environment)* receives the "Action" command from the F3 function in order to allow interaction with the external environment, and then to build the "World_Model" which corresponds to the representation of the environment as it is perceived by the system. The "World_Model" may serve as input to the F5 function *(Collect data)* since it can contain several information that are relevant for various usages as presented in section 4.3. For example, photos can be collected, from which building data such as dimensions or local placement of building objects can be measured. The "World_Model" is also used by the F1 function to provide the operator with the visual feedback while performing the mission.

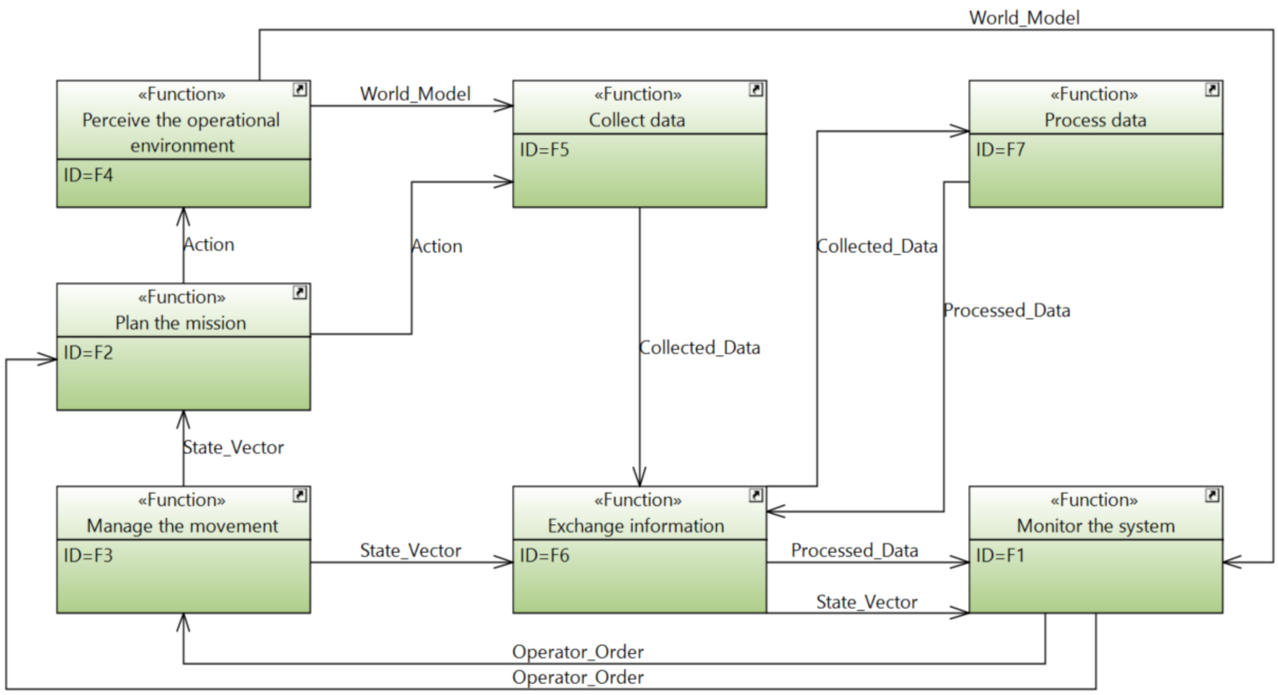

Figure 6 – Initial functional architecture of the indoor multi-usages drone system.

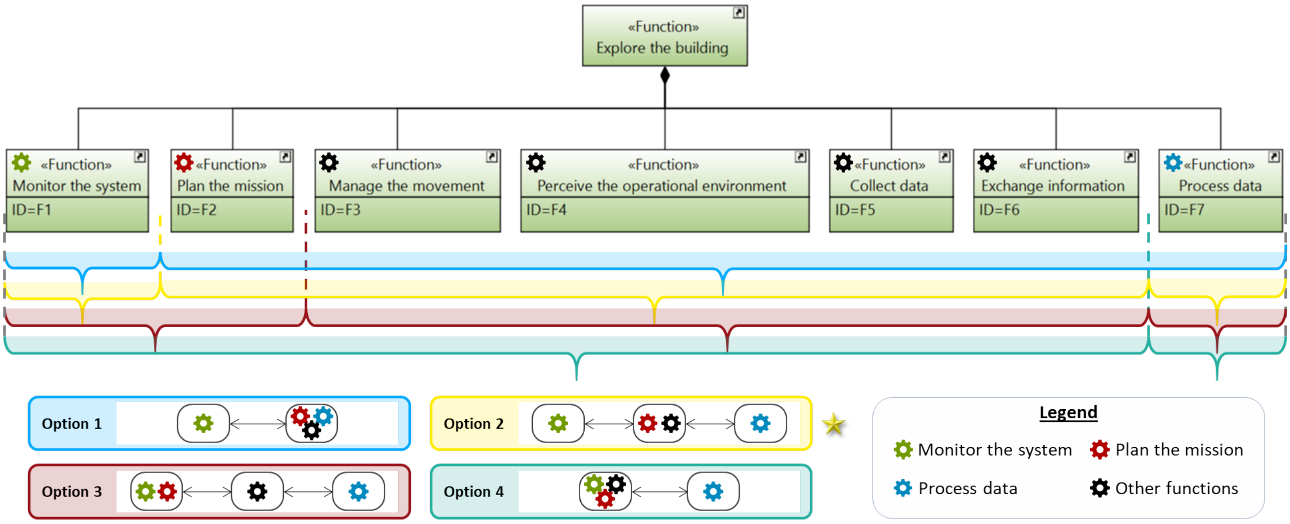

Figure 7 – Options for the logical architecture of the indoor multi-usages system.

4.5 Logical Architecture Analysis

The Logical Architecture Analysis consists in translating the functional architecture into a logical architecture which is a first decomposition of the system of interest, showing how it can be organized. The functions of the functional architecture are allocated to logical components which can be technical solutions, but being identified at high level.

As it is shown in Figure7, four options of logical architectures for the system of interest have been discussed, comprising different variants ranging from having all the intelligence and data processing embedded on the same mobile platform (option 1), to having the mobile part moving inside the building and all analysis taking place “at a distance” (options 2, 3 and 4).

The retained option (option 2), as depicted by the block diagram in Figure 8, is composed of three main logical components, referred to as subsystems (level n-1) of the whole indoor multi-usages system:

1. The *Monitoring subsystem*, to which the F1 and F6 functions are allocated, corresponds to the subsystem which is responsible for monitoring the indoor mobile system while it is performing the mission on the field, in order to ensure the mission is driven well and safely. This subsystem is also responsible for managing the operator orders which may be influenced by the state vector or the provided building data (such as existing 2D, 3D, or BIM models) that have been pre-processed to support the execution of the mission.

2. The *Indoor mobile subsystem*, corresponds to the subsystem that is used in the field to explore and collect data inside the building of interest. This mobile subsystem can be further decomposed into five modules that are:

   - The *Mission Planning Module*, to which the F2 function is allocated, is responsible for planning the mission by triggering the actions to be performed,
   - The *Motion Management Module*, to which the F3 function is allocated, is responsible for managing the movement of the mobile subsystem,
   - The *Perception Module*, to which the F4 function is allocated, is responsible for the interaction with the operational environment,
   - The *Data Collection Module*, to which the F5 function is allocated, is responsible for collecting the required data, and
   - The *Communication Module*, to which the F6 function is allocated, is responsible for ensuring the exchanges with the other subsystems and the external systems.

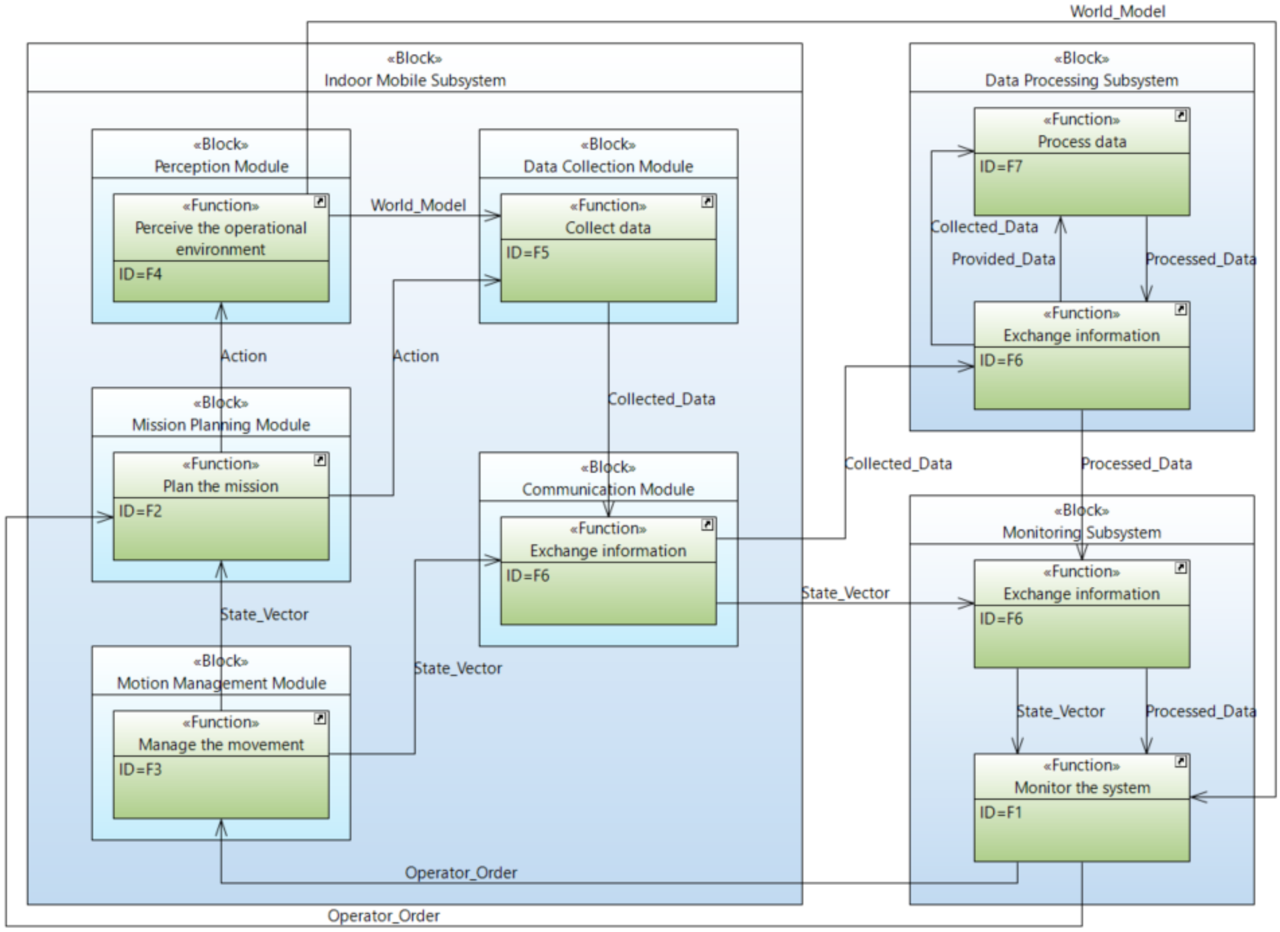

Figure 8 – Initial logical architecture of the indoor multi-usages drone system.

3. The *Data processing subsystem*, to which the F6 and F7 functions are allocated, corresponds to the subsystem which is equipped with a computer to process the collected and the provided data, in order to get the expected results to satisfy the mission objectives.

The benefits of this architecture include the ability to design the system step by step. The architecture proposed in Figure 8 corresponds to a remotely controlled mobile subsystem, which is providing the collected data to the data processing subsystem with sufficient computing power. The indoor mobile subsystem can rely on the use of UAVs, or the use of UGVs such as a rovers rolling on the ground, or even the combination of the two. Based on the expected services related to the intended mission derived from the functional requirements; for instance the digitization and inspection of a commercial building, or the evaluation of the health of an historical building in danger; this customizable architecture depicted in Figure 8 allows adapting the different subsystems and modules to optimize the execution of the mission.
Moreover, considering the behavioral and structural requirements, for instance related to the ability to operate inside buildings with multiple storeys, or inside construction sites where there are rubble on the ground, UAVs are seen as preferred solutions to allow satisfying as much requirements as possible.
As presented in section 3, the iterative and recursive SE method proposed in this paper may be applied to these subsystems of the logical architecture until getting the physical architecture with the precised characteristics of each components. Further, this architecture can evolve towards more automated or autonomous systems over time with the maturity of the design and the associated technology.

5. Conclusions and Perspectives

Drones have increasingly been used to accomplish missions in the building industry, especially for outdoor inspection and digitization activities. Nowadays, the building industry is currently in need for outstanding solutions to address upcoming challenges related to operations inside buildings.
To answer that need, this paper proposes the use of multi-usages drones able to perform various services inside buildings, ranging from inspection, digitization, monitoring health and evaluation of technical performances of the building. These indoor multi-usages drones are expected to be adapted to four different operational environments, which are building during its exploitation phase, construction site, building in danger, and post-incident inspection.
Developing a multi-usages drone for the previously identified operational environments raises new design challenges that increase the complexity of the system. A Systems Engineering approach is applied to address the complexity of the development of the system, in order to build up a customizable architecture for the indoor multi-usages drone.
This work, which is a part of the 'Indoor Multi-Usages Drone Acquisition' (IMUDA) project, will go on in the following directions. The logical architecture will be further developed and translated into physical architecture that will be composed of physical technological components. To do so, workshops with a technical team which is part of the stakeholders, will allow exploring the feasibility of a design fulfilling the expressed requirements. This may lead to the evolution of the of functional requirements study due to technical non-feasibility, or the specification of additional behavioral and structural requirements that should be satisfied by the physical architecture. Once the physical architecture and the components will be identified, the prototyping of the drone will start, and further the architectures can evolve towards more complex ones in order to extend the mission of the drone to encompass additional services based on the needs of the building perspective.

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7. Copyright Statement

8. Acknowledgements

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References

[1] Kaiwen Chen, Georg Reichard, Abiola Akanmu, and Xin Xu. Geo-registering UAV-captured close-range images to GIS-based spatial model for building façade inspections. *Automation in Construction*, 122:103503, 2021.

[2] Ilídio S Dias, Inês Flores-Colen, and Ana Silva. Critical analysis about emerging technologies for building's façade inspection. *Buildings*, 11(2):53, 2021.

[3] Mouchira Lahiani. Benefits of BIM implementation in the French construction industry. *IOP Conference Series: Earth and Environmental Science*, 588(4):042055, 2020.

[4] Kaitlin Henderson and Alejandro Salado. Value and benefits of Model-Based Systems Engineering (MBSE): Evidence from the literature. *Systems Engineering*, 24(1), January 2021.

[5] Eric Razafimahazo, Pierre de Saqui-Sannes, Rob A Vingerhoeds, Claude Baron, Julien Soula, and Romain Mège. Mastering complexity for indoor inspection drone development. In *2021 IEEE International Symposium on Systems Engineering (ISSE)*, pages 1–8. IEEE, 2021.

[6] Tullio Joseph Tanzi, L Apvrille, and Y Roudier. Towards a new architecture for autonomous data collection. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, 40, 2015.

[7] Mahmoud Hussein, Réda Nouacer, Federico Corradi, Yassine Ouhammou, Eugenio Villar, Carlo Tieri, and Rodrigo Castiñeira. Key technologies for safe and autonomous drones. *Microprocessors and Microsystems*, 87:104348, 2021.

[8] Johvany Gustave, Jamy Chahal, and Assia Belbachir. Functional architecture using ROS for autonomous UAVs. In *ICINCO*, pages 506–512, 2020.

[9] Kaiyu Zheng. ROS navigation tuning guide. In *Robot Operating System (ROS)*, pages 197–226. Springer, 2021.

[10] Rachid Alami, Raja Chatila, Sara Fleury, Malik Ghallab, and Félix Ingrand. An architecture for autonomy. *The International Journal of Robotics Research*, 17(4):315–337, 1998.

[11] Ludovic Apvrille, Pierre de Saqui-Sannes, and Rob A. Vingerhoeds. An educational case study of using SysML and TTool for Unmanned Aerial Vehicles Design. *IEEE Journal on Miniaturization for Air and Space Systems*, 1(2):117..129, 2020.

[12] OMG. *OMG Systems Modeling Language*. Object Management Group, https://www.omgsysml.org/SysML-2.htm, 2022.

[13] OMG. OMG | Object Management Group, 2022.

[14] INCOSE. INCOSE | INternational COuncil on Systems Engineering, 2022.

[15] Eclipse. *Eclipse Papyrus Modeling environment*. https://www.eclipse.org/papyrus/, 2022.

[16] David D Walden, Garry J Roedler, Kevin Forsberg, R Douglas Hamelin, and Thomas M Shortell. *Systems engineering handbook: A guide for system life cycle processes and activities*. John Wiley & Sons, 2015.

[17] Ahmed Abdelhafiz, Ashraf Balabel, Mamdooh Alwetaishi, Amal Shamseldin, Usama Issa, Ibrahim Sharaky, Mohammed Al-Surf, and Mosleh Al-Harthi. An innovative approach to check buildings insulation efficiency using thermal cameras. *Ain Shams Engineering Journal*, 13(5):101740, 2022.

[18] M Hasan Shariq and Ben Richard Hughes. Revolutionising building inspection techniques to meet large-scale energy demands: A review of the state-of-the-art. *Renewable and Sustainable Energy Reviews*, 130:109979, 2020.

[19] AFIS. Systems engineering and SysML in national education (in French), 2018.

[20] Pierre de Saqui-Sannes, Rob Vingerhoeds, Nasrine Damouche, Eric Razafimahazo, Ombeline Aïello, and Maisa Cietto. Mind maps upstream SysML v2 diagrams. In *2022 IEEE International Systems Conference (SysCon)*, pages 1–8. IEEE, 2022.

[21] Frances Brazier, Pieter van Langen, Stephan Lukosch, and Rob A. Vingerhoeds. *Complex Systems: Design, engineering, governance*. In: Projects and People: Mastering Success. NAP Foundation Press, 2018.

[22] SysML v2 Submission Team (SST). OMG Systems Modeling Language (OMG SysML™), v2.0, April 2022.

[23] Muhammad Umar Khalid, Muhammad Khalid Bashir, and Darryl Newport. Development of a building information modelling (BIM)-based real-time data integration system using a building management system (BMS). In *Building Information Modelling, Building Performance, Design and Smart Construction*, pages 93–104. Springer, 2017.