Journal Title
XX(X):1–15
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DOI: 10.1177/ToBeAssigned
www.sagepub.com/
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Modeling smart apiculture ecosystem: An ontology-based approach

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Abstract

This article presents a model of a smart apiculture ecosystem that uses ontology at its core. The apiculture domain is chosen for its essential role in the global food market and both direct and indirect impact on the majority of agricultural domains. The main contribution of the research is to provide an approach for data-driven modeling of smart ecosystems. To achieve this, a domain-specific ontology is created, as an extension to SSN ontology. Based on the created ontology, a smart ecosystem is analyzed and a model for smart apiary IT platform is developed. The used process and the created model push towards standardization of data in agricultural domain. It provides a framework for future development of smart agriculture ecosystems, knowledge management solutions, better decision-making in business processes and can serve as a basis for future development of AI-based prediction and recommendation systems.

Keywords

Apiculture, Beekeeping, Smart Ecosystem, Ontology, SSN

Introduction

Agriculture is considered as one of the core industries. It faces the constant challenge of providing enough food for the entire global population. On the other hand, there is a need for balancing natural resources with sustainable practices. This requires continuing endeavors toward efficiency and efficacy of agricultural processes[1]. The paradigm of precision agriculture aims to optimize crop production and to improve the quality of the final products[2]. As one of the agricultural domains that has great influence on all others, apiculture is chosen as a focus of the research. This is supported by the fact that bees are a major factor in pollination of crops and ultimately their growth and yield[3]. Additionally, the problem of bee mortality has been well recognized, with their population decreasing in size[4].

In literature and on the market, there are multiple precision agriculture solutions that enable remote tracking beehives and important factors that influence the health of bees[5,6]. Integration of multiple systems in precision agriculture brings challenges such as lack of interoperability and data standardization. The interoperability problem reduces efficiency of developed solutions and chances of their wide adoption[7]. Many authors agree that modern agricultural ecosystems have a need for integration of large-scale data from heterogenous sources in order to make this data available for integration and analytical processes[8,9]. One of the approaches for solving this problem is the development of ontologies. In literature, Semantic Sensor Network (SSN) ontology is used as a basis for IoT integration in precision agriculture, explaining the processes of data collection. Considering the complexity of agricultural industry and its numerous subdomains, SSN can be used to develop general agricultural model but more detailed extension for this ontology is needed to provide domain specific details[10]. Specifically, what current scientific contributions are lacking is domain specific ontology extension and a model for agriculture to solve interoperability, integration and standardization gaps.

The aim of this paper is to propose a model for a smart apiculture ecosystem by utilizing an ontology-based approach. The primary objective is to enhance interoperability, data integrity, and data-driven decision making in apiculture. Structuring diverse data from heterogeneous sources is a key aspect and can be achieved with an ontology-based approach[11]. Using the proposed approach enables efficient hive monitoring, optimization of resources, and supports sustainable beekeeping practices. The proposed model serves as a foundation for standardization in smart apiculture systems, facilitating better communication between different stakeholders, technological solutions, and data-driven analytics.

The remainder of this paper is structured as follows: Section 2 provides an overview of the key theoretical concepts relevant to the research problem, including ecosystems, smart ecosystems, the Internet of Things, ontologies, and an analysis of existing smart apiculture solutions. Section 3 introduces a domain-specific extension (module) of SSN, named BEESNN, along with an analysis of key stakeholders and a model of the smart apiculture ecosystem, including a model of its IT platform. Section 4 presents the design of a prototype application for smart apiculture, detailing its requirements and capabilities.

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Finally, Section 5 offers a discussion of the findings and the conclusion.

Related work

The introduction of smart devices has proven its value in improving efficiency in ecosystems by introducing remote real-time monitoring and data sharing between stakeholders. Smart ecosystems are created by stakeholders with the goal of developing a functional system. They are built and refined through their collective engagement and their mutual interactions with the goal of collecting information and using it in their processes and in decision-making [12,13]. Development of a such ecosystem is instigated by the need to share information between stakeholders. Creating mechanisms for fast communication and knowledge sharing represents the core of smart ecosystems. It is enabled through integration of information technologies in existing processes providing additional information for decision making [12,13]. Smart ecosystems provide value through integration of IoT devices that collect and utilize sensory data. Data from physical environment is collected, analyzed and presented to stakeholders. This enables continuous monitoring of environments even in remote locations and improves efficiency of processes. Data is constantly shared between stakeholders, keeping security as a main priority [13–15].

Internet of Things represents a network of interconnected devices that allows data to be collected and exchanged between the nodes of the network. IoT connects traditional devices into smart systems and integrates several complementary technologies to gather data and increase efficiency in various processes [16,17]. IoT based smart environments utilize a range of technologies, including sensors, communication systems, data fusion, and cybersecurity. Sensor technologies are commonly used to collect data from multiple locations, partly preprocess the collected data and store it at a central database. Data fusion technologies are used to integrate data coming from multiple sensors to increase accuracy and trust in the collected data. Cybersecurity technologies are also incorporated into every part of the system to ensure trust in collected data [15]. Considering the heterogeneity of data sources and used technologies, one of the solutions is development and implementation of ontologies.

Implementation of ontologies in smart ecosystems enables formalization of large amount collected data. Ontology refers to a structured framework for representing knowledge in a domain. Ontologies are created to limit complexity and to organize information [18,19]. Main reason for using ontologies is the categorization of entities and their relationships. Entities are concepts in a domain, relationships explain how entities relate to each other and communicate, and attributes are properties of an entity. Ontologies are widely used for data collection, data representation, and reasoning. For example, in machine learning and AI, ontologies provide structured datasets for training and reasoning systems with emphasis on providing specific explanations to users [20]. They also serve as a foundation for establishing data standardization, ensuring consistency and interoperability across different systems [21].

Smart ecosystems in agriculture

In the domain of the agricultural industry, the application of smart devices can significantly increase the efficiency of the processes and the system in general. In smart agriculture, sensors, micro controllers and other edge devices are essential to collect data from the physical world. Gathered data is then analyzed providing data-based suggestions to users or even initiating automated processes. Smart agriculture solutions include numerous applications including soil monitoring, smart irrigation, weather forecasting, livestock farming and supply chain tracking solutions. These examples are described in the following part of the paper.

Smart devices are integrated in agriculture in multiple domains such as a smart irrigation system. As one of the key processes in agriculture, it has a substantial benefit on plant growth. Collecting soil moisture data and providing precise amounts of water directly influences the efficiency of the entire system. Sensory data can be analyzed in real-time data providing suggestions for corrective actions [22]. Soil monitoring directly influences yield and resource allocation, thus is considered a crucial aspect of agriculture [23].

Authors also provide solutions for weather forecasting and field monitoring using sensors. Firstly, the data is preprocessed and then used to predict weather conditions. Secondly, collected images are processed and analyzed to provide additional information about weather conditions and possible diseases, triggering automated corrective action by system [24].

Other authors focus on precision agriculture in the domain of livestock farming. A large amount of data is collected through heterogeneous sources including sensor data, climate data, satellite imagery, statistical and government data. This provides a base for precise predictions in farming operations and supports business decisions but brings out a problem of data integration and interoperability [9].

In agriculture, every supply chain segment has an impact on the quality of the end product. For this reason, smart agriculture solutions are also implemented to track food through the supply chain. This provides additional information to all stakeholders, improving trust between them and providing fact-checked information to final consumers [25].

Very few researchers have proposed or developed a comprehensive ecosystem for smart beehive management. One scientific paper [26] presented an ecosystem for open data sharing aiming to enhance data accessibility and interoperability in IoT for beehive monitoring. It examines the primary stakeholders involved in data storage, processing, and distribution, and subsequently proposes the development of an open, collaborative framework for apiculture data sets. Although well-designed, this ecosystem only illustrates a small portion of the complex surrounding that smart beehive management system is located in.

Analysis of hive management platforms and solutions

Beehive monitoring systems can generally be divided into three categories based on their functionality and purpose. Most commercially available products focus on basic data collection and monitoring, while fewer systems provide advanced analysis or predictive capabilities[27]. Comparative analysis of currently available hive management platforms and solutions is presented in Table 1.

Analyzing Table 1 we could conclude that the majority of current solutions gather data such as humidity, weight and temperature inside or outside of beehive, thus indicating that this data is crucial for monitoring the basic condition of bee colonies. Some solutions such as AmoHive and Broominder gather in-hive acoustics and analyze bees' behaviors, on the other hand some use images or radars to count bees that enter or leave the hive.

Noticeable differences are shown in the functionality provided. Most of the solutions focus on data collection and visualization through web platforms or mobile applications. Small fraction of solutions provides some advanced functionalities such as BeeMate and AmoHive that utilize artificial intelligence for pest detection, warnings and bee classification, thereby improving colony management capabilities and enabling faster data-driven decision making. With that in mind, solutions equipped with advanced data processing capabilities stand out significantly from simpler systems that are limited to monitoring basic parameters.

The connectivity of these systems also varies, with different technologies being used for data transmission, including WiFi, mobile networks, Bluetooth, and satellite connections. Systems like HiveMind rely on a satellite hub to transmit data several times a day, which is particularly useful in areas with weaker infrastructure.

Most of the analyzed systems feature user-friendly interfaces that provide an overview of the collected data, often with customizable alert options. Systems like BeeMate offer live camera streaming, giving users a clear and detailed visual insight into the hive's status and bees activities.

While there are advanced devices that incorporate artificial intelligence and integrated analytical functionalities, the majority of available systems remain focused on basic data collection without implementing predictive models or more complex analyses. These distinctions highlight clear opportunities for improvement, particularly in the areas of prediction and in-depth data analysis, which could significantly enhance the efficiency of beekeeping colony management.

Recent scientific research increasingly focuses on automated, non-intrusive monitoring systems to better understand hive conditions and bee behavior. While traditional methods relied on manual data collection, newer approaches integrate sensors for temperature, humidity, and weight to monitor hive activity, bee population, and environmental changes[27]. Systems like Beemon stand out by incorporating audio and visual recordings to capture bee behavior at the hive entrance, enabling the detection of subtle behavioral shifts and early signs of colony stress, such as disease or resource shortages[5]. In contrast, the SBMaCS system focuses on developing a self-sufficient bee monitoring solution that harnesses power from bee vibrations[6]. These advancements, supported by modern communication protocols and real-time visualization platforms, allow continuous monitoring, facilitate early intervention, and significantly improve conventional beekeeping practices.

Research questions

Given an increasing number of smart devices being integrated into ecosystems, there is a need for specifying concrete steps in modeling such ecosystems. In this paper, an example of smart apiculture ecosystem is used. The second aspect is successful future adoption of proposed model which is why modeling starts with data in focus through an ontology-based approach. Using well-established ontologies and building on top of them enables them to be easily reused in further research. Considering the focus of the research and comparative analysis of existing solutions, the main research questions that the research aims to answer are:

RQ1: How can existing ontologies be extended to represent smart ecosystems focusing on apiculture?

RQ2: How can an ontology-based modeling approach be used to improve interoperability and data standardization?

RQ3: How can an ontology be used to further model smart ecosystems?

Modeling smart apiculture ecosystem

Smart ecosystems provide innovation that is data-driven[36], thus it only makes sense to model smart apiculture ecosystem using a data-based approach. A key step is defining the data that will be collected and later used throughout the ecosystem. Creating an ontology has proven to be useful for data collection, representation and organization[21]. Ontology-based modeling provides a stepstone for sharing and reusing agricultural data as well as providing a solution for integration with other relevant sources[37].

To fully harness the interoperability of ontologies, it is essential to expand existing ones that align with the given context. In our case, we utilize the Sensor, Observation, Sample, and Actuator (SOSA) and Semantic Sensor Network (SSN) ontologies for representing sensor data, while for structuring linked data, we adopt the DOLCE+DnS Ultralite (DUL) ontology.

SOSA serves as a lightweight core module of SSN, providing a flexible and coherent foundation through a well-defined set of common classes and properties. The concepts introduced in SOSA are designed for seamless exchange across various SSN applications and modules. SSN extends SOSA by offering greater expressivity for modeling sensor networks, observations, deployments, and processes, making it particularly well-suited for complex IoT ecosystems that demand detailed semantic annotations[38–40].

DUL provides a formal framework for organizing domain-specific concepts, ensuring consistency, interoperability, and reusability. It introduces essential ontological constructs such as data, events, roles, and qualities, which enhance knowledge representation and seamless integration across heterogeneous datasets[41].

Designing a beehive ontology

In smart ecosystems ontology is used to organize and manage information systematically and facilitate better data retrieval and integration. Designing a beehive ontology is a key step in modelling smart apiculture ecosystem and understanding all data that needs to be gathered. In this study, we propose an ontology that represents knowledge about smart beehive

Table 1. Comparative analysis of hive management platforms and solutions

Device, URL	Sensors	Connectivity	User interface	Comment
AmoHive [28]	Temperature and humidity in and outside of a hive, Weight, Solar Irradiation, GPS location, Acoustict	Cell network	Android application that visualizes and uses AI to process data and alert users	With its broad range of measurements, including solar irradiation and GPS tracking, AmoHive is a versatile system. The use of AI for data processing and user alerts adds value by providing advanced insights beyond raw sensor data.
ApiagoHive [29]	Weight, Temperatures, Humidity	WiFi	Mobile application for data visualization	ApiagoHive offers basic environmental monitoring with a focus on temperature, humidity, and weight. While the system is user-friendly with its mobile app, it lacks advanced analytics or predictive functionalities.
BeeMate [30]	Bee count using HD camera, In-hive temperature, humidity and acoustic	/	Cloud-based application, mobile and web, livestream from camera, AI classification and pests detection.	The device integrates HD camera and AI-powered pest detection, which enhances its capability beyond basic monitoring. The addition of livestreaming provides real-time insights, making it suitable for users requiring immediate visual confirmation of hive activity.
Beemon [5]	Microphone, camera, humidity and temperature	MQTT	A suite of interfaces includes tools for video and audio analysis, live video streaming with annotations, data visualization and analytics, and real-time hive monitoring with health alerts.	This system serves as a comprehensive prototype that collects and visualizes essential data. Additionally, it utilizes computer vision for bee counting and analyzes audio recordings from within the hive.
Broodminder [31]	In-hive temperature and humidity, Weight, Acoustic and Bee counter based on radar	Gateway with WiFi, Cellular or Bluetooth	Mobile application that visualizes gathered data with configurable alerts	This system provides comprehensive sensor data collection, including temperature, humidity, weight, and acoustics. However, while it offers alerts, its functionality focuses primarily on monitoring rather than predictive analysis for hive health improvement.
HiveBeat [32]	Temperature, Humidity and Movement	Radio frequency, WiFi	Cloud-based application. Dashboard that provides data visualization and adds custom alerts and notifications. Map with GPS location of Hives	HiveBeat offers essential environmental monitoring alongside movement detection. Features like custom alerts, GPS mapping, and WiFi connectivity provide an enhanced user experience.
Hivemind [33]	In-hive humidity and temperature, Bee counting, Weight, Rain gauge	Satellite hub, that sends data 4 times a day	Cloud-Based Application, Web and mobile that visualize gathered data	This device could be used only for data gathering thus not providing advance analysis or predictive capabilities that can enhance user experience.
IoBee [34]	Bee counting and pests detection using camera, Temperature, Humidity, Acoustic	Mesh network	Cloud-Based Application, Web and mobile that sends warnings and visualize gathered data	The company claims to fight Honey-Bee Colony Mortality through IoT and uses mesh network to overcome connectivity issues at the end user is notified about hive health and possible problems.
SBMaCS [6]	Humidity, weight, temperature, flame sensor, PIR sensor, An electronic fan, electromagnetic heat, digital camera.	LoRa	Mobile application for data visualization and system control.	This prototype researches the potential of a self-sustaining system powered by a piezoelectric transducer that captures energy from bee-generated vibrations.
Smarthive [35]	Automated equipment for extracting honeycombs.	/	/	This system focuses on automating honey extraction, which is a unique feature compared to other monitoring solutions. However, it lacks environmental or hive health sensors, making it a niche product tailored for honey production optimization.

ecosystem including entities and relationships between them. Ontologies are used for their support of modeling complex domains and improving interoperability of multiple data sources. In the case of beehive ecosystem, ontology is needed to describe the multidisciplinary nature of the proposed ecosystem.

The ontology shown in Figure 1 is modeled using SOSA/SSN ontologies. The instances of classes are added to showcase an example in the domain of beehive monitoring and collecting essential data for proving quality of honey. The main sosa:FeatureOfInterest class is a specific hive that has multiple sosa:ObservableProperty instances that are important, such as air temperature, weight, humidity, etc. In this example, air temperature is observed by sosa:Sensor, in this case DHT22 sensor. In specific time intervals, observations about air temperature contain important data such as result of observation and result time. They also have phenomenon time, which is usually an interval in which the observation is made. For example, not every instance of air temperature will be stored in the system, but rather an average in a time range. The sosa:Sensor class is a subclass of ssn:System, so it is essentially a part of the system or a subsystem. All of the sensors are hosted on sosa:Platform which is a microcontroller such as Arduino. Here a procedure for optimal data collection rate is implemented. Also, the first steps of analyzing data are made here, using data fusion procedure. Both data collection rate and data fusion are instances of sosa:Procedure class. Arduino is a part of our system, but at the same time is used as a platform for other subsystems, in this case sensors. Each beehive is equipped with one Arduino and multiple essential sensors. They represent the edge nodes of our system used for data collection. All data in one apiary is then sent to one device and then merged. In this figure, is represented by Raspberry Pi microcomputer, which serves as a gateway device for further communication in apiary ecosystem. This part of ontology is an example made using SSN, without additional classes and relations.

For designing apiary ecosystem, certain extensions to the SSN ontology are needed to show other ecosystem elements. These new classes are introduced by expanding SSN with subclasses or using DUL as top-level ontology for additional classes. We introduce bhsnn:Service, as a subclass of the ssn:System and at the same time a subclass of dul:Code class from a SystemLite ontology of systems, plugin to DOLCE Ultralite. Instances of bhssn:Service class include ServerAPI, ClientAPI, AnalyticsAPI and ConfigurationAPI. Additionally, we introduce bhssn:CloudPlatform as subclass of the sosa:Platform class. This distinction is important for differentiation between physical platforms such as RaspberryPi and Arduino, and cloud platforms that are not physical objects in our system but rather used as an external infrastructure. AWS is an instance of bhssn:CloudPlatform that hosts our APIs. In our ontology, we introduce one more class, which is bhssn:Alert, a subclass of dul:Event. In Figure 2 we can see an instance of bhssn:Alert class and how it communicates with an instance of dul:Organization. Smartphone is used as a platform for our beekeepers. So here we introduce isOwnedBy relation between specific beekeeper and smartphone. Our alert is initiated by a ServerAPI which is then sent to a smartphone as a platform for our beekeeper. The smartphone then notifies a beekeeper about warnings and needed actions.

The last part of our ontology is related to data collection and storing data. We use the dul:Data structure class and add subclass bhssn:Non-RelationalDB. Here is a HiveDB01 as an instance of a non-relational database where all data collected by sensors will be stored. This instance is also hosted on AWS bhssn:CloudPlatform. WebService is also an instant of bhssn:Service class, which is hosted on RaspberryPi. This web service is used to merge all gathered data and upload data to our hive database which is enabled by introducing uploadDataTo as a new relationship between our classes.

Factors of influence in apiculture Multiple factors need to be considered to determine the health of a bee colony, influence the position of the hive, and predict the quality and quantity of produced honey. Main factors can be grouped in the following categories:

(i) Climate factors
(ii) Location factors
(iii) Environmental factors
(iv) Internal beehive factors

These factor groups represent new classes in our ontology: bhssn:ClimateProperty, bhssn:EnvironmentalProperty, bhssn:InternalHiveProperty and bhssn:LocationDataProperty. This segment of our ontology is presented in Figure 3.

Climate conditions that are most favorable to bees and their activities are dry and warm weather. In this context, factors that influence behavior of bees the most are air temperature, air humidity, wind speed and solar irradiance. These factors are instances of bhssn:ClimateProperty class of our ontology. The optimal value range for observations of these factors can vary depending on the bee species and subspecies.

The optimal temperature for bees and their activity is around 18.5°C. Lower temperatures slow down bees' activity and totally stop at 12°C. Temperatures higher than optimal require more activity on keeping the beehive cool, thus lowering honey and nectar yields[42,43]. Air humidity for optimal bees' activity is in 64-76% range, greatly varying depending on temperature and species[42,43]. Wind can have a significant impact on bees. Depending on the wind speed, bees use more energy for their flight with speeds in 32-40 km/h range completely stopping their activity. Precipitation can decrease the distance that bees can travel to reach food and even stop their activity completely. Solar irradiance (Sun exposure) is generally beneficial for bees with optimal values ranging from 600 to 800 lux for intensity and irradiance in 10 - 20 mW/cm2 range[42,43].

Locational factors that have the greatest impact on bee colony and honey production are distance from pasture, distance from water, layout of beehives and their orientation. These factors are instances of bhssn:LocationProperty class of our ontology which extends sosa:ObservableProperty class.

Distance from pasture should be under the average of 1526.1 meters for optimal quantity and quality of produced honey, with maximum distance for Apis mellifera carnica subspecies reaching 5983 meters[44]. Distance from water is

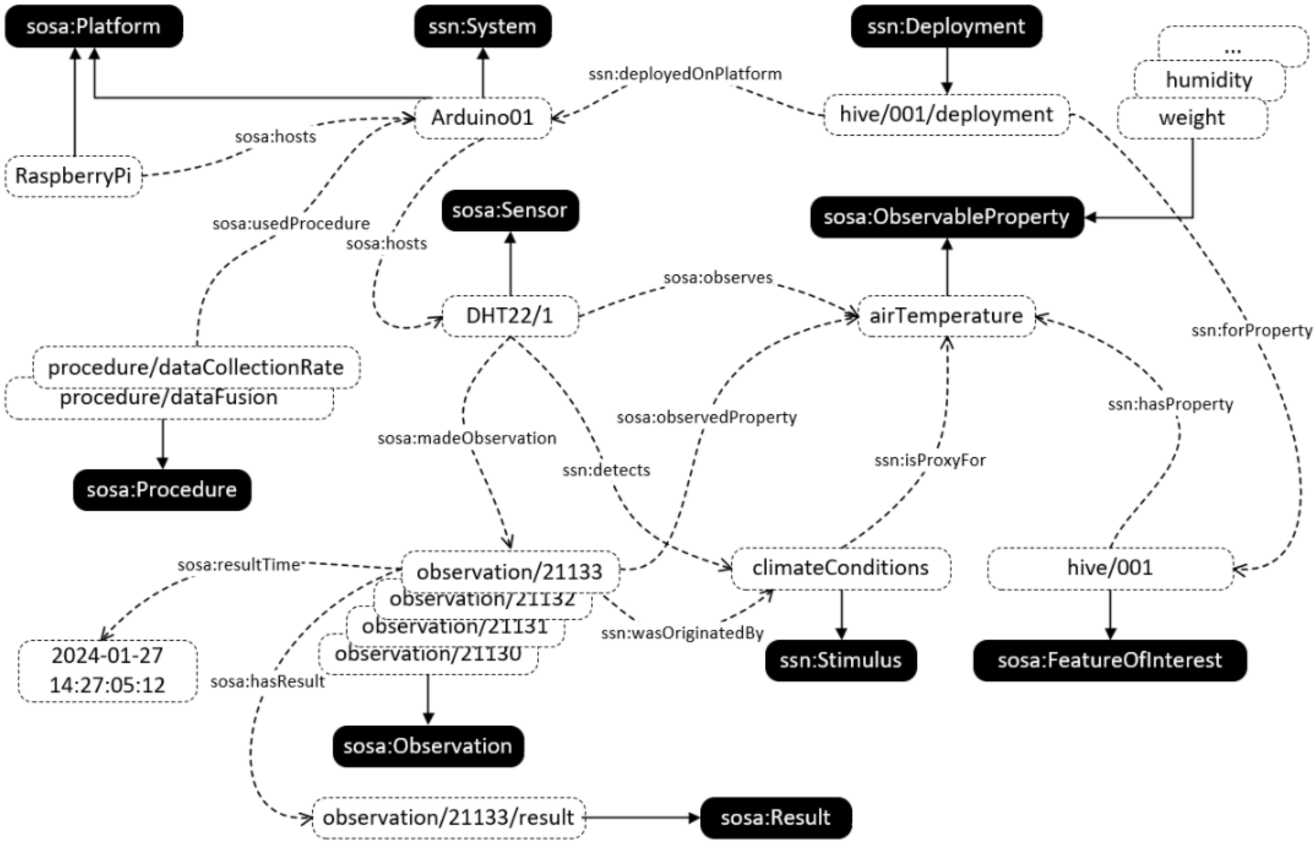

Figure 1. Example of apiary data collection using SSN ontology.

crucial because the water is used to dissolve food, as well as keeping the beehive cool during summer. If the water source is far from beehive, more bees will be tasked with gathering water resulting in lower honey yields[43,45]. The optimal beehive layout is in groups of 3-5 hives uniformly distributed with the distance of around 160 meters in between. Beehives are often grouped on the trailer, in which case they should be placed further in the field, keeping in mind the wind direction to enable the flower scent to reach the bees[43]. Beehive orientation plays an important role and influences other factors. Beehives should face south or southeast (in northern hemisphere) to get enough sun exposure. Placing beehives under young trees proved to be optimal providing just enough shade from excessive sun exposure while at the same time shielding them from strong winds[43,46].

Environmental factors have a great impact on beehive health, as unfavorable conditions can significantly increase bee mortality and affect both honey yield and quality. Key factors such as the presence of weeds, pesticides, and air quality are all instances of bhssn:EnvironmentalProperty.

In the production of mono-floral honey, weeds are an important factor to monitor. Their presence near cultivated crops may attract bees, potentially affecting the purity of the honey. The presence of pesticides in the air and in the pasture increases bee mortality, raises the risk of spreading disease, and ultimately reduces honey quality[47]. Air pollution weakens bees by reducing survival, disrupting foraging, and limiting flower visits. Respirable Suspended Particulate Matter (RSPM) accumulates on their bodies, impairing navigation and sensory functions. It also affects their immune and circulatory systems, causing heart irregularities and altered blood cell levels. Additionally, pollution-induced stress changes gene expression, further compromising their health[3].

Internal beehive factors include internal temperature, internal humidity, sound level, observed frequency and beehive weight which represent instances of bhssn:InternalHiveProperty class of our ontology. Internal temperature and humidity are of great importance for beehive health assessments, as bees actively regulate inner temperature and humidity[45]. By analyzing sudden changes in data that can indicate a high stress level, beekeepers can perform swift actions to reduce those levels. Stress could be caused by pests or other environmental factors[27]. Internal temperature and humidity are also used to detect and predict possible swarming activities. First on swarming initiation temperature rises for couple of degrees and then lowers when swarming is active, this shows a pattern that can be leveraged for detecting swarming activity[48]. The weight of a beehive can provide insight into the functioning and health of the bee colony. Weight sensors continuously measure the hive and periodically send data to beekeepers. The hive's weight can fluctuate even within a single day, allowing conclusions to be drawn about how many bees are actively foraging, how successful they are, and how far they travel based on the time spent outside the hive[49]. Sound level and observed frequency are good indicators of bee's activity. For instance, a study[50] found a strong correlation between sound levels and internal hive temperature. By analyzing bee activity under various environmental conditions, researchers

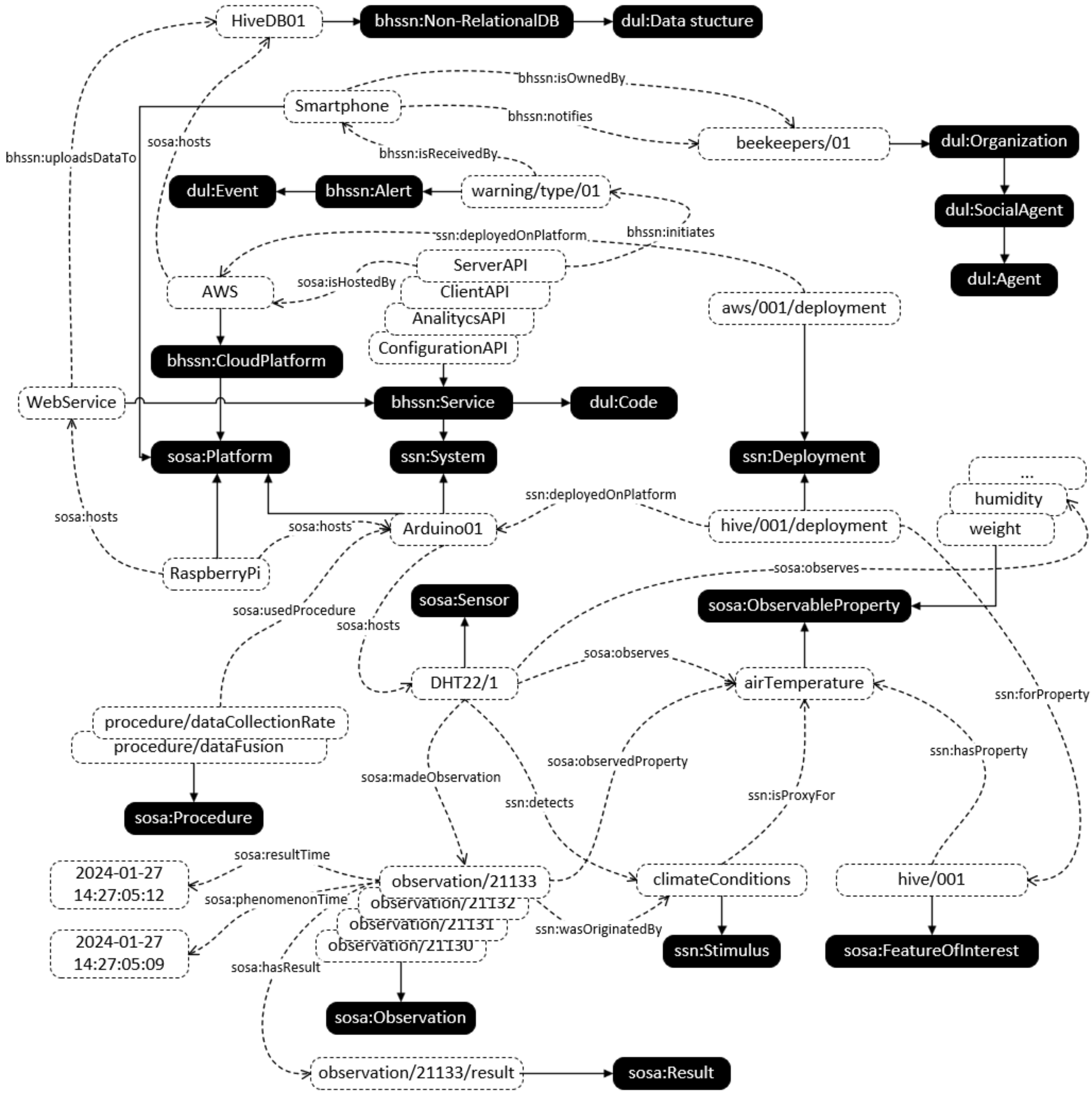

Figure 2. Beehive SSN ontology, extended SSN ontology with additional classes based on DUL top-level ontology.

successfully identified sound patterns closely linked to the warming and cooling processes within the hive. On the other hand[48] demonstrates that swarming activities can be detected based on internal sound levels and frequency analysis. Increased sound levels and shifts in wingbeat frequencies serve as indicators of heightened activity, allowing beekeepers and scientists to anticipate swarming before it occurs.

Stakeholders Stakeholders are an essential part of every ecosystem. The main focus of our work is the relationship between beekeepers and service providers and their interaction through the web application.

After the analysis of stakeholders, the following were identified:

(i) *System integrator* – responsible for designing a functional system by integrating product and service components supplied by various vendors[51]. Focuses on the design, integration, and implementation of the Smart Beehive System, ensuring compatibility between different elements. Additionally, develops necessary services to enhance and optimize integrated solutions.

(ii) *Beekeeper* – key role is regular maintenance of apiaries to ensure colony health and maximize honey production which subsequently increases honey yields. These activities include maintaining optimal conditions for bees and protection against pesticides, diseases and unfavorable climate conditions. Activities also include honey harvesting and selection of the

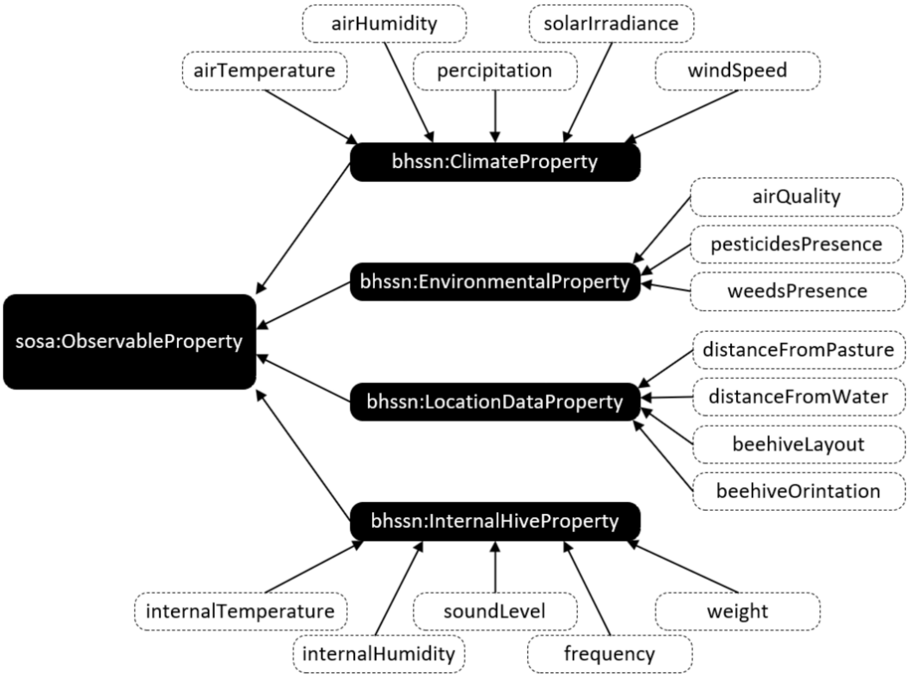

Figure 3. Subclasses of sosa:ObservableProperty and their instances.

best bees for breeding in order to maintain a healthy community that will be resistant to disease.

(iii) *Hardware supplier* – Provides the necessary hardware components for the Smart Beehive System, ensuring compatibility, quality, and reliability. These components are later integrated into the system to enable its full functionality.

(iv) *Cloud service provider* - provides the necessary infrastructure for Smart Beehive System from data acquisition and its storage to ensuring scalable, secure and reliable data processing, analytics, and remote accessibility for efficient hive monitoring and management[52].

(v) *Beehive equipment supplier* – ensures quality products for beekeepers that can easily be integrated with Smart Beehive System. It also provides necessary parts for regular beehive maintenance.

(vi) *External data providers* – supply additional relevant data from various sources including other smart systems, such as weather conditions, satellite imaging and maps to enhance the Smart Beehive System's monitoring and predictive capabilities[53].

(vii) *Supply chain system* - ensures effective distribution, logistics and delivery management of Smart Beehive System. Provides seamless integration into existing beekeeping operations and customer support.

(viii) *Certification body* – provides written assurance (certificate) that the product in question meets specific requirements[54]. The certificate is issued for the Smart Beehive System, confirming its compliance with relevant standards. Additionally, the certification body can later issue certificates for honey authenticity, ensuring its traceability and verified origin, thereby enhancing consumer trust and market credibility.

(ix) *Governance* – a key part of the system, the government body establishes policies, standards, and regulations to ensure smart systems operate ethically, securely, and in compliance with industry best practices, promoting transparency and data integrity[55]. In collaboration with environmental organizations, it ensures compliance with sustainability standards and environmental regulations. Additionally, environmental organizations advocate for new, unregulated practices to be incorporated into smart systems, fostering a greener and more sustainable future.

(x) *Customers* - end users of the Smart Beehive System, including partner institutions and buyers. Partner institutions, such as research organizations and agricultural agencies, utilize the system to share data and gain more insight into honey production process emphasizing trust between partners. Buyers can use data from the application to inform themselves about the honey production process and make conscious data-based decisions when buying products.

Smart apiculture ecosystem

The smart ecosystem is built around a Smart Beehive Management System. Various stakeholders contribute to its development and operation: governance bodies set regulations, suppliers provide hardware, cloud and AI services, external data sources enhance decision-making, supply chain systems facilitate logistics and beekeepers utilize the system for hive management. Figure 4 illustrates these connections, showcasing the ecosystem that supports smart apiculture.

System integrator designs and develops systems for smart beehive management, considering compatibility and interchangeability of crucial parts and subsystems. Through

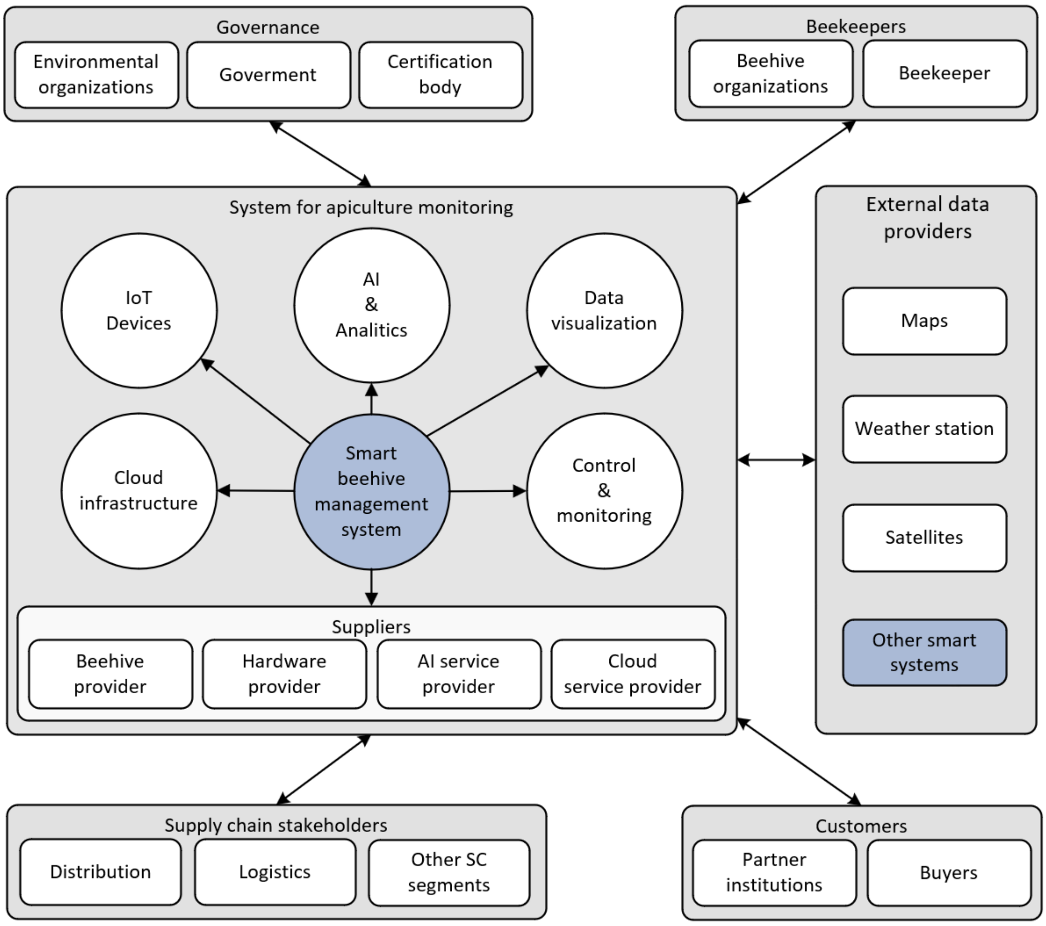

Figure 4. Smart apiculture ecosystem with stakeholders.

cooperation with different actors, system integrator ensures reliability and enhances beehive management.

One of the key acters in this ecosystem is the hardware provider, whose role is supplying key components and subsystems. Those parts are then integrated into beehives which are provided by beehive equipment providers together with other equipment necessary for beehive management.

To ensure a fully functional system, system integrator incorporates other available services such as cloud infrastructure and artificial intelligence models, tailoring them to the specific needs of users. System integrator internally develops the services that are not available, ensuring their quality and compatibility with the entire system while securing a competitive advantage.

System integrator builds long term relationships with suppliers, distributors and logistics partners, to secure unhindered function of ecosystem. Throughout the entire development and implementation process, it ensures the system's compliance with regulations and the recommendations of environmental organizations, enabling sustainable beekeeping management through precision agriculture. The smart beehive management system provides beekeepers with insights into key apiary parameters, enabling data-driven decision-making rather than relying on past experiences. The system collects data from the hive in real time and displays them as histograms of important parameters such as temperature, humidity, air quality and others.

Beekeepers are notified about changes inside beehives such as sudden changes in environmental conditions or the occurrence of diseases, with recommendations on appropriate actions. Thus, lowering the number of necessary visits to the beehive, increasing management efficiency and minimizing losses, which contributes to the health of bee colonies and optimization of yields. To provide increased system precision and enhance analytic capabilities, system integrator obtains data from external data sources including satellite images, weather forecasts and data from other smart systems. By combining this data with self-collected information, the system can detect potential risks early and recommend the best strategies for apiary preservation.

Smart apiculture IT platform

Smart apiculture IT platform consists of multiple interconnected components. Creating a detailed model of that platform enables us to better understand the role of each component, how they communicate and gain insight into the general flow of data. The proposed system consists of three main parts:

(i) Smart apiculture system
(ii) Cloud infrastructure and services
(iii) Web application

Proposed smart apiculture IT platform, its components and interactions are presented on Figure 5.

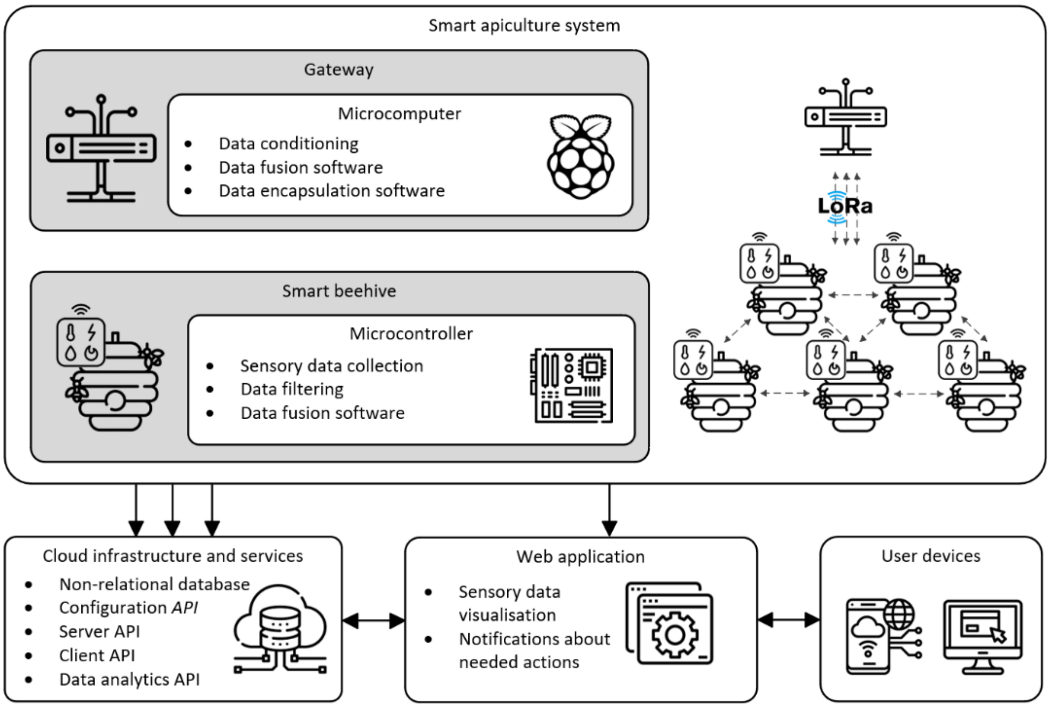

Figure 5. Smart apiary IT platform model[56].
This figure has been designed using resources from Flaticon.com

Proposed smart apiculture IT platform consists of smart apiculture system, cloud infrastructure and services, and web application. Main components of smart apiculture system are smart beehive, a device serving as a gateway and needed network infrastructure. Smart beehive is equipped with microcontroller such as Arduino and multiple sensors for data collection. Microcontroller coordinates sensory data collection rate and lightly filters and preprocesses collected data. Data from each beehive in apiary is then send to a central device. Different network technologies can be used to support this process, such as Wi-Fi, Bluetooth or LoRa. Needed infrastructure includes Bluetooth or LoRa modules for our microcontroller. Specifically, LoRa can be used for secluded areas where data needs to be transferred over long distances with low energy consumption rate. It also brings the benefit of low cost of data transfer, since we are not relying on mobile network operators. Data from all beehives in apiary is then collected on a microcomputer, where data fusion and data encapsulation software are installed to further process data. Before uploading data to cloud database, here we can also encapsulate, compress or encrypt data if needed.

All prepared data is then uploaded to the database. The database for smart apiary platform needs to be located on a cloud infrastructure[57]. This enables storing historical data, analysis and easier communication with beekeeper's application. The data on the cloud is used to show historical data gathered by sensors about their apiary and a specific beehive. Using the resources of a cloud platform, analytics API is implemented and used to analyse specific trends based on gathered data. The user is then notified if any of parameters is out of defined range and actions by the beekeeper are needed.

Designing a prototype for apiculture management platform

Effective beekeeping relies on precise monitoring, understanding environmental conditions, and timely decision-making. The following section outlines the key software requirements for an apiculture management platform, detailing its core functionalities, including hive monitoring, placement evaluation, environmental analysis, alert systems, and data integration capabilities.

Software requirements for apiculture management platform

The apiculture management platform incorporates various functionalities to facilitate efficient beekeeping operations. By providing digital tools for hive management, health tracking, and environmental analysis, the platform helps beekeepers to optimize productivity and make data-driven decisions.

One of the key features of the platform is hive monitoring, which enables beekeepers to track real-time conditions within their hives. This functionality relies on a network of IoT sensors installed inside the beehive. These sensors continuously collect data on crucial parameters such as temperature, humidity, weight and bee activity. The gathered information is transmitted over the network to a cloud service provider, where it is securely stored and processed. Collected data is presented to the user in the form of live data and histograms. This real-time monitoring system allows for early detection of potential issues, helping beekeepers take timely measures to maintain optimal hive conditions and ensure colony health.

Another functionality is intended to help beekeepers evaluate hive placement. The system analyzes GPS data transmitted by the hive and calculates key factors, such as distance from water, distance from other hives and distance from pasture. By processing this information, the platform suggests more suitable locations that can enhance honey production and overall bee well-being. Additionally, environmental analysis is conducted, based on collected data and weather precipitation, and their potential impact on bee's colony. This functionality can help beekeepers to plan hive inspections, feeding schedules, and honey harvesting.

To enhance the efficiency of beekeeping operations, the platform incorporates a smart alert system that keeps beekeeper informed of critical changes. Using artificial intelligence and machine learning, the system continuously analyzes collected data, identifying anomalies and deviations from optimal conditions. When anomalies are discovered, automated alerts are triggered and potential solutions are suggested, allowing beekeepers to take well informed data-driven action. This proactive approach helps prevent potential risks, minimize the number of beehive visits and ensure bee colony health, thus later increasing yields.

To lay the foundation for greater interoperability in IoT ecosystems, the beehive management application provides a public API that facilitates seamless data exchange with other smart systems. By exposing collected hive data in a standardized and accessible format, the platform encourages integration with agricultural technologies, environmental monitoring tools, and research initiatives.

Web based apiculture management application

The proposed web application is presented in Figure 6, containing three essential pages that beekeepers would use.

Common to all shown screens is the navigation bar at the top, which includes a menu icon that opens a dropdown menu for navigation. It also features a notification bell that, when clicked, displays recent notifications. Clicking on the beehive icon returns the user to the home screen.

The screen on the left displays the home page, which consists of two main sections. The first section shows a mapped area with pins representing each apiary or beehive connected to the application. These pins are automatically placed based on GPS data transmitted by the connected hives. Clicking on a pin navigates the user to the specific apiary screen. The second section displays recent alerts categorized by priority level. The priority is indicated by a border color: orange for urgent, green for semi-urgent, and colorless for non-urgent alerts. Alert also contains apiary name, brief description and timestamp. Clicking on an alert expands it, revealing a detailed description and suggested next steps. Additionally, clicking on the apiary name redirects the user to the corresponding apiary screen. The middle and right screens display apiary-specific data, divided into two real-time data groups. External (environmental) data includes key environmental parameters such as temperature, humidity, wind speed, precipitation, and solar irradiance. Internal hive data consists of measurements taken inside the hive, including internal temperature, humidity, weight, and a sound graph showing the frequency spectrum and sound intensity levels. This data provides beekeepers with valuable insights into both the hive's internal conditions and the surrounding environment, enabling them to make informed, data-driven decisions. Clicking on any internal or external data point opens a pop-up window displaying its histogram.

After the internal and external data groups, apiary-specific alerts are displayed in chronological order. Alerts are generated based on predefined thresholds and anomalies detected by artificial intelligence and machine learning models in the collected data, enabling beekeepers to respond swiftly to potential issues affecting the hive or its environment. Alerts function the same way as on the home screen, but when expanded, they not only provide detailed insights and recommended actions but also emphasize the specific data points that triggered the alert, allowing users to quickly identify and analyze the relevant information.

Discussion and Conclusion

SSN ontology is used as a basis for IoT integration in precision agriculture, explaining the processes of data collection[38]. Building on top of the well-established SSN ontology and using it for ontology-based modeling and extending it with domain specific details provides a straightforward approach to modeling smart ecosystems in agriculture. Benefits of using ontology as a basis for further modeling of a smart ecosystem are in solving the interoperability problem, improving efficiency of future developed solutions, providing large-scale data for more detailed analytical process and data representation.

An ontology-based modeling approach can provide benefits in further standardization in precision agriculture ecosystems by providing a uniform way of data collection, management and analytics. This encourages sharing and reusing data from multiple heterogenous sources[11]. Developed ontology can be used as a step in further standardization in precision agriculture.

Using an ontology for modeling smart ecosystems provides a basis for modeling databases, helps in identifying stakeholders of the system and provides basis for creating system architecture, its components and their interactions.

Implications

The research presented in this paper has implications for various stakeholders, including beekeepers, system integrators, governance entities, and external data providers. Its primary goal is to establish an ontology-based foundation that enables standardization and interoperability of heterogeneous data generated by IoT systems in apiculture. Implications are summarized in Table 2.

Limitations

The model presented in the paper focuses on beekeepers and beekeeper organizations and the raw honey production process. To make sure the quality of honey is up to standards, certification bodies should be an integral part of the ecosystem. The proposed ontology can easily be extended to include additional stakeholders and to cover necessary honey chemical properties. Specific local preferences, guidelines, and policies were not a part of the research. This keeps the developed ontology and model flexible for further development for specific geographical regions.

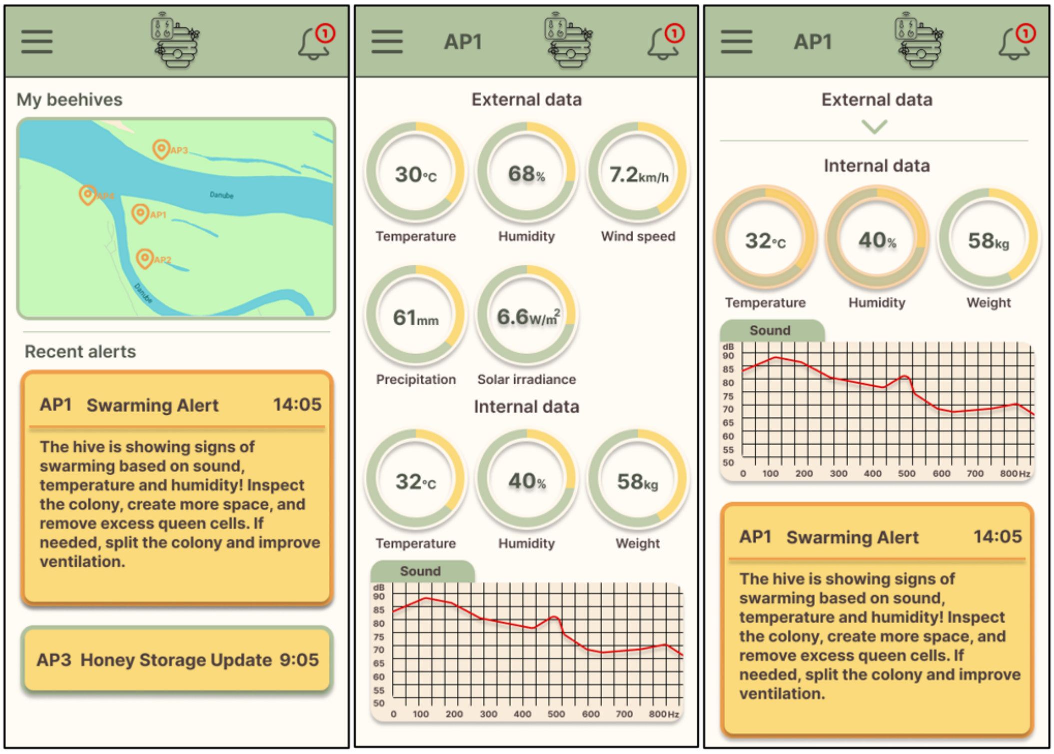

Figure 6. Design of the smart apiculture web application.

Table 2. Implications for stakeholders

Stakeholder Group	Implications
Beekeepers	Decisions that beekeepers make are data driven.
Researchers	Approach for modeling agricultural domain-specific ontologies. Approach for developing data-driven smart ecosystems. Researchers leverage presented framework for future smart agricultural ecosystems and knowledge management solutions. Researchers can use the developed ontology as a foundation for future AI prediction and recommendation system development.
Governance	Governance could take advantage of the developed ontology as a foundation for data standardization and achieving IoT interoperability.
External data sources	External data sources can leverage the framework to improve data exchange with other stakeholders. External data sources benefit from the developed ontology as a foundation for structuring and standardizing agricultural data, thus increasing interoperability.

Future work

Future work regarding this topic will be in the direction of expanding the developed model to support consumers as end users of the product. Secondly, we aim to fully develop an application based on a developed model and proposed functionalities. External data sources will be integrated to support data sharing in smart agriculture. The goal is to eventually track honey in the whole supply chain to ensure quality of final products, provide additional information for consumers and all other partners in the supply chain.

Acknowledgments

Statements and declarations

Not applicable.

Ethical considerations

Ethical approval was not required.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Declaration of conflicting interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding statement

The authors received no financial support for the research, authorship, and/or publication of this article.

Data availability

The datasets generated during and/or analyzed during the current study are available in the Github repository, https://github.com/petarfon/beehive-ssn-ontology

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