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The Design of Human-in-the-Loop Cyber-Physical Systems for Monitoring the Ecosystem of Historic Villages

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Highlights:

What are the main findings?

- A model and the related methodology for designing human-in-the-loop cyber–physical systems to protect historic villages.
- A definition of patterns, based on the situational awareness approach, for the distribution of human and automated intelligence in an edge-cloud architecture.

What are the implications of the main findings?

- The design models and the related methodology can be used as guidelines for the design of human-in-the-loop cyber–physical systems based on situational awareness, smart objects, and edge-cloud networks.
- This paper promotes the implementation of decision-making processes finalized to reduce risks, improve safety procedures, and provide a knowledge base to protect the cultural heritage of historic villages.

Abstract: Today, historic villages represent a widespread and relevant reality of the Italian administrative structure. To preserve their value for future generations, smart city applications can contribute to implement effective monitoring and decision-making processes devoted to safeguarding their fragile ecosystem. Starting from a situational awareness model, this study proposes a method for designing human-in-the-loop cyber-physical systems that allow the design of monitoring and decision-making applications for historic villages. Both the model and the design method can be used as a reference for the realization of human-in-the-loop cyber-physical systems that consist of human beings, smart objects, edge devices, and cloud components in edge-cloud architectures. The output of the research, consisting of the graphical models for the definition of monitoring architectures and the method for the design of human-in-the-loop cyber-physical systems, was validated in the context of the village of Sant'Agata dei Goti through the implementation of a human-in-the-loop cyber-physical system for monitoring sites aiming at their management, conservation, protection, and fruition.

Keywords: human-in-the-loop cyber-physical systems; smart object; edge-cloud architectures; smart city

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1. Introduction

Historic villages represent the living embodiment of nations' rich cultural heritage, providing valuable insights into their past, fostering a deep sense of identity, and attracting visitors from around the world. Since historic villages represent the legacy of the past to be passed on to future generations, they are often preserved and protected. On the one hand, there is growing interest in their conservation in consideration of the increase in tourist flows and the economic benefits deriving from it for the resident population. On the other hand, the combined effect of anthropic activities [1], geological hazards [2], or climate change [3] constitute a risk factor concerning the preservation of this important historical, economic, environmental, and cultural heritage. Therefore, safeguarding and preserving historical villages is a problem that is being addressed by many researchers concerning cases that have been studied in many parts of the world addressing different historical, cultural, and environmental scenarios in Europe [4], China [5], Italy [6], and other countries as well [7,8]. In Italy, historic villages represent a widespread and relevant reality of the Italian administrative structure. Based on the above considerations, there is a clear need to put in place actions aimed at protecting and securing historic villages for their regeneration and cultural, social, and economic development. One of the certainly necessary actions is that of integrated monitoring of historic villages to identify threats and risks and, if possible, indicate solutions for the elimination of the former and the reduction of the latter.

Risks can be reduced in a historic village by monitoring the stability of ancient structures and environmental conditions in real time, promptly reporting any anomalies such as subsidence or changes in humidity, allowing preventive action to be taken to avoid irreparable damage.

In recent years, the problem of integrated monitoring of heritage buildings for their preservation and protection has affected several valuable urban areas and historic centers [9–11], and those sites located in extremely aggressive environments or areas of high exposure from natural and anthropogenic hazards [12]. However, integrated monitoring of the delicate ecosystems of historic villages has not received sufficient attention in the literature. On these grounds, in this work, it was decided to analyze the Borgo di Sant’Agata dei Goti (a historic village in southern Italy) as a pilot case because of the presence of all the archaeological, historical, cultural, environmental, economic, and social components that form a fragile and complex ecosystem. The case study is representative of hundreds of historic Italian villages that have similar characteristics to Sant’Agata dei Goti. We address the problem of integrated monitoring of a historical village as a complex ecosystem with a large number of components and relationships, which has variety and variability of components and relationships and which cannot be modeled and understood in a unique way. From a monitoring perspective, such an ecosystem requires the monitoring of numerous sites or subsystems of a different nature and with different monitoring purposes. Each site must be managed with its methods, techniques, and tools, suitable for the protection and conservation of the site under consideration. Cyber-Physical Systems (CPS) or Human-in-the-Loop Cyber-Physical Systems (HiLCPS) supporting the monitoring activity of historic villages reflects this systemic complexity. Integrated monitoring of historical villages is aimed at realizing monitoring processes implemented respectively by (a) automatic systems; (b) humans; and (c) a combination of automatic systems and humans. These monitoring processes are finalized to reduce risks, improve safety procedures, and provide a knowledge base for preserving and conserving high artistic and cultural value goods. To achieve these goals, this paper explores the contribution of smart city technologies and applications [13,14]. Despite the growing number of scientific papers show a tenseness toward greater automation in several application areas, research on the role humans can play in systems that combine automation and human capabilities has been gaining momentum in recent years [15,16]. Therefore, the trend toward an increasing degree of autonomy for artificial systems is being counterbalanced by the need to place greater emphasis on the role humans can play in monitoring, control, and decision-making processes. For example, Industry 5.0 complements the Industry 4.0 by promoting the transition to a sustainable, human-centric, and resilient European industry through research and innovation [17]. From this paradigm shift HiLCPSs, a particular class of CPSs, are expected to make an important contribution to the improvement of monitoring and decision-making processes in various application areas. The importance of the human-in-the-loop concept is well known. In [18], it is emphasized that many safety-critical systems are interactive in the sense that they interact with humans who take a central role in the proper functioning of the system. Starting from the situational awareness (SA) model [19] that we adapt to the monitoring problem of historic villages, this study proposes graphical models, described in Section 5, for the definition of monitoring and decision support architectures, and describes in Section 4 the five steps of the design of HiLCPS dedicated to protecting historical villages. Both the models and the design method can be used as a reference for the realization of HiLCPS that consist of human beings, smart objects, edge devices, and cloud components in edge-cloud architectures. This work is a continuation of a previous study [11] that defined the SA model for monitoring historic buildings and extends it to explore the following research questions:

> RQ1: Can SA guide and facilitate the design and implementation of systems for monitoring historic villages?
> RQ2: What is the contribution of HiLCPS to improve the monitoring processes of historical/cultural sites?

According to Ashby's Law of Requisite Variety [20] , to effectively manage a complex system that has multiple states or variables, the control or monitoring system must be complex enough to cover the same variety as the system under control. If a complex system has many parts or possible configurations, the management or control system must have enough flexibility and capability to deal with each of them. The investigation of research question RQ1 aims precisely at understanding what contribution SA can make in the design of HiLCPSs, i.e., complex systems composed of many interacting heterogeneous parts that have to fulfil monitoring and control tasks in historical villages.

With the support of HiLCPS, decision-making processes and feedback actions can be taken by humans and automated systems on their behalf or in collaboration, to the protection of historic villages. To this purpose, we use situational awareness theory; this approach is different from the design approach appearing in the literature because the SA model is used as a guideline for the design of smart objects and edge architectures in a scenario where both automatic systems and humans are involved in SA decision-making processes. The expected benefits of the proposed architectural models and the related method are:

- Guidance in the design of HiCPS.
- Reuse of architectures based on SA and smart objects.
- Reuse of patterns for the distribution of human and automated intelligence in a HiLCPS.
- Integrated monitoring of sites belonging to historic villages.

To validate our research and to evaluate its potential benefits in historical villages, the case study discussed in this paper illustrates the implementation of a HiLCPS for integrated monitoring and control of Sant'Agata dei Goti. The paper is organized as follows. The next section reviews the background, first discussing some work on SA of reference for our research and then evaluating the state of the art of enabling technologies for CPS implementation. Section 3 describes the case study of Sant'Agata dei Goti. Section 4 resumes the research methodology discussing the action research scenario and the method defined for the design and implementation of HiLCPS. After the presentation of the model that integrates SA and CPS that will guide the design and implementation of HiLCPS, Section 5 describes the steps for the design of smart objects and edge computing architectures of a CPS that must support decision-making processes. The results obtained by the implementation of a HiLCPS for integrated monitoring and control of Sant'Agata dei Goti are shown in Section 6. After the discussion in Section 7, about the positive implications as well as limitations of this research, Section 8 resumes the findings and closes the paper.

2. Scientific and Technical Background

Our approach to integrated monitoring of historic villages involves the use of a situational awareness-based reference model for the design of HiLCPS to support monitoring and decision-making.

2.1. Situational Awareness

Endsley [19,21] defines SA as the "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". The model of SA and consequent dynamic decision-making consider three distinct levels:

- Level 1. Perception of the elements in the environment.
- Level 2. Comprehension of the current situation.
- Level 3. Projection of future status.

SA examines how operators acquire, interpret, and use information to understand their working environment and how this influences their performance. It emphasizes the importance of perceiving essential elements in the environment and how they can use this information to make informed decisions. A relevant part of SA concerns the areas of system design and evaluation and has received considerable attention from the human factors research community. Using the goal-directed task analysis (GDTA) methodology [21], a hierarchy of goals, decisions, and associated informational requirements can be developed beginning from the goals of the human operator in the given task situation. Furthermore, the work discussed in [22] shows that categorization facilitates the execution of GDTA to identify SA requirements. Shifting the focus from individual operators to cognitive systems that comprise automated systems [23], an increasingly important research area focuses on a systems perspective trying to combine the SA of individual operators with that of automated systems aiming at the achievement of a joint cognitive system consisting of human and technological agents. In this scenario, SA is viewed as an emergent property of collaborative systems, something that resides in the interaction between elements of the system and not in the heads of individual operators working in that system [24]. For what concerns the application domain discussed in the case study of Section 3, the conservation, and protection of historical, artistic, and cultural heritage, the contribution of SA is recent. Ref. [25] shows how SA has been applied to the health monitoring of Heritage Buildings and [26] discusses the utilization of a digital cultural heritage cube that can be utilized for rapid situational awareness, periodic monitoring, and precision analyses.

2.2. Cyber-Physical Systems

Lee and Seshia describe a CPS as an integration of computation with physical processes whose behavior is defined by the system's cyber and physical parts [27]. Embedded computers and networks monitor and control the physical processes, usually with feedback loops, where physical processes affect computations and vice versa [28]. This integration mainly includes computation, communication, and control aspects of the physical systems and is based on the tight conjoining of and coordination between computational and physical resources.

After the influential paper of [29], the need for CPS research in the following areas became evident:

- Abstraction and architectures.
- Distributed computing and networked control.
- Verification and validation.

Therefore, some of the main contributions to the design of CPS have been proposed by [30] who discusses in detail the principles of their design, specification, modeling, and analysis, and by [31] who illustrates six design principles for Industry 4.0 (interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity) of which CPS are a key component. The literature review proposed by [32] discusses the current state of the art, characteristics, design methodologies, applications, and challenges for CPS. The authors also highlight how new research developments can improve the collaboration between humans and CPS.

In HiLCPS for the monitoring and control of historic villages, this collaborative work manifests itself by assigning tasks to humans and automated components, taking into account their respective strengths, and then combining the behavior of each in order to achieve better performance. Examples of combined systems are those that monitor a bridge or a work of art as described in Section 6.

As already noted in the introduction, systems that consider interaction with human beings are becoming more and more important, and it can be expected that future technologies will take interaction with human beings into greater consideration to develop collaborative work [33]. The Human-in-Loop (HIL) concept has its origins in multiple fields, and its development has been influenced by advancements in engineering, artificial intelligence, human-computer interaction, and automation. In [16] the term HiL refers to human agents who operate or monitor a process. In a HiL system, users receive services from and affect the performance of a system. In manufacturing industries, it is common the implementation of HiL systems known as supervisory control systems where human workers oversee an otherwise autonomous process and are responsible for adjusting certain set points that may influence the system [34]. For example, in a system consisting of a worker and a milling machine, the program controlling the implementation of the process performed by the milling machine has been initialized to set the spindle speed at 2000 rpm. During the execution of the machining process, the worker can decide to vary the spindle speed to achieve more precise work that meets the design specifications of the workpiece being machined, thereby increasing the efficiency of the machining process. Similarly, a surgeon who is operating on a cancer patient using a Gamma Knife machine (which allows high doses of radiation to be administered with extreme precision on a target inside the skull), can intervene on the machine by altering the initially planned duration of treatment or the amount of radiation administered to the patient. A Human-in-the-Loop Cyber-Physical System (HiLCPS) refers to a class of systems that integrate monitoring, human decision-making, and interaction into the feedback loop of traditional CPS. In such systems, humans play a crucial role in monitoring, analyzing, and sometimes controlling the cyber and physical elements [35]. The integration of human expertise enhances the system's ability to handle tasks that require cognitive reasoning, especially in environments where full automation may not be ideal or safe. These systems combine real-time data from the physical world, computational algorithms from the cyber domain, and human input to achieve more flexible and intelligent operations. A HiLCPS is made of a network of people, processes, data, and physical devices to produce semi-automated or automated responses to changing conditions in the real world. In the context of HiLCPS, starting from the modeling of human behavior and the collection of information about human factors, ref. [36] provide examples of assessment of human reliability. Considering the socio-technical aspects and the role of HiL in smart factories [16], explore different levels of human involvement in a CPS and their relative importance. The design of HiLCPS is covered by [37]. Key components of HiLCPS are smart objects. A smart object (SO) is essentially a small micro-electronic device that consists of a communication device, typically a low-power radio, a small microprocessor, and a sensor or actuator [38]. In other words, an SO is an autonomously functioning hardware/software entity that contains its sensing, processing, and networking capabilities. An SO can both sense and interact with external and internal elements; furthermore, it possesses application logic [39]. The set of self-* awareness features of SOs listed in Table 1, resumes those discussed in [40] and provides further references. Self-* awareness features will be used to define the reference architecture of smart objects proposed in Section 5.2. The class of Self-aware CPS that operate by bringing together CPS and self-aware computing is discussed in [41]. Smart sensor systems also incorporate machine learning (ML) that can be used to develop sophisticated models for sensing applications. Ref. [42] describes how the sensor technologies are coupled with ML "smart" models and how these systems achieve practical benefits. Ref. [43] highlights how ML can address various issues associated with IoT data and can be deployed effectively as it necessitates minimal human intervention. One promising technology that will have a major impact on CPS and HiLCPS is edge computing where the "edge" is described as any computing and network resources positioned along the route between data sources and cloud data centers [44]. Data processing is optimized to occur as near to where it is created, consequently enhancing response times and utilizing fewer bandwidths. Technologies allowing computation to occur at the edge of the network can be used for downstream data about cloud services and upstream data on behalf of IoT services. A detailed description of the current research efforts in edge-based CPS can be found in [45]. In [46] the authors examine the drivers and requirements for the use of edge computing in critical industrial applications and discuss the role of edge computing in industrial edge-based CPS.

Table 1. References to self-* features of Smart Objects.

Self-* Features	Meaning	References
Self-configuring	The process where newly deployed nodes are configured by automatic installation procedures to get the necessary basic configuration for system operation.	[47]
Self-awareness	The capability of an SO to recognize itself as an individual entity and its current state. It covers the aspects of sensor/actuator identification to establish an access path to the object, localization, status diagnosis, etc.	[48–50]
Self-protecting	The control logic to protect the privacy and against security attacks.	[51]
Self-healing	The capability of an SO to recover from damages and restore its functionality.	[52–54]
Self-optimizing	Self-optimizing SO can learn from their own experience, adjust their behavior, and improve their performance without requiring direct input from a human operator.	[55]
Self-adaptiveness	Self-adaptiveness refers to the ability of a system or object to dynamically adjust its behavior and/or configuration based on changes in its environment or usage patterns, without external intervention. This can be achieved through various techniques such as machine learning, feedback control, or rule-based approaches.	[56–59]

3. Case Study

The case study describes the TISMA project which through the implementation of a HiLCPS for the monitoring and control of a historic village, aims to:

- Develop an automated diagnostic procedure with which it is possible to plan ordinary and extraordinary maintenance interventions on the structure and infrastructure of a historic village.
- Assess the level of risk to structures and infrastructure from seismic, hydraulic, meteo-hydrogeological, or anthropogenic threats.

From these aims, it was decided to analyze the village of Sant'Agata de' Goti as a pilot case because is a multidimensional integrated ecosystem, due to the co-presence of the archaeological, historical, cultural, environmental, economic, and social components with which to validate the results of our research. Sant'Agata dei Goti is an ancient village of the Campania region in Italy with just over 10,000 inhabitants and is situated on a tuff rock and surrounded by natural beauty as shown in Figure 1.

Numerous architectural, cultural, and environmental assets are part of this village. The historic center develops in a semicircle and stretches for one kilometer in length. Hills surround the area. In the northern part of the territory, necropolises dating back to 300 B.C. have been uncovered. The village is rich in splendid monuments, such as the Ducal Castle, built by the Lombards and later expanded by the Normans in the 11th century. Of particular interest are: the Church of the Annunziata, dating back to the 1300s, which was once outside the city but is now fully incorporated into the village; the Church of San Mennato, dating from the 12th century; the Church of San Francesco, which houses an archaeological exhibition with sections dedicated to the Samnites and the Lombard period; and finally, the bridge over the Martorano River, which serves as the entrance to the village and rises majestically over the tuff cliff. To illustrate the different monitoring needs of the sites covered by this research, we will refer to:

(a) **Tuffaceous ridge and historic village.** The monitoring needs concern hydrogeological, seismic, and meteo-climatic phenomena as well as anthropogenic risks. A photo monitoring system was implemented by which small displacements and deformations of the tuffaceous ridge can be measured, based on the comparison of multi-temporal images of the object subjected to continuous observation using high-resolution cameras (Figure 2a).

(b) **The bridge over Martorano Creek.** The bridge is the main access route to the village; it is a triple-arch structure with two foundation piers. The bridge is subject to structural monitoring using a network of wireless biaxial clinometers with high acquisition frequency, located in the piers and abutments of the bridge (Figure 2b). The bridge is also subjected to periodic vibrational monitoring measurements aimed at studying the dynamic behavior of the structure.

(c) **The church of San Francesco.** It is a vast structure consisting of a church and a convent. The church dates to the 13th century but was modified in the 1700s, so both the exterior and interior appearance is Baroque. The ceiling of the church is made of wood, in the manner of a starry sky, painted in gold and blue. Furthermore, many medieval paintings enrich the walls and vaults. The church is periodically monitored with a UAV system and specialized stations (Figure 2c). Diagnostic investigations using non-invasive methodologies on the decorative apparatus and works of different types kept inside the church are aimed at studying the state of preservation, through the understanding of degradation phenomena and, possibly, the correlation between them and the recorded microclimatic conditions.

(d) **The Mustilli winery's winemaking rooms.** They are dug into the tuff about 100 m deep and ensure the right temperature and humidity (Figure 2d). Checks are made in the cellar (radon, CO_2, humidity, and temperature) and outside on the forecourt (environmental and weather-pluvial). Those in the cellar are necessary to protect visitors descending into the tuff cave, while those on the forecourt are used to convey the status of the site to tourists.

(e) **The Eco Museum.** Includes photo monitoring stations along the Martorana River where there are typical plant species and medieval buildings (wash house) and the Promenade where under the watchful eye of a monitoring system with information panels are placed MEMS equipped with control BLEs and APPs on Mobile that guide tourists on customizable routes. Details about the Eco Museum and other monitored sites can be found at the TISMA project website https://www.tisma.eu (accessed on 10 June 2024).

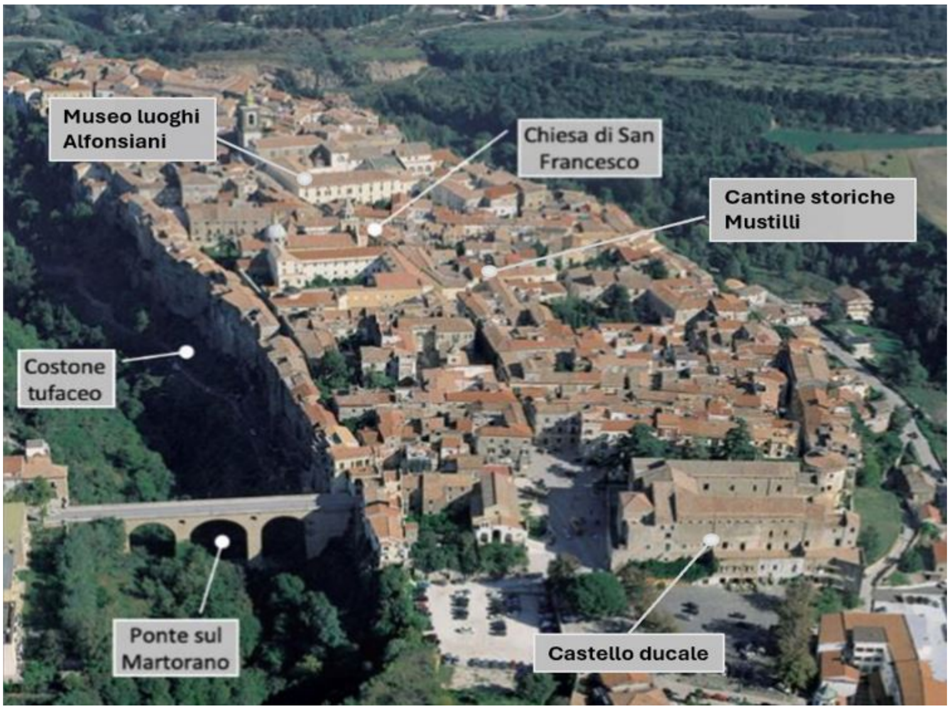


Figure 1. Location of sites of historical interest for monitoring the historical centre of S. Agata dei Goti.

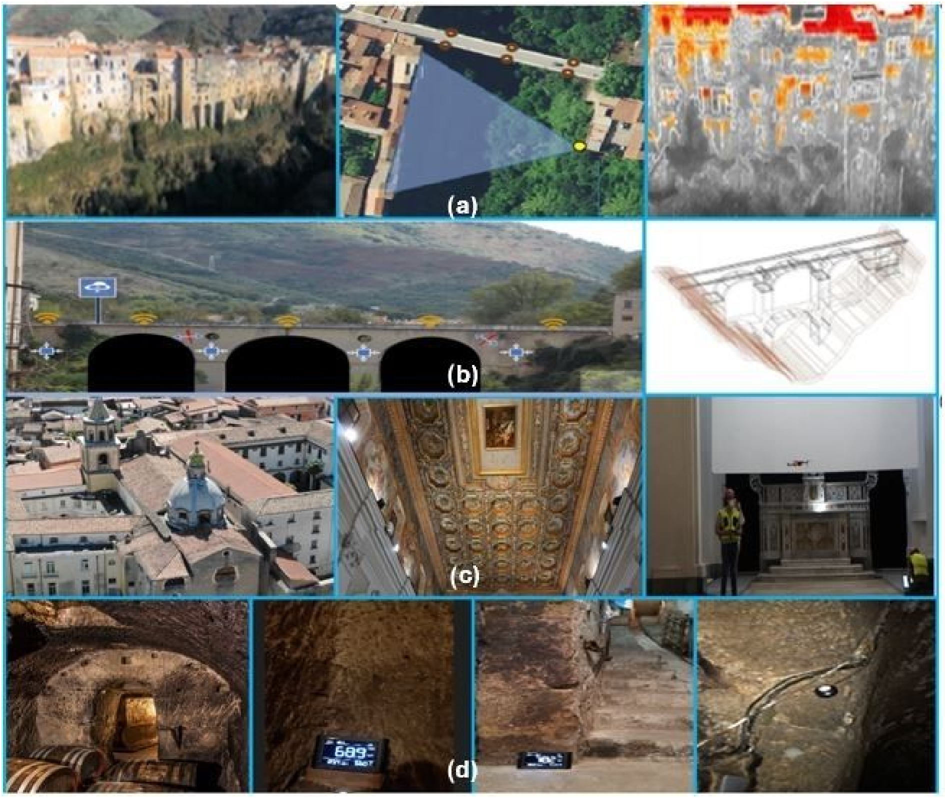


Figure 2. Examples of site monitoring in Sant'Agata dei Goti. (**a**) Tuffaceous ridge and historic village; (**b**) The bridge over Martorano Creek; (**c**) The church of San Francesco; (**d**) The Mustilli winery's winemaking rooms.

4. Research Methodology

This study has adopted an action research approach [60], which seeks to solve current practical problems while simultaneously expanding scientific knowledge. Action research is an iterative process involving researchers and practitioners acting together on a particular cycle of activities, including problem diagnosis, active intervention, and reflective learning. Participatory action research emphasizes participant collaboration. This approach, adopted in the development of the case study described in Section 5, has involved collaboration between the researchers from academia and the managers working in the Sant'Agata dei Goti municipality. The research team has undertaken the following tasks:

- Conducted interviews with key stakeholders.
- Analyzed the interviews.
- Identified the scientific approach to propose solutions to innovation needs.
- Implemented the HiLCPS for the monitoring of the ecosystem of Sant'Agata dei Goti.
- Illustrated a demo and collected feedback from the participants.
- Collected data from the HilCPS and analyze them.

  The managers of the historic village of Sant'Agata dei Goti have undertaken the following tasks:
- Identified the sites to monitor, the problems to solve, and the innovation needs.
- Scheduled the interviews with stakeholders.
- Collected data necessary for the design and implementation of a CPS for the protection and preservation of the historical heritage of Sant'Agata dei Goti
- Validated the results.

During the joint working sessions, it became clear that solving the monitoring and control problems in such a complex ecosystem as Sant'Agata dei Goti would require human actions and automated technological systems, or even their combination. The researchers, therefore, turned to the study of HiLCPS systems and their design from SA theory. In addition, during the development of the case study the following steps, detailed in the next section, were defined for the design of HiLCPS.

1. Use an SA model that combines decision-making processes taken by humans and automated systems.
2. Design smart objects using the SA model as a guideline.
3. Distribute the intelligence in the HiLCPS.
4. Design the data ingestion process.
5. Integrate the monitoring processes.

The key information to evaluate for planning the monitoring interventions has been obtained using a questionnaire containing 25 questions classified into: identification and state of conservation of buildings, environmental and structural risks, identification of natural resources, threats from tourism or other human activities, and protection from natural disasters. Table A1, in Appendix A, shows an extract of the main questions submitted to the managers of the municipality of Sant'Agata dei Goti, with an indication of the answers and, from these, possible monitoring solutions through the implementation of CPS or HiLCPS.

The design method meets the expectations of action research in generating new scientific knowledge applicable to other application domains.

5. The Situational Awareness Approach to the Design of Cyber-Physical Systems

This section develops the discussion of designing a HiLCPS using the SA approach. The starting point is the SA model, which is reported in Figure 3. Then, Sections 5.2 and 5.3 describe the use of SA to design both the architecture of a generic SO and the distribution of intelligence in a HiLCPS to be implemented in an edge-cloud network. It follows a discussion about the need and features of data ingestion processes in an edge-cloud network and on ML for smart objects and edge-computing. Finally, a discussion on how to design the integration of monitoring processes closes the section.

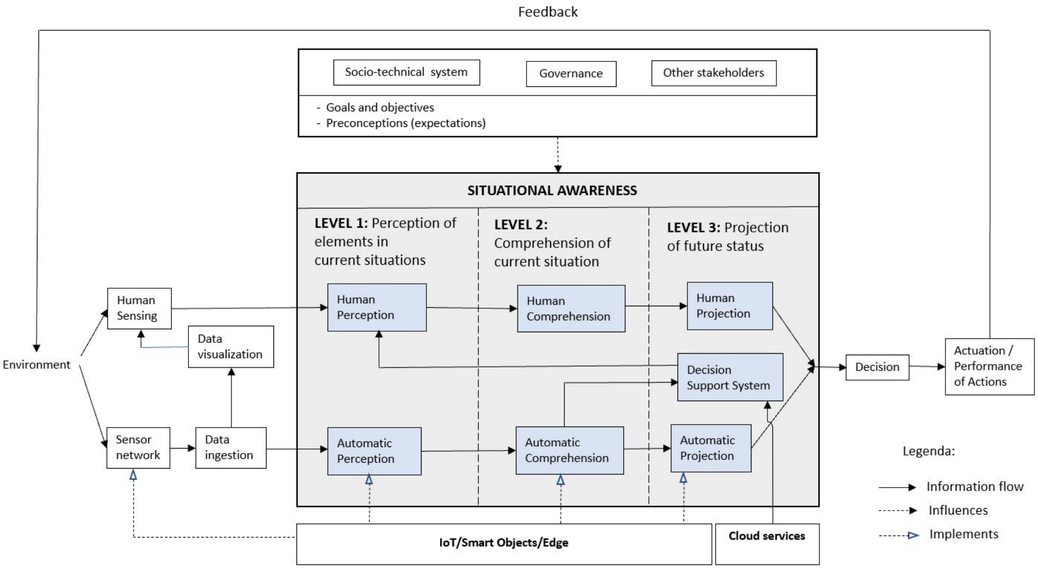


Figure 3. Integrating human and automated situational awareness decision process.

5.1. Combining Human and Automated Situational Awareness

To realize step (1) of the HiLCPS design method given in the previous section, we will refer to a model proposed for the representation of decision-making processes taken by both humans and automated systems [11]. The model, shown in Figure 3, is inspired by the Endsley model [19] and concerns the separation of human and automatic behaviors involved in a decision problem and how these behaviors cooperate to achieve a goal or perform a job. It has been proposed as a reference for the design of systems aimed at protecting historic buildings. Still, it can be applied in all scenarios where many stakeholders, like people who have governance roles and people who work in the socio-technical system to make decisions about the preservation and protection of historical and cultural heritage. Figure 3 illustrates how in a decision-making system that integrates human and automatic components there are three decision-making processes to consider that can be carried out by:

(a) Human beings.
(b) Automated systems.
(c) Combination of automatic and human behavior.

The "perception-comprehension-projection" cycle of SA is the same either in the case of human or automated decision-making processes but the role of technology in building automatic systems for monitoring and control purposes must be specified.

Regarding point (a), the decision-making process performed by a human being is triggered by the availability of data, possibly collected by sensors, and made usable by a subsystem that deals with data ingestion and data visualization. After human sensing, the process goes through the stages of "human perception, human comprehension, human projection" before arriving at a decision and subsequent actuation. The decision maker who carries out this type of process can be influenced by external agents, e.g., the governance of the organization where it operates, its socio-technical system, or other stakeholders who express expectations and wish to achieve goals through the execution of SA-guided decision-making. Point (b), on the other hand, concerns fully automatic decision-making processes. When the problem is sufficiently defined, and solvable by automatic components without human intervention, then the decision process involves the "automatic perception, automatic comprehension, automatic projection" path followed by a decision and eventual implementation that are also automatic. Automatic perception has the following functions: it enables transformations and merging operations to take place, and it structures data in a way that facilitates automatic comprehension. One or more algorithms perform the analysis of the incoming data from the previous phase, returning processed data and improving the understanding of the data collected by the sensors.

Fully automatic decision-making processes can be used for simple or recurring problems, typically to be solved in real-time, and are handled independently by that part of the CPS that does not require human involvement. Point (c) concerns problems in which human decision-making can be enhanced by an automatic support system. In this case, the automatic process begins with the data ingestion stage and continues through the "automatic perception, automatic comprehension" pathway, feeding into a decision support system (DSS). The latter can receive data either from the automated SA process or from other data sources made available by the cloud services connected to the software architecture. The knowledge base managed by the DSS sets the scenario for the initiation of a new "perception, comprehension, projection" cycle carried out by the human being.

The model shown in Figure 3 serves two purposes. As argued above, it firstly represents the three processes of monitoring and decision-making that human beings, automated systems, and a combination of automatic and human behavior can carry out. On the other hand, the model should also be interpreted as a high-level representation of a HiLCP. Indeed, the "IoT, Smart Objects/Edge" component at the bottom of the figure indicates some of the technological elements required to implement the sensor network and the automatic perception, comprehension, and projection phases. The other component "Cloud services" represents the web services that can be invoked to retrieve historical information previously stored in a cloud server and typically used by human decision-makers. From the perspective of the realisation of a HiLCPS, the DSS component is particularly relevant. It represents the point where a decision has to be made as to whether a monitoring process that has so far followed the 'automatic perception, automatic comprehension' phases should trigger a human-managed decision-making process or continue in automatic mode by triggering the remaining projection phase. The DSS is the contact point between the two types of decision-making processes, the human and the automatic. When the CPS serving a fully automatic process is enriched with human behaviour, the combined system becomes a HiLCPS.

SOs are selected to implement the required sensor network for monitoring environmental conditions. They possess greater storage and computing capabilities than smart transducers. Unlike IoT devices, which focus mainly on connectivity, an SO incorporates a higher level of intelligence and autonomy. Thanks to their advanced computational resources, smart objects can perform sophisticated algorithms such as self-awareness and machine learning, enabling autonomous and dynamic management. This greatly enhances their use in Cyber-Physical Systems (CPS), which require responsiveness, adaptability, and intelligence. SOs are the essential components that provide the input for the data ingestion phase. Furthermore, they contribute to implementing the perception-comprehension-projection modules.

5.2. Design Smart Objects Using the SA Model as a Guideline

The role that CPSs can play in enhancing monitoring, control, and decision-making processes is based on both a clear definition of its functional architecture and the features that emerging IoT technologies make available. First, the smart objects, their memorization, processing, and interconnection capabilities, coupled with the use of distributed collective intelligence, are the building blocks for the realization of CPSs that support SA decision processes. Second, the edge-cloud approach to the realization of smart sensor networks can be used to improve network performances. Additionally, a data ingestion process is required to capture, cleanse, and organize data from multiple sources before importing them into a cloud storage device.

In the model of Figure 3 smart objects have been used to implement a SA decision process that considers both human and automated decisions. They are used as key components for the realization of a wireless sensor network and the implementation of automated perception, comprehension, and projection functionalities. In turn, an SO can be seen as a device involved in a "perception -comprehension -projection -decision -actuation" cycle to reach one or more goals; therefore, we can use the SA model as a guideline for the design of SOs. This point of view is illustrated in Figure 4 which shows our proposal for a functional architecture of SOs that has been inspired by the Hendlsey model [14]. First, the SO perception is divided into two parts:

- **Exteroception.** The capability of an SO to recognize, acquire, and represent states of elements present in the external environment. It is possible through transducers that convert physical variables, such as temperature, pressure, acceleration, etc. into electrical signals.
- **Interoception.** The capability of an SO to acquire its internal state is made of location, battery level, connectivity status, network activity, etc., forwarding it to the comprehension phase of the decisional process. It is possible because digital data and analog signals can be read by the SO electronic circuits.

The comprehension phase comprises two main parts, those that concern SO awareness and those that implement application logic. In its turn, SO awareness is divided into two parts:

1. Context-awareness. It regards the SO's capability to recognize, acquire, interpret, and respond to stimuli from the environment where it is immersed. It involves sensing and comprehending the physical and behavioral aspects of elements present in the environment.
2. Self-* features. The SO's capabilities are to recognize itself as an individual entity and to act autonomously so that the SO behaves as expected, to improve its performances, and to adapt its behavior to environmental changes.

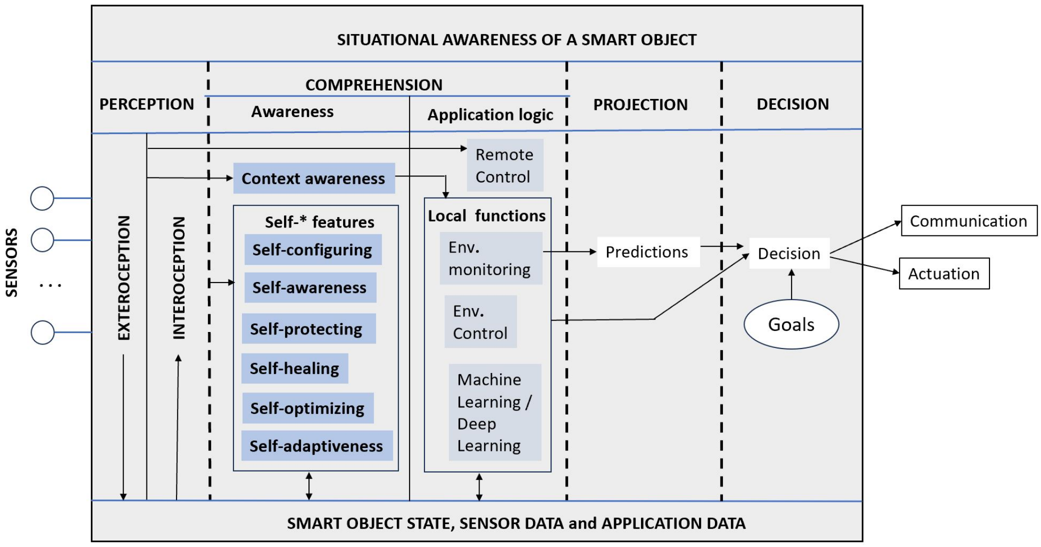


Figure 4. Design of smart object architecture guided by situational awareness.

As for the application logic functions performed by the SO, these can be of two types. The first concerns remote control by which a human being or an automated mechanism can remotely issue commands to the SO; the second type refers to application functions performed locally that are typically geared toward monitoring and controlling the environment in which the SO operates. Understanding the external environment can also be enhanced using ML or deep learning algorithms. ML is used in SO to enable them to learn from their environment and improve their performance. It focuses on using statistical techniques to give systems the ability to "learn" from data and identify patterns without being explicitly programmed. Deep learning uses a set of neural network algorithms to learn from large amounts of data. The networks use multiple layers of neurons to learn complex functions and identify patterns in data. Both ML and deep learning can be used to learn from data and make predictions. Note that in the model of Figure 4, apart from a list of goals that go into input to the decision phase, two possible information flows can drive the decision. The first goes directly from one of the local functions, for example, environmental control, to the decision phase. This is convenient because simple decisions can be taken immediately because of a simple analysis of observed data e.g., when an observed value exceeds a given threshold. The second path can be taken when the comprehension of phenomena based on ML or deep learning algorithms leads to a predictive scenario that can guide the decision. Finally, the decision involves one or two actions, the communication of a message or the actuation of a command. The communication mechanism is necessary to satisfy several information needs such as sending a notification, a warning, or an alarm; the actuation is necessary instead when a command to drive a mechanism external to the SO must be released.

5.3. Distribute the Intelligence

Our approach to the realization of HiLCPS systems involves applying the proposed SA model not only to the design of SOs and edge nodes but also to understanding where intelligence, both computational and human, should be distributed. Since decision-making can occur at multiple points in the architecture, at various levels, and in different ways, it is first necessary to specify where in a distributed architecture the automatic perception, comprehension, and projection phases leading to a decision are implemented. In Figure 5 we can see three types of distributed architectures: (1) IoT smart-Cloud; (2) IoT-Edge-Cloud; (3) SO-Edge-Cloud, where network endpoints can be sensors/actuators (single circle in the figure) or groups of homogeneous sensors (double circle). In each architecture, it is possible to distribute automatic intelligence in the network nodes depending on the characteristics of decision-making and real-time requirements. For example, the "IoT smart-cloud architecture” shown in Figure 5a) can be used in two circumstances; the first is when relatively simple real-time problems can be solved by an IoT smart sensor that utilizes its constrained computational resources to handle the entire decision-making process. This is evident in scenarios like assessing parameters that need to stay within predefined limits. Here, the sensor interprets environmental data, executes the automatic comprehension phase (such as when data exceeds set limits) and the automatic projection phase (sending alert messages or initiating feedback actions). The second scenario considers problems where the automatic perception is borne by the IOT smart node, while the automatic comprehension is done by resources located in the cloud rendering data intelligible by human beings. Then, an entire cycle of “perception, comprehension, projection” can be carried out by the human being. This pattern is applicable when it is necessary to do analytical-type processing that requires sufficient computational and storage capacity and proper visualization algorithms. In the IoT-Edge-Cloud architecture of Figure 5b, the possibilities for the distribution of computational intelligence change. The IoT node can perform only the automatic perception phase, leaving the possibility of distributing the comprehension and projection phases to the edge and cloud nodes. For example, in the third pattern, automatic comprehension and projection phases are done at the edge server. This pattern can be used for real-time and near-real-time decision-making needs. On the other hand, in the fourth pattern, the automatic comprehension is done at the edge server to predispose the data for a cycle of “perception, comprehension, projection” performed by the human being during the interactions with web services exposed by cloud servers. This pattern is oriented toward long-term analytical investigation. Finally, the SO-Edge-Cloud architecture of Figure 5c is suitable when computational and storage capacity needs are greater because artificial intelligence and ML algorithms are required for problem-solving.

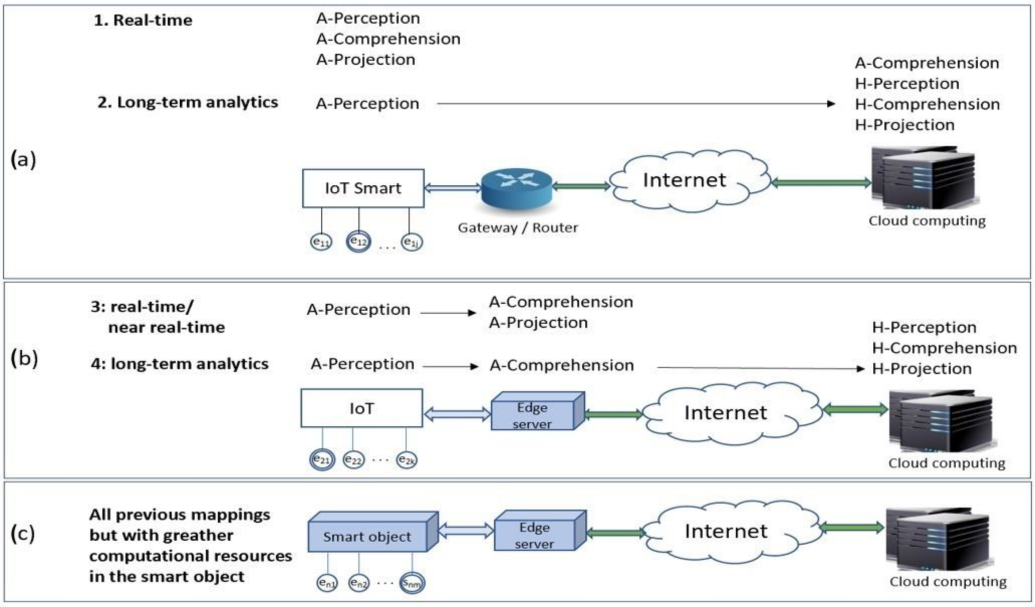


Figure 5. Mapping perception, comprehension, and projection phases on edge-cloud architectures. (**a**) IoT smart-cloud; (**b**) IoT-edge-cloud; (**c**) SO-edge-cloud.

In the previous discussion of CPS architectures, the focus is on those decision-making processes that are either taken automatically or are used to prepare a decision, downstream of the computational flow, when data reaches the cloud. However, as already pointed out in the recent literature recalled in Section 2, the combination of work done by human operators with that done by intelligent machines can lead to increased performance of the integrated HiLCPS. The interaction, aimed at increasing performance, is thought of as human-machine collaboration and denotes the different allocation of physical and cognitive work between human and technological resources. In a HiLCPS there are different types of agents, i.e., entities active in the integrated ecosystem, which can perform actions both in the virtual and in the physical part of the CPS:

1. Automated agents. These are the hardware/software SOs immersed in the ecosystem and capable of performing actions in a self-deterministic and seamless manner. Examples of SOs are microclimatic or clinometric stations.
2. Human agents. Humans operate as active elements of the CPS using devices that enable the digitization of data related to the integrated ecosystem. They are in charge of acting during data ingestion and sending to storage servers; they can also perform monitoring and control of parts of a physical system, such as supervising a machine tool during the execution of a production process. Downstream of the data ingestion process, the data are analyzed by human experts to evaluate/validate the inputs and make any decisions. An example is the collection of data for multispectral photographic monitoring of a historical building using a digitizing device. After the collection process, the data are then used by restoration experts.
3. Mixed agents. They involve the close interaction between a human agent and an SO device. The human acts as the control system by sending command messages using a control device to an actuator that is managed by an SO agent. An example is remote drone piloting.

5.4. Design the Data Ingestion Processes

Data ingestion is the initial phase of the data processing pipeline, involving the collection and importing of raw data from various sources into a centralized storage or processing system. This process is crucial for preparing data for analysis and decision-making. Its design must consider the features of the data ingestion process and the role that ML algorithms can play in improving its quality.

Data input can occur in at least two different points in the model proposed in Figure 1 (and in the corresponding architecture that implements it), namely:

1. From the sensor network to the "automatic perception" component.
2. From data already recorded in other sources to feed the DSS.

The need for long-term recording of large amounts of data requires their harmonization and management, and this may preliminarily require transfer to centralized repositories maintained in cloud servers. The following features must be considered for the design of robust data management in an edge-cloud architecture:

- The variety of sensors that can potentially be used.
- Different transfer rates from sensors.
- Format of the captured and transmitted data.
- Type of problem (real-time, near real-time, long-term analytics) for which the data is needed.
- Modes of data transmission (streaming, batch).
- Different data sources that feed the DSS.

The variety and complexity of all these features require, from a data acquisition perspective, data ingestion processes to acquire data from various sources and upload them to a central data repository. Designers must make certain decisions regarding data ingestion processes that relate to the deployment of data ingestion software and the make-or-buy choice. These decisions may depend on the nature of the problem to be solved (real-time, near real-time, long-term analytics) and the technology of the components that capture the data. For example, in a real-time problem that can be solved locally using IoT smart, purpose-designed data ingestion software might be advantageous for performance reasons. A more structured process of data ingestion is shown in Figure 6 (where solid and dashed arrows represent data streams and function implementations, respectively), where data is collected at multiple points in the edge-cloud architecture and then piped to cloud servers to make it available to human decision makers. In such a scenario, it may be useful to consider data ingestion tools usually made available by cloud service providers.

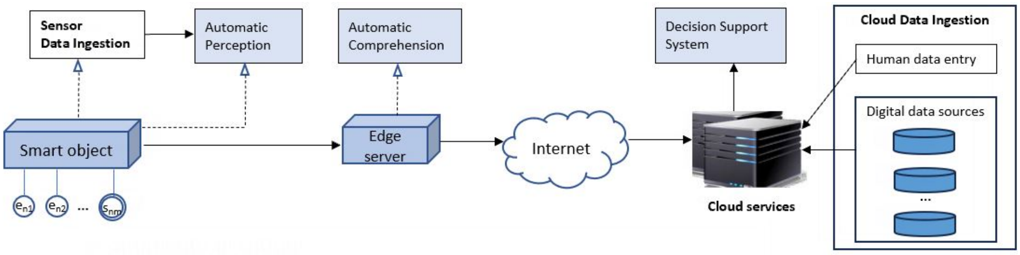


Figure 6. A data ingestion process in an edge-cloud architecture.

5.5. Integrate the Monitoring Processes

This section highlights the holistic approach taken to integrate various components of the monitoring system to ensure the sustainable management and preservation of historic villages. The design of integrated monitoring processes in Sant'Agata dei Goti addressed aspects concerning data, graphical user interface (GUI), computation, monitoring, and decision-making processes. The method used for the integration of these aspects is interactive granular computing (IGrC) [61], an extension of granular computing (GrC) [62,63] that introduces complex granules making it possible to model interactive computations. GrC is a computational paradigm that aims to solve complex problems by breaking them into smaller, manageable parts, called granules. As human understanding and human problem solving involve perception, abstraction, representation, and understanding, GrC has been indicated as a particularly suitable choice for implementing different aspects and phases of SA [64]. IGrC is an extension of Granular Computing that introduces the concept of dynamic interaction between the granules and the system, including the human or computational component in the decision-making process. The interaction allows the granules to dynamically adapt based on feedback obtained during the execution of the decision process. The hierarchical structure of GrC and the dynamic interaction characteristics of IgrC (granules can be changed according to new information or user input) were used to design the integration of monitoring processes in the following aspects:

Data integration starts with the acquisition of different data sets collected from various monitoring tools (e.g., environmental sensors, structural sensors, geospatial data, ect), that are integrated to provide a comprehensive view of the village. A key component of this integration is the data lake, a centralized repository that allows storing both structured and unstructured data at any scale. The data lake serves as a scalable storage solution that facilitates efficient data retrieval and analytics, enabling the analysis of a wide range of monitoring parameters. It is part of the "Cloud services" module in the model of Figure 3. GrC can handle heterogeneous and uncertain data from different sources (sensors, images, historians) by creating granules representing various levels of detail.

The integration of a Graphical User Interface is crucial for user interaction with the system. The methods dealing with this aspect are well-established; however, the design of user interfaces interacting with CPSs can benefit from the interactivity of the IGrC that allows the graphical interface to be adapted according to user feedback, simplifying visualisation and navigation between granules of information at different levels of granularity. An example of Graphical User Interface is given in Figure 7. The website of the Tisma project also includes numerous videos offering a holistic view of the intervention in Sant'Agata dei Goti.

Integrating computational methods ensures that complex analyses can be performed efficiently, offering insights into the health of the historic villages, predicting potential issues (such as structural degradation or environmental threats), and suggesting preventive actions. GrC enables computations to be performed at different levels of granularity, ensuring that the system processes data efficiently. For example, if the system detects an anomaly or an issue at a high-level granule, it can trigger more detailed computations at finer levels to investigate further.

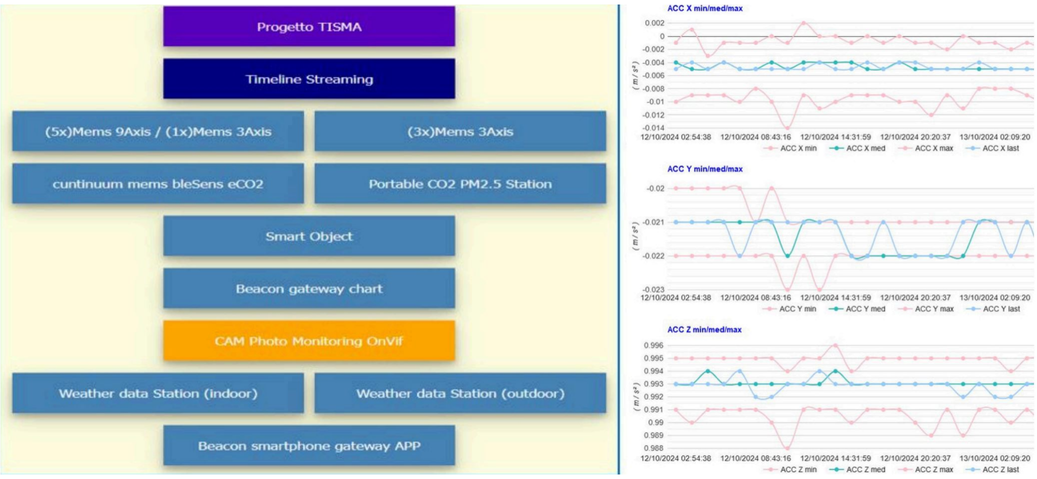


Figure 7. Example of GUI from the project web site www.tisma.eu (accessed on 10 June 2024) which shows the trend of min, med and max values of a 3-axial accelerometer over periods of one hour.

Finally, monitoring and decision processes can be facilitated by IGrC as follows. Monitoring processes can be monitored in real-time, changing surveillance parameters and data granules in response to detected changes, optimizing continuous monitoring. Decision-making processes can be made interactive and adaptive, allowing users to explore different options through granules, and improving the quality of decisions based on uncertain or incomplete data.

6. Implementation and Results

In a historic village, CPS/HiLCPS can significantly enhance monitoring by integrating sensors and IoT devices to protect heritage sites and manage resources. These systems allow for real-time monitoring of structural integrity, environmental conditions (humidity, temperature, etc.), and visitor activities, helping preserve fragile buildings and artifacts. Remote monitoring enables authorities to oversee large, spread-out areas without constant physical presence. Predictive maintenance features can detect early signs of deterioration, allowing preventive action.

Six monitoring sites were set up during the implementation of the project. For each site, the characteristics, the planned actions, the part of HiLCPS involved (human or automatic), and the sensors/technologies used are summarized in Table 2. Many of the monitoring actions concern the estimation of hydrogeological hazards, meteo-climatic, seismic, and anthropogenic risks. Given the variety of sites and monitoring needs in Sant'Agata dei Goti, the HiLCPS implemented provided for situations in which decision-making and feedback actions can be taken by humans and automated systems both autonomously and collaboratively with each other.

The parameters to be monitored depend on the sites under consideration. For example, the conservation of works of art in San Francesco church involves a process of monitoring the microclimate of the rooms where the works of art are kept (using temperature, humidity, sulfur dioxide, and nitrogen dioxide sensors), while the assessment of the static nature of a bridge can be done using a biaxial clinometer and a triaxial accelerometer. Figure 7 shows an example of a Graphic User Interface taken from the website of the Tisma project; the first snapshot shows the list of the various types of sensors installed in the field, and the second shows the trend of measurements taken by a triaxial accelerometer placed on an external wall of the church of San Francesco.

In analogy to the interpretation of CPS in the industrial field, where the physical part coincides for example with a production line and the cyber part with the control system that maintains a virtual representation of the production line and implements monitoring, control, simulation and decision-making programs, in historical villages the physical part corresponds to real-world physical objects (sites, infrastructures, works of art, etc.) and the cyber part corresponds to the hw/sw system that maintains a virtual representation of the historical village with monitoring, control, simulation and decision-making functions. The sensors and actuators are the points where the physical and virtual parts come into contact.

Table 2. Six sites for monitoring the historic village of Sant'Agata dei Goti.

	Site Characteristics	**Action**	**Involved CPS Part**	**Sersor/Technics**
Tuffacesous ridge	The medieval village of Sant'Agata dei Goti is nestled on a tuff spur and surrounded by nature	Photo monitoring with Programmed Fixed Multispectral Camera. Routine inspection/risk assessment	IOT + edge + human analyst	Thermal Digital Image Correlation
Martorano bridge	The bridge over the Martorano stream is the main access route to the historic center	Continuous monitoring of structural parameters	IOT SMART + edge	Clinometer sensors
Diffuse museum	Historic center and natural beauty of Sant'Agata dei Goti	continuous monitoring of environmental parameters	SMART OBJECT	Weather pluviometer station + specific sensors
San Francesco church	Religious building whose first construction in the 13th century underwent intense transformations in the 18th centuryi	Routine inspection for maintenance planning	IOT + edge + human analyst	Microclimatic station + specific sensors
Quarry in the tuff Mustilli winery	Ancient tuff cellars	Continuous monitoring of specific Environmental IoT	IOT SMART + edge	environmental station sensors: CO_2, PM2.5, radon
Rainone palace	17th-century historic mansion located in the center of Sant'Agata dei Goti	Indoor monitoring: Routine inspection and maintenance. Climate comfort	SMART OBJECT	Microclimatic station+MEMS oscillometer

In some cases, there is a need to automatically manage environmental situations that require real-time response to avoid risks to humans.

This is the case in the Mustilli winery (see Figure 2d) and the tuffaceous ridge (Figures 8 and 9). For what concerns the winery, the CPS generates a message, visible from the App for tourists, advising against visiting the winery when the radon level exceeds a certain threshold. When the radon level is dangerous to human life, the CPS generates instead an alert signal sent to the winery janitor to enable him to close access. When there are real-time needs, the part of the edge-cloud architecture involved is that shown in Figure 5b) and Figure 5c where the edge server takes charge of the data received from the sensors, performs the understanding phase and eventually triggers the projection phase if the threshold values are exceeded. Automatic monitoring of the tuffaceous ridge requires that data are acquired continuously allowing displacements to be monitored with sub-centimetres accuracies relative to the scenario under investigation in the visible and infrared ranges. As for the photographic sensor, a dual-sensor camera with two aligned sensors each having a separate lens of different focal lengths has been used (Figure 8a,b). The technique used to analyze the collected photos is the standard Digital Image Correlation technique that allows spatially continuous and automatic monitoring of sectors of the scenario characterized by ongoing deformation processes, providing quantitative estimation about rates and trends of displacement. Figure 9. shows a software application for displaying displacement time series related to pixels included in the selected area of the tuffaceous ridge or buildings above it. It is worth noting that the SO to which the cameras were connected is equipped with software to automatically understand the sensed data and makes a decision regarding sending an alert (smart early alarm deriving from the automatic cycle "perception, comprehension, projection, decision, and actuation). The SO is also equipped with capabilities to communicate to edge or cloud servers so that the collected photos can be historicized in server databases for big data analytics purposes or the activation of a cycle for human perception, comprehension, and projection.

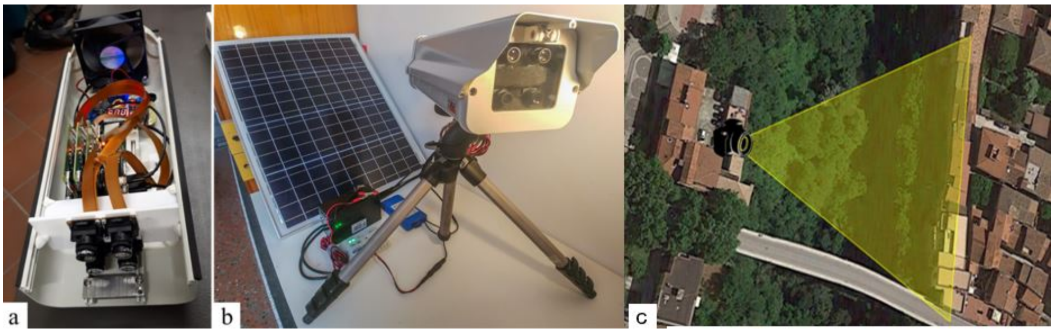
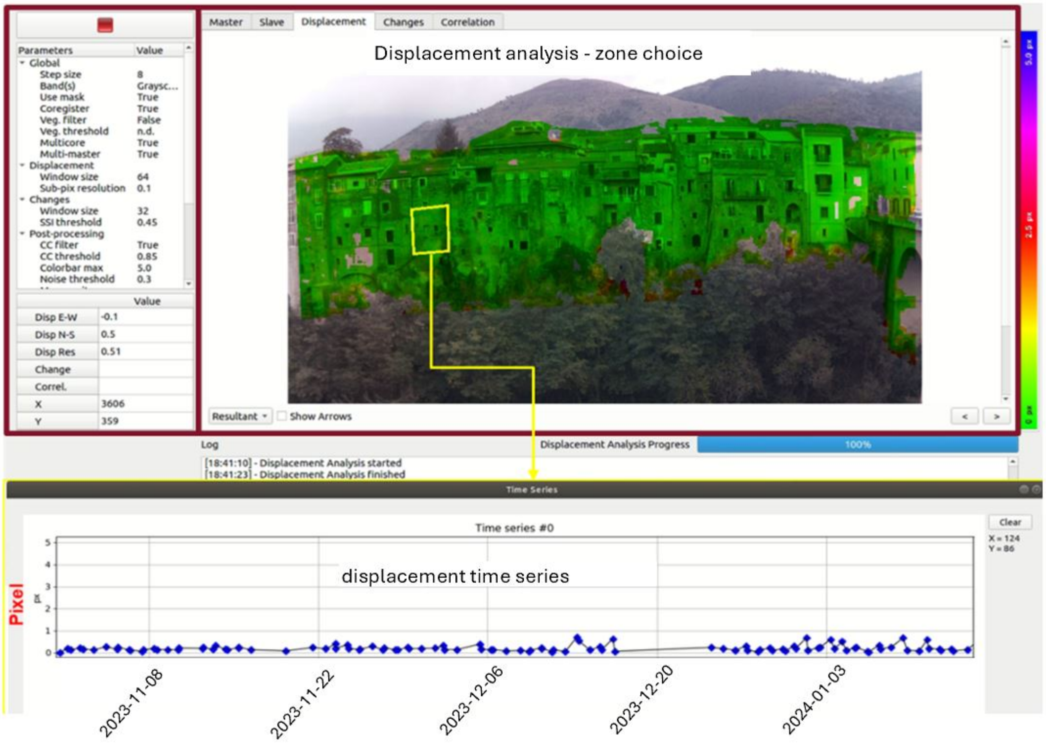


Figure 8. Photo monitoring system. (**a**) smart object with photographic sensors, (**b**) PV panel and batteries for off-grid configuration, (**c**) field deployment.



Parameters	Value
Global	
Step size	8
Band(s)	Graysc...
Use mask	True
Coregister	True
Veg. filter	False
Veg. threshold	n.d.
Multicore	True
Multi-master	True
Displacement	
Window size	64
Sub-pix resolution	0.1
Changes	
Window size	32
SSI threshold	0.45
Post-processing	
CC filter	True
CC threshold	0.85
Colorbar max	5.0
Noise threshold	0.3

	Value
Disp E-W	-0.1
Disp N-S	0.5
Disp Res	0.51
Change	
Correl.	
X	3606
Y	359

Log

```
[18:41:10] - Displacement Analysis started
[18:41:23] - Displacement Analysis finished
```

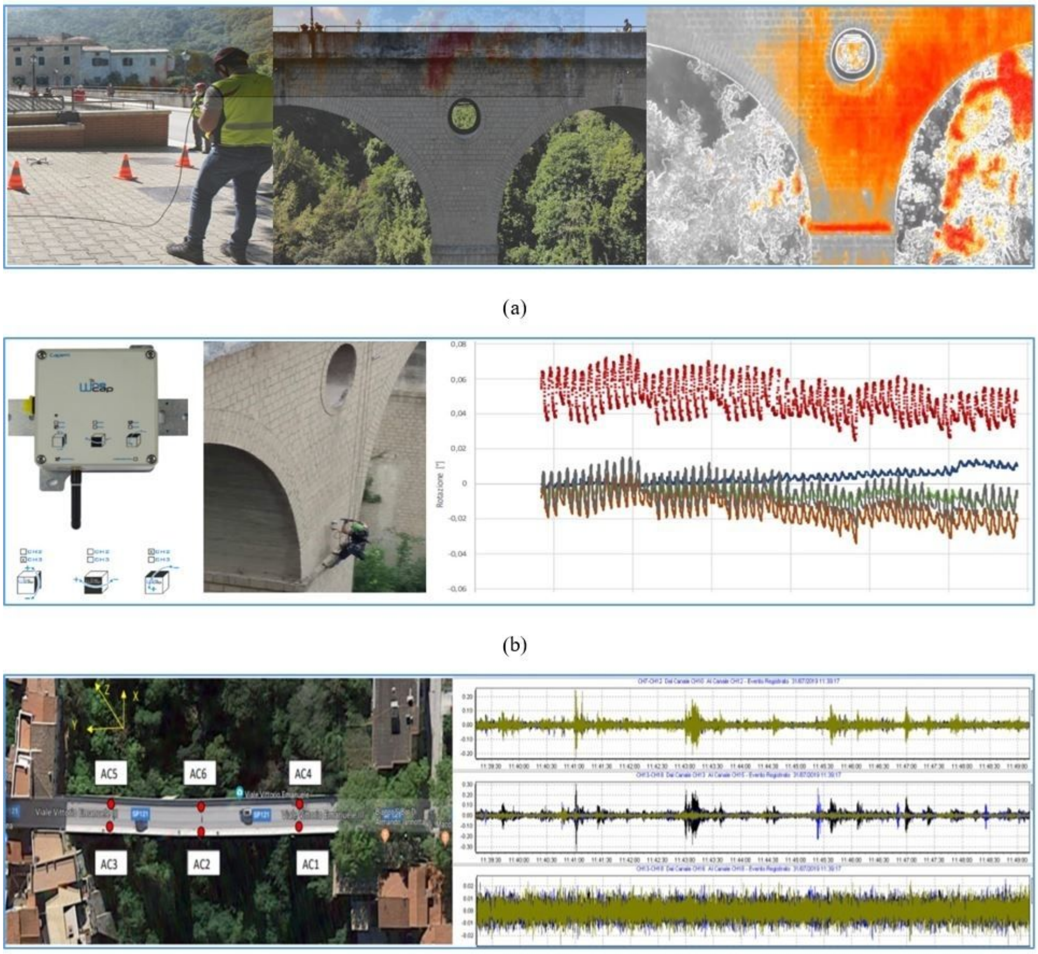
X = 124
Y = 86

Figure 9. Time series of displacement of the tuffaceous ridge and buildings.

A second scenario concerns monitoring and control actions that are carried out primarily by humans. For example, periodic replacement of radon sensors in the Mustilli winery allows a monitoring system to be continuously operational and effective. A different situation is when experts perform periodic inspections on the status of sites of interest. In this case, the process handled autonomously by humans typically involves writing a technical report that is recorded in the servers of the edge-cloud architecture for knowledge management purposes. In this case, the part of the architecture solicited is the cloud data ingestion shown on the right side of Figure 6. In the third scenario, monitoring St. Agata dei Goti requires collaboration between automated subsystems and human beings that make up the HiLCPS to improve the performance of the site monitoring process. Automatic components measure environmental variables captured by sensors. The strengths of automatic systems refer to the continuous assessment of the situation and the ability to respond in real-time in an emergency or dangerous situation. In many cases, the role of humans concerns problem-solving and decision-making in changing scenarios where uncertainty makes it difficult to pursue decisions based on incomplete information. This scenario can be seen in the monitoring of both the Martorano Bridge and the San Francesco Church. Routine inspections and risk assessments are pursued by well-identified HiLCPS components. For example, the action with two steps related to the Martorano Bridge:

1. Routine inspection with a thermal camera on UAV Parrot drone.
2. Planning ordinary and extraordinary maintenance,

is first executed by a pilot controlling the flight of a smart IOT drone on which a thermal imaging camera has been mounted (Figure 10a). The thermogram indicates overheated areas that may require further investigation to assess the condition of the bridge. Two types of wireless sensors were placed on the piers and arches of the bridge: biaxial clinometers (Figure 10b), which are used to measure the tilt in the horizontal plane of a plane to which they are integral, and triaxial accelerometers. The graph shown in Figure 10c is of the AC2 accelerometer positioned in the center of the bridge, where more significant vibrations occur than those measured by the AC1 and AC3 accelerometers positioned closer to the sides of the bridge.



(a)

(b)

(c)

Figure 10. HiLCPS for the Martorano bridge. (**a**) Routine inspection with camera on UAV Parrot drone. (**b**) Sensors installation and biaxial clinometer output, (**c**) triaxial accelerometers output.

The bridge monitoring activity consists of an integrated process in which actions performed by the automatic components of the HiLCPS are interwoven with those performed by humans. An example of automatic behavior concerns data collected by the inclinometers and accelerometers that feed a monitoring and control system. When the value of one or more of the data exceeds a range deemed to be safe, a red light of a traffic signal comes on, signaling that access to the bridge is prohibited. At the same time, a message is sent to the local police who can decide on the most appropriate interventions following the alert. On the other side, the periodic inspection of the bridge involves several human roles: the drone programmer, the pilot, and the civil engineering expert to analyze the collected data directly on the field. Furthermore, data collected from all types of sensors are transmitted from the CPS to cloud servers where an expert can combine data from different sources to derive a better understanding of the health status of the bridge. Data are also stored for future uses such as predictive analysis using ML algorithms. The last application that we describe in this case study concerns the part of HiLCPS implemented for the church of San Francesco. The site presents characteristics that require an intervention substantially different from that of the bridge described previously, even if the implementation of the communication system and smart objects is like the previous one being guided by the models described in Section 5. For the analysis of the condition of the works of art contained in the church and the interior and exterior architectural assets, the role of the human being is decisive in the following aspects:

- Knowledge of the works of art being examined and their constituent materials or added during previous interventions.
- Diagnosis of the degradation that artistic, historical, archaeological, and architectural artifacts undergo due to the effects exerted by climate and microclimate.

Therefore, the human being is an integral part of the HiLCPS dedicated to the periodic monitoring of the church. The study of the physical, chemical, and biological mechanisms that affect the environment-cultural heritage interaction, both indoor and outdoor, is based on measurement sensors that allow the collection of data related to the evolution of environmental agents that can cause damage to the works of art. Monitoring sensors have been used for:

(a) Diagnostic investigations using standard methodologies non-invasive on the frescoes and other works of art kept inside the church.
(b) Outdoor environmental monitoring for the evaluation of the effects of air pollution (from traffic and urban settlement) and changes climate change on cultural heritage.
(c) Monitoring of indoor environmental and thermo-hygrometric parameters for the evaluation of the conditions of conservation and use of the works in museums or other contexts of historical-archaeological interest.

A study concerning the point (a) is discussed in [65]. Figure 11a shows the data collection using an XRF spectrometer for the painting depicting the "Deposition of the Dead Christ" executed on a wood panel.

Figure 11. HiLCPS for the San Francesco church. (**a**) routine inspection of frescoes with XRF spectrometer, (**b**) routine inspection of the wooden ceiling, vaults, and stucco work with UAV Parrot drone.

X-ray fluorescence (XRF), performed on sample areas under UV illumination and IR reflectography, allows for the identification of the pigments used in the original or restoration paint layers and the identification of any marker elements that may provide useful information for knowledge of the works and their historical and conservation history. The thermographic survey carried out by drones (Figure 11b) on some structural elements and artworks revealed some thermal anomalies both at the intrados of the dome and in the elevation, related to limited detachments of the plaster layers and water infiltration. An example of point (c) concerns the continuous monitoring of indoor environmental and thermohygrometric parameters (CO_2, PM2.5, temperature, and humidity) carried out in San Francesco Church. The data collected will enable scholars, from the knowledge of the artworks examined and their constituent materials or added during previous interventions, to assess the effects of pollutants and environmental changes causing damage to the artworks.

The capabilities of the HiLCPS implemented for the case study described in this section are made possible by the presence of human, automatic, and mixed agents in the HiLCPS system. Automated agents typically operate continuously while human and mixed agents enable routine inspections and maintenance activities that are critical to both the proper functioning of civil infrastructure and the mitigation of hazards related to human activities or natural phenomena.

7. Discussion

Since the first years after the term CPS came into existence, the implemented systems have shown their full potential for innovation to introduce new and more advanced solutions in many application domains. As complex systems, they require multidisciplinary expertise for their realization. Therefore, design principles and methodologies for the implementation of CPS have been studied by many researchers. The six design principles proposed by [31] for Industry 4.0 (interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity) are quite general and applicable to the design of CPS in other sectors as well. The three architectures that are shown in Figure 5 match these principles either they are implemented individually or combined in a distributed network. In the review on CPS design [32], it is observed that currently there is no standardized design process for the development of a CPS. However, landmarks for researchers and practitioners dealing with CPS design exist in the literature. In [27] both the modeling of physical dynamics and of discrete dynamics are covered; then, continuous and discrete dynamics are combined in a hybrid model. To answer the research questions posed in the introduction, this study investigated the role of SA in guiding the design and implementation of monitoring systems for historic villages, as well as assessing the contribution of HiLCPS to the improvement of monitoring processes for historic and cultural sites.

> RQ1: Can SA guide and facilitate the design and implementation of systems for monitoring historic villages?

The case study development shown to us that the SA can indeed guide and facilitate the design and implementation of systems for monitoring historic villages in the two main aspects: design of HiLCPSs and design of SOs. Regarding the design of HiLCPS:

1. *Perception of Elements in the Environment:* SA helps in identifying key elements that need to be monitored in historic villages, such as the structural integrity of different kinds of sites, environmental changes, or visitor behaviors. By understanding these elements, CPS and HiLCPS can be designed to capture relevant data through sensors, cameras, SOs, and other IoT devices. As shown by the model in Figure 3, automatic perception and human sensing trigger decision-making processes that can be taken by (a) automatic systems; (b) humans; and (c) a combination of automatic systems and humans. The model also fulfills the role of the high-level architecture of a HiLCPS.
2. *Comprehension of Current Status:* By processing data collected from various sensors, the SA allows humans or automated systems to make sense of the current state of the village.

3. *Projection of Future Status:* SA can support the design of systems that predict future changes in the environment. This could involve forecasting environmental threats or human-induced damage, ensuring timely interventions.
4. *Decision Support:* In realizing a HiLCPS for the case study, the DSS plays a crucial role as the decision point between automatic and human-managed processes. It determines whether the monitoring process, after completing the 'automatic perception and comprehension' phases, should proceed automatically or involve human decision-making. The DSS bridges the two approaches, and when human behavior is integrated into a fully automatic CPS, the system evolves into a HiLCPS. DSS can also integrate various monitoring components to provide decision support, alerting stakeholders to necessary actions in real-time, such as evacuation during natural disasters or conservation efforts when certain risk thresholds are met.

Regarding the design of an SO:

An SO can be viewed as a device engaged in the "perception-comprehension-projection-decision-actuation" cycle to achieve specific goals. Thus, the SA model serves as a useful framework for guiding the design of SOs.

In a few words, the SA approach to HiLCPS design guides the design and reuse of both: SA-based architectures and SOs. It also provides the reuse of models for the distribution of human and automated intelligence in a HiLCPS.

RQ2: What is the contribution of HiLCPS to improving the monitoring processes of historical/cultural sites?

The following advantages of implementing a HiLCPS for monitoring historical villages emerged from the experience gained during the case study:

1. *Real-time monitoring and analysis of heritage sites:* This enables the early detection of problems such as structural weakening, environmental degradation, or risky activities. For example, as shown in the case study, the analysis of time series of tuffaceous ridge displacement or patterns of potential deterioration of work arts deduced from sensor data can help predict potential damage before it becomes critical.
2. *Data-Driven Decision Making:* This allows automated systems to implement relatively simple decisions, such as switching the traffic lights on the Martorano bridge to red when the analysis of vibrational data collected by accelerometers indicates a dangerous situation. On the other hand, stakeholders can make informed decisions on the maintenance, restoration or protection of historic sites based on solid evidence.
3. *Preservation of Cultural Heritage:* By combining automatic monitoring tools with human analytical capabilities, HiLCPS helps preserve cultural heritage.
4. *Collaboration and Communication:* HiLCPS also fosters collaboration between stakeholders, such as conservationists, historians, and engineers. The systems can provide a shared platform for accessing data, allowing discussion of strategies for site preservation.

In short, by leveraging SA and HiLCPS, the monitoring and preservation of historic villages and cultural sites can be more proactive, effective, and adaptable to various challenges.

The implementation of effective decisional processes in CPS is central to our research. With an SA model that combines human and automated situational awareness decision processes, this work discusses how the SA model can be used as a guideline for the design of HiLCPS. The role of decision processes implemented by CPS has been highlighted by [66]. The author illustrates the game theory and rule-based decisions as conceptual tools to implement decision processes. Our approach to implementing decision processes uses the SA theory and is different from those proposed by Nardelli which is instead based on game theory. It brings a twofold benefit resulting from the mutual influence between SA and CPS. Indeed, on the one hand, SA can serve as a guideline for CPS design, and on the other hand, CPS provides automatic support for the implementation of situational awareness decision-making processes. From the point of view of CPS architectures, our interest is in the research efforts in edge-based CPS because of their capabilities to overcome the current limitations of embedded systems and cloud computing [44]. In particular, in the context of edge-cloud architectures, we address the design of the class of HiLCPS where decision-making processes and feedback actions can be taken by humans and automated systems on their behalf or in collaboration. The design of this class of systems was studied by [67] who proposed a high-level architecture of HiLCPS together with a framework for their systematic design and staged verification. Starting from three design principles: (1) Complete CPS functionality (involving humans), (2) Achieve understandability, and (3) Manage user attention, ref. [37] present a conceptual framework to understand how humans and autonomous CPS can cooperate, as well as techniques to use this framework to effectively design human integration in CPS. Being based on the SA theory, the HiLCPS design method we propose naturally meets these principles. However, our proposal differs from the work of [37,67] in the following aspects. First, the focus of our work is on the design of CPS using SA as a design guideline. Second, the architecture taken as a reference for the implementation of CPS is the edge-cloud architecture; third, by SA theory, precise guidance is given on where to deploy the automatic intelligence in the edge-cloud architecture to implement decision-making processes taken by both humans and automatic systems. The models introduced in Section 5.3 indicate where to distribute intelligence in HiLCPS implemented in an edge-cloud architecture and provide an example of how to integrate human, automatic, and mixed agents in this architecture. In terms of the scope of this research, a basic method for monitoring historical places is condition monitoring, i.e., the act of measuring the change in the state, number or presence of features of something. Monitoring the condition of historic sites is fundamental to their protection, and condition monitoring helps ensure that management practices adapt to any changes. Walton [68] argues that for each type of historical site, e.g., archaeological sites, building structures, etc., a different mix of condition monitoring methods may be required and provides a series of forms to detect the different characteristics of the sites under monitoring. Similarly, our solution is based on the monitoring of site conditions as a basic method necessary for decision-making, which, in our case, is enhanced with the help of a HiLCPS that brings both the strengths of automated systems and those of humans. Many research proposals focus on the conservation of historic buildings. One approach widely used in the literature is Historic Building Information Modeling [69–71] a digital approach used for managing, documenting, and conserving heritage and historic buildings. This includes using advanced scanning technologies (like laser scanning or photogrammetry) to create precise 3D models of historic structures. Important as it is, Historic Building Information Modelling must be considered only one of the approaches that are necessary for the conservation of historic villages. In a holistic view, in addition to the protection of buildings, it is necessary to enable the protection of natural heritage, monuments, and works of art. It is also necessary to allow for the monitoring of the environment and human activities that may pose safety risks to the inhabitants.

The application of SA to heritage protection is recent. [25] assesses the health of a historic building through real-time monitoring of key parameters. In contrast, Section 5.1 takes a deeper look into the decision-making process that characterizes SA models for heritage buildings. In addition, our choice of the edge-cloud paradigm as the basic architectural solution for the implementation of HiLCPS, allows us to extend the range of applications not only to the protection of a single historic building but to the protection of complex ecosystems such as the historic village of Sant'Agata dei Goti. To the best of our knowledge, the SA approach to CPS design in the edge-cloud architecture described in this paper is original and contributes to the design and implementation of decisional processes in HiLCPS. As illustrated in Figure 3, and from the discussion of Section 4, HiLCPS and SA mutually influence each other in the following aspects:

(a) SA influences the designing of HiLCPS systems.
(b) HiLCPS is used to implement SA-based decision-making systems.

This article focuses on the first point. SA decision-making applications implemented using HiLCPS can be set up using a strategy such as Goal-Directed Task Analysis [21]. This problem was addressed in our previous work [11] that categorizes human-oriented requirements and automatic system requirements, further decomposing the functional specifications of a decision-making system into human and automatic perception, understanding, and projection. A limitation of this work concerns aspects related to human sensations. The role of human beings considered in this research is that of active entities of a HiLCPS capable of performing monitoring and control operations as well as making decisions. Those aspects involving psychological states, emotions, and predictions of the actions of humans have not been addressed. The modeling of human behavior in HiLCPSs is discussed in [33,36].

8. Conclusions

In this paper, we propose a design technique for HiLCPS using the SA model described in Figure 3. The model, which represents both human and automated decision-making processes, is the starting point for the design of HiLCPS. Our approach takes the SA levels of perception, comprehension, and projection as a reference for the design and implementation of SO, edge devices, and cloud components in an edge-cloud architecture. The advantage of this approach is twofold. On the one hand, the SA model can be used as a guideline for the design of HiLCPS. On the other hand, reverting the point of view, the new technology of HiLCPS can contribute to the improvement of SA decision processes. This unifying approach, based on SA, leads to conceptual simplification that can reduce the complexity of design activities. The schema "perception-comprehension-projection" is used several times during the design activities focusing attention, from time to time on SO, edge devices, humans, or the entire edge-cloud architecture. The application of this scheme has the merit of allowing the reduction of the complexity of HiLCPS design. Designing the architecture of a HiLCPS system requires that certain decisions be made to adapt the system to the application domain in which it will operate. Section 4 shows three architectural scenarios where it is necessary to specify the distribution of the intelligence in the network and to identify the algorithms to be implemented. The paper presents a case study describing the TISMA project in which a HiLCPS was implemented for integrated monitoring of historic villages for innovative management, conservation, and protection of this important historical, artistic, and cultural heritage. Automation-assisted technologies, such as drones and multispectral and pan and tilt cameras equipped with multiple imaging and sensing systems, are used for three applications (Martorano bridge, Eco Museum, and tuffaceous wall supporting medieval inhabited buildings). With the implementation of the TISMA project, Infrastructure Visual Inspection opens a new frontier of HiLCPS, in that it is possible to see the Human-Sensors-Actuator interaction in the entire monitoring and control process. Indeed, the routine inspection and maintenance made by combining in various ways human, automatic, and mixed agents, are critical and visual inspection technologies play a crucial role in the inspection and maintenance of civil infrastructures. The acquisition of scientific knowledge provided by the methodology makes it possible to replicate the SA approach to HiLCPS design in various other scenarios. Applications of this approach are underway in scenarios involving landslide monitoring, and for monitoring hazards in port areas. This research can be developed in several directions. First, it is necessary to investigate the nature and structure of the interactions that occur among the various components of the HiLCPS. Recent studies have led to the proposal of a reference architecture of human cyber-physical systems and the fundamental design principles that underlie human-CPS interaction [72,73]. We believe that formal specification of relationships and interactions between system components that are different (humans, hardware, software, other real-world elements) will provide a better understanding of the communication, computation, and control aspects that underlie the design of a HiLCPS. In this regard, a study is underway that, using the interaction type model [74] is aimed at defining formal specifications of relationships and interactions among the components of a HiLCPS. The second research line focuses on usability [75–77] to facilitate communication between humans and machines. Research results obtained in these areas need to be reinterpreted to seek better interaction between humans and automated systems to optimize the overall performance of HiLCPS. Finally, the systematic overview on edge computing for CPSs presented in [45] focuses on the intersection of various edge computing paradigms and CPS and applications and emphasizes the need for further research on trustworthiness and dependability. This need is even more evident in the case of HiLCPS systems where the human component can lead to situations of uncertainty and non-determinism in the behavior of these classes of systems.

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Appendix A

In Table A1 an excerpt from the questionnaire submitted to the managers of Sant'Agata dei Goti.

Table A1. An excerpt from the questionnaire submitted to the managers of Sant'Agata dei Goti.

Question	Answer	Variables to Monitor	CPS and Human Role
1. Which sites, buildings or structures in the village are considered to be of particular historical or architectural value?	Tuffaceous ridge and historic village, bridge Martorano, churches of San Francesco and Annunziata, Mustilli vinification rooms, Eco Museum, Rainone palace, ducal castle, museum in Alphonsian places, wash house Reullo	Environmental sensors for outdoor monitoring (temperature, humidity, wind speed, micro-movements of structures, cracks	CPS: monitor degradation over time using sensors or drones Human role: Evaluate the effects of climate change and other risk factors on the site and take preventive actions
2. Are there any valuable works of art or artifacts to preserve for future generations?	Frescoes and paintings in the churches of San Francesco, dell'Annunziata and Alfonsinian places	Environmental sensors for indoor microclimate monitoring (temperature, humidity sulfur dioxide, nitrogen dioxide sensors, etc.)	CPS: monitor degradation over time using sensors or drones Human role: Assessing the effects of atmospheric agents and human activities
3. Have any sites or facilities been identified that need immediate monitoring action?	Martorano bridge, tuffaceous ridge, artwork in the church of San Francesco	Sensors for analyzing the displacements of the tuffaceous ridge and buildings incident upon it. Sensors for assessing the degradation of paintings and frescoes	CPS: monitor degradation over time using sensors or drones Human role: Material degradation assessments and maintenance/ restoration decision
4. Have significant changes been made to the architecture of the village in recent decades? What maintenance work has been carried out?	The main changes made in recent years concern the road system and maintenance work on historic buildings	Environmental sensors for outdoor monitoring (temperature, humidity, wind speed, micro-movements of structures, cracks)	CPS: none Human role: Regular monitoring of the state of the buildings to detect the effectiveness of maintenance work and identify areas that need further attention

Table A1. *Cont.*

Question	Answer	Variables to Monitor	CPS and Human Role
5. What natural elements contribute to the landscape value of the village?	Tuffaceous ridge, Martorano river, hills, valuable woodland areas	Air and water quality sensors, pollution and erosion detectors, cameras in the visible and infrared range for fire detection)	CPS: Continuous monitoring of landscape and natural resources Human role: Interpretation of data and application of environmental regulations Decisions on conservation measures (e.g., creation of protected areas)
6. Are there environmental risks that could threaten the integrity of the village?	Rock erosion, floods, fires, earth movements, climate change	Sensors needed to detect potential risks in different types of environmental threats	CPS: Detection of critical changes Human role: Risk assessment and decision-making in the event of an alert. Initiation of corrective actions required (e.g., civil engineering or evacuation measures)
7. What is the impact of tourism on the village?	Excessive loading on buildings and sensitive or hazardous areas must be detected	People counting sensors, environmental sensors, Radon detection in Mustilli cellars	CPS: monitor tourist influx and the impact on buildings and the environment Human role: Balancing economic development with heritage protection. Decision on regulations

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