


Horti-IoT: a new data framework for Dutch horticulture

RESEARCH ARTICLE

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Abstract

Consistency issues limit the sharing of horticultural data across multiple systems, resulting in challenges for users to analyze data effectively across various systems utilizing artificial intelligence technology. Introducing data governance principles can help standardize and unify data practices, making it easier for analysts to locate, comprehend, transfer and integrate data from diverse sources to enable data-driven horticulture. Implementing data governance and principles specific to horticulture can assist in standardizing the layout and format of data structures from different sources. This study aims to propose a new governance framework, Horti-IoT, based on the Data Management Body of Knowledge and several structured frameworks for the Internet of Things (IoT) governance that will lead to data-driven horticulture. This study is empirical in nature. The Dutch horticulture stakeholders are involved in this initiative, providing the data, knowledge, and experiences needed for this study. The data stream from various sources, including camera images, sap flow sensors, climate sensors and manually measured growth data. The key findings following the implementation of the Horti-IoT framework's principles are reduced workload for data analysts, efficiency in plant monitoring, savings time in pre-processing, enhanced water resource management, reduced system administrator contacts and compliance with General Data Privacy Regulation. The new proposed Horti-IoT framework, compatible with Dutch horticulture, is presented. The data were obtained from the Lab greenhouse at the World Horti Centre in the Netherlands, in the framework of the Regionale SIA RAAK MKB call March 2022-September 2024 subsidy funds for project title 'Gewasgroei Goed Gemeten (GeGoGe). This project is a collaboration between three educational institutions. Inholland University of Applied Science, the Hague University of Applied Science, Lentiz Vocational School, and stakeholders.

Keywords: applied artificial intelligence, DAMA-DMBOK framework, data-driven horticulture, data governance and principles, IoT reference frameworks.

JEL codes: Q10, Q16, Q18, C93

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1. Introduction

The Dutch horticulture greenhouse industry stands at the intersection of innovation, sustainability, and technological advancement. As the globe faces the difficulties of population increase, climate change and resource scarcity, the importance of efficient and sustainable horticulture practices has never been more pronounced. Within this context, harnessing the power of data has emerged as a transformative force, enabling precision farming, digital growing, resource optimization and informed decision-making.

The Netherlands is a pioneer leader in greenhouse horticulture, known for its innovative approaches and sustainable farming practices. Autonomous greenhouses and digital growing represent the next frontier in this field, offering the potential to further enhance productivity, resilience, and environmental sustainability in agriculture. However, this progress also brings forth a deluge of data from diverse sources such as sensors, robotics, Internet of Things (IoT) devices, and manual observations. It will be challenging for users' analysts to locate, comprehend, transmit, and combine data from many sources and systems. Effective data governance becomes paramount to extracting actionable insights, ensuring data accuracy, facilitating analytics, and safeguarding sensitive information.

In response to these imperatives, this study presents a comprehensive proposal for a new IoT governance framework, Horti-IoT, explicitly tailored to the Dutch horticulture greenhouse sector. This framework encapsulates a holistic approach to data management, encompassing the entire data lifecycle from collection to utilization. It intends to address, facilitate, and enhance decision-making and operational excellence for data analysts.

This proposed framework aims to provide a structured and adaptable approach that empowers stakeholders within the horticulture industry to employ data-driven insights for improved decision-making and operational excellence. The approach is rooted in collaboration, recognizing the diverse array of stakeholders — from greenhouse operators and researchers to suppliers and regulatory bodies — each contributing a unique perspective and expertise. The stakeholders vary from expert researchers from Inholland University of Applied Sciences, The Hague University of Applied Sciences and Lentiz Vocational Education Group; engineers and biologists are from GRN Consultancy (SME), Lets Grow and 2Grow (SME), while expert growers and farmers are from 2Harvest (SME), AVAG, Axia (SME), GreenPort West Holland, Hortitech (SME), Duijvestijn Tomaten (SME), Reijm kwekerij (SME), Tomato world, Van der Knaap, Verify (SME).

This introduction sets the first stage for the contribution and motivations for developing an IoT governance framework for Dutch horticulture, Horti-IoT. Begin with an overview of data management and data governance, IT governance, and IoT governance, and then investigate IT and IoT governance frameworks, IoT reference models, IoT layers, and data principles. As part of the methodology, this work inspired and investigated various open sources academical and commercial IoT frameworks, including the IoT-Gov structured framework for Internet of Things governance (Sedrati *et al.*, 2023), the Gartner framework (Memon *et al.*, 2020), the Microsoft Azure framework (Kikuchi *et al.*, 2017), Amazon Web Services (AWS) (Chakraborty & Aithal, 2023) and the DAMA framework (DAMA International, 2017).

2. Literature review

A brief literature review outlines existing research and perspectives related to data governance, digitalization in agriculture, and greenhouse management, which will provide a foundation for the proposed data governance framework for the Dutch horticulture greenhouse industry.

- (1) Data governance in agriculture: Data governance has gained significant attention across various industries. Researcher like (Jouanjean *et al.*, 2020) emphasize the importance of data quality and security, while (Santamaría and Castellanos, 2023) propose policy and privacy for agricultural data governance settings. As agriculture becomes increasingly data-intensive, implementing effective data governance frameworks is crucial to ensuring accurate decision-making and sustainable practices.

- (2) IoT and greenhouse management: The integration of Internet of Things (IoT) technologies in greenhouse conditions is explored by Maraveas *et al.* (2022). Their work showcases how IoT-enabled UAVs, big data analytics, RFID devices, intelligent machines, satellites, sensors, actuators, and AI generate vast amounts of data, requiring optimal resource management and robust data governance strategies to handle data effectively. This intersection highlights the need for tailored data governance frameworks to manage the unique challenges greenhouse environments pose.
- (3) Precision agriculture, big data and AI technology utilization: Precision agriculture is a driving force in modern farming, aiming to optimize resource usage and crop yields. Bhat and Huang (2021) discuss the role of big data and AI in precision agriculture and emphasize the significance of data-driven insights in decision-making processes. A comprehensive data governance framework ensure that the data collected from greenhouse environments contributes to the precision agriculture paradigm.
- (4) Sustainable agriculture and data-driven innovation: Sustainable practices are at the heart of the Dutch horticulture greenhouse industry. Researchers like Rozenstein *et al.* (2023) examine how data-driven innovation can enhance sustainability in agriculture. The paper highlights the need for structured data governance approaches that facilitate collaboration among stakeholders to address sustainability challenges.
- (5) Digital growing and autonomous greenhouse: Digital growing is the application of digital technology such as sensors, data analytics, artificial intelligence, and automation in agriculture and horticulture. These technologies allow growers to get real-time data on temperature, humidity, light levels, soil moisture, and fertilizer levels. Growers can utilize this data to make informed decisions about adjusting growing conditions to optimize plant growth and resource use efficiency (Geelen *et al.*, 2024). The concept of autonomous greenhouses, particularly in the Netherlands has gained significant attention in recent years as part of efforts to enhance agricultural efficiency and sustainability. These greenhouses leverage advanced technologies such as artificial intelligence, robotics, sensors, and climate control systems to operate with minimal human intervention while maximizing crop yields and resource efficiency (Geelen *et al.*, 2024).
- (6) Regulatory compliance and data security: Ensuring compliance with data protection regulations and securing sensitive agricultural data are critical concerns. Researchers like Kaur *et al.* (2022) discuss the challenges of data security and compliance in the agricultural sector. A robust data governance framework should address these challenges by implementing mechanisms for data anonymization, encryption, and controlled access based on login and password information.
- (7) Data sharing, privacy and ethics and ownership in agriculture: Collaboration and data sharing are central to driving innovation in agriculture. The study of Kaur *et al.* (2022) also investigates the possible benefits and limitations of collaborative data sharing among various agricultural stakeholders. To enhance trust between the public and private sectors, the study suggested addressing the subject of data sharing and data regulation in the early stages of the business model development. A data governance framework should provide guidelines for secure and ethical data sharing while preserving the interests of each party involved. The ethical considerations surrounding data ownership, access, and usage are pertinent in agricultural settings have also been studied by Kaur *et al.* (2022). The study delves into the ethical dimensions of data governance in agriculture, underscoring the need for transparent data ownership policies and guidelines for responsible data usage.

3. Implications for policymakers and food and agribusiness firms

Agricultural and the horticultural products contribute 9% to The Netherlands' gross domestic product. Annual output increases incur high labor costs, and issues with water resource management, data exchange, garbage-in garbage-out data and plant health control. Having a standardized framework for data governance in horticulture, specifically greenhouse management, will provide a foundation solution for the Dutch horticulture greenhouse industry. A proposed data governance framework for the Dutch horticulture greenhouse industry, which incorporates insights from these many perspectives, can harness current expertise to meet the specific challenges and opportunities given by this setting. A thorough and efficient data governance

plan that promotes innovation, sustainability, and industry expansion established a customized framework to meet the requirements of suppliers, researchers, greenhouse operators, and regulatory agencies. However, the involvement and collaboration of governments, policymakers, universities, corporations, food, agribusiness firms and consumers are essential factors in accelerating the mainstream adoption of sustainable data-driven agriculture/horticulture. Governments may establish a framework for research and education, universities can perform research and teaching, businesses can push innovation and execution, and consumers can influence demand. When these organizations collaborate, they form a potent force for positive change in the agriculture sector. As a result, these agents should recognize and apply the suggested data governance framework and data principles.

4. Methodology

The objective contribution of this study includes the following:

- (1) State of the art of data management and data governance, IT and IoT governance and IT and IoT governance frameworks, IoT reference models, data principles and framework layers are presented. To understand the current situation, Sedrati *et al.* (2023) and the study of Dasgupta *et al.* (2019) conducted state-of-the-art research, investigating both data governance and IoT references governance frameworks and mapping them towards the defined requirements. Conclusions from the state-of-the-art study by Sedrati *et al.* (2023) confirm the necessity of a new IoT governance framework. However, this study acknowledges that the framework of Sedrati *et al.* (2023) relies on a particular standard framework, and this study believes that other commercial frameworks that are accessible and would offer more value — such as but not limited to DAMA and Gartner — should be taken into consideration for horticulture frameworks.
- (2) Propose a new IoT governance framework: Horti-IoT framework operating with five processes as defined by Sedrati *et al.* (2023): (1) identify needs; (2) assess decision-making ability; (3) Define the governance model, stakeholders and roles; (4) implement and deploy the model; (5) evaluate the model.
- (3) Implement and evaluate in the field by two case studies. To implement the Horti-IoT framework, a horticulture two scenario use-case studies are deployed: (1) smart climate and sap flow resource water management optimalization, and (2) monitoring head thickness growth using a RGBD camera. These two scenarios use access to the control system, multiple sensors, a smart irrigation system and different communication APIs. The prototypes are first defined, describing their requirements and needs.
- (4) Provide a list of data principles for the horticulture framework.

5. Background

Before introducing the IoT governance framework, one first needs to dig into the state of the art of data management and data governance, IT governance and IoT governance (Figure 1) and then investigate IT and IoT governance frameworks, IoT reference models, IoT layers and data principles.

5.1 Data management and data governance

Data management involves creating and executing procedures, architectures, policies and practices to oversee the whole data lifecycle. This includes the planning, execution, and supervising of activities involved in acquiring, controlling, protecting, delivering, and enhancing data assets (Dasgupta *et al.*, 2019). Data governance is a broader term that refers to the importance of data and data assets in IoT devices. According to Korhonen *et al.* (2013), data governance entails an organizational approach to managing data and information, formalizing policies and processes to cover the entire data life cycle, from acquisition to use to elimination. Organizations must apply governance to IoT devices, applications and data, but governance is also necessary to control the privacy of IoT users. The term “governance” refers to various procedures

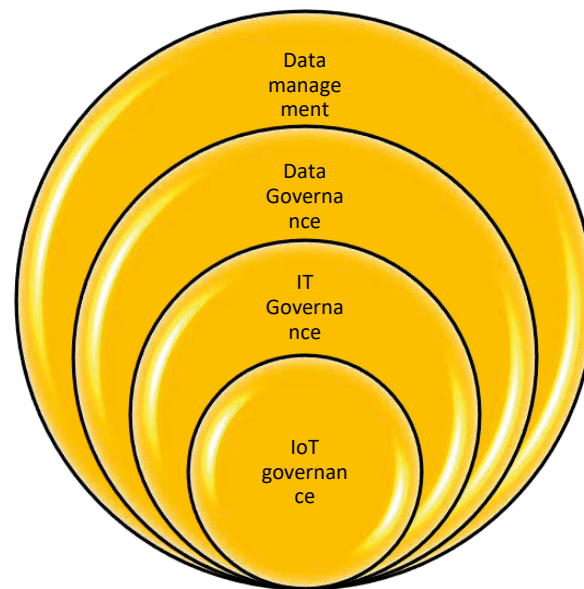


Figure 1. Relationship data management, data governance, IT governance, IoT governance.

and frameworks employed to control and decide in various contexts. Figure 2 depicts the data governance (according to the data management body of knowledge: the DAMA DMBOK) wheel (DAMA International, 2017). The DAMA DMBOK is the international industry standard for data management and governance. The ten components in this wheel constitute development of data management. These components are data architecture, data quality, meta data, data warehousing and business intelligence, reference and master data, document and content management, data integration and interoperability, data security and privacy, data storage and operations and data modeling and design.

5.1.1 Data architecture

Data architecture is a foundational framework governing an organization's data assets' design, structure, and integration. A well-defined data architecture is a blueprint for organizing and managing various data assets, encompassing databases, data warehouses, and other repositories. It promotes a shared understanding of data structures, definitions, and relationships, fostering consistency and coherence in data usage.

5.1.2 Data quality

Data quality or accuracy and reliability are pivotal for informed decision-making. Implementing quality control processes is imperative to ensure the trustworthiness of collected data. Data quality is fundamental to effective decision-making in any sector, e.g., in agriculture. The principles outlined in DAMA DMBOK (DAMA International, 2017) guide establishing data quality standards, data cleansing processes, and data validation to enhance data quality in, for example, agricultural settings.

5.1.3 Metadata

Metadata, also called meta information, encompasses "data that offers insights about other data" without delving into the actual content of the data, such as the textual components of a message or the intrinsic characteristics of an image. The metadata classifications are diverse, with one prominent category being descriptive metadata, which encapsulates informative details about a given resource (Johnson *et al.*, 2015).

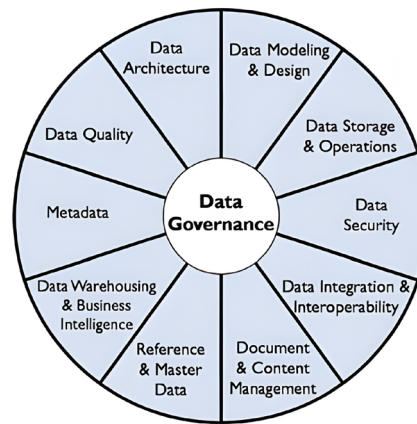


Figure 2. The DAMA DMBOK wheel (DAMA International, 2017).

5.1.4 Data warehousing and business intelligence

Data warehousing and business intelligence (BI) are pivotal in modern organizations, enabling informed decision-making and strategic planning. A data warehouse is an integrated storage that collects data from numerous sources and converts it into a format suitable for analysis. On the other hand, business intelligence involves using tools and technologies to analyze and interpret this data, providing valuable insights to support organizational decision-making. Integration of data warehousing and BI systems assists organizations in harnessing the potential of their data for competitive advantage.

5.1.5 Reference and master data

The focus of reference and master data lies in the reconciliation and upkeep of fundamental shared data, ensuring uniform utilization across systems and facilitating the availability of the most precise, timely, and pertinent representation of the truth regarding vital business entities.

5.1.6 Document and content management

Document and content management involves systematically organizing, storing, retrieving, and tracking electronic and physical documents. This process ensures efficient document lifecycle management, version control, and compliance with regulatory requirements. On the other hand, content management encompasses the strategic handling of digital assets, including text, images, and multimedia, to facilitate collaboration, streamline workflows, and enhance information accessibility.

5.1.7 Data integration and interoperability

Data integration and interoperability ensure that information from varied origins can be seamlessly combined and analyzed cohesively. Agricultural projects often rely on data from diverse sources, and this component fosters a comprehensive understanding of the agricultural ecosystem.

5.1.8 Data security and privacy

Robust data security, privacy and data anonymization techniques are essential. The agricultural sector handles sensitive data, including farm-level data, crop yields, and personal information. Protecting sensitive agricultural data from unauthorized access and cybersecurity threats remains a significant concern. Leveraging DAMA DMBOK, data governance practices must address data security, encryption, access controls, and compliance with privacy regulations.

5.1.9 Data storage and operations

Efficient data storage and operations are paramount to ensuring that the copious volumes of agricultural data collected and organized, secure and readily accessible. Contemporary data frameworks often rely on cloud-based solutions due to their scalability, redundancy, and real-time data access capabilities for stakeholders.

5.1.10 Data modelling and design

Data modeling and design involve systematically representing data structures, relationships, and business rules to comprehensively understand the organization's data assets. This process aids in aligning business requirements with the corresponding data structures, promoting data integrity, and ensuring consistency across various systems and applications.

5.2 IT and IoT governance

IT governance is the process of managing and monitoring risks associated with an organization's IT resources, including servers, computer networks, and applications, in accordance with an organization's goals and strategy (Peterson, 2004; Tallon *et al.*, 2013). The IoT refers to a collection of technologies that facilitate the connection of sensors and electronic devices to a network for data sharing. With the increasing number of low-cost "system on a chip" devices, cloud computing and 4G and 5G wireless internet networks, the objective of "sensing up" all these equipment has become a reality. The Internet of Things is expanding rapidly, increasing its capabilities and complexity. For this reason, IT leaders and stakeholders should consider regulations and procedures for defining and managing concerns like data sharing, privacy, and security. IoT governance is, therefore, meant to serve this purpose. The IoT governance foundation extends from the principles of IT governance. IoT governance is concerned with the lifecycle of IoT equipment's, sensors, metadata, and IoT applications inside organizations (Dasgupta *et al.*, 2019).

5.3 IT and IoT governance framework

An IT governance framework serves as a guide that describes an organization's strategies for implementing, managing, and reporting on IT governance. Several IT governance frameworks exist, including Information Technology Infrastructure Library (ITIL), ISO 27001 and Control Objectives for Information and Related Technology (COBIT) (Dasgupta *et al.*, 2019). The COBIT framework, developed by the Information Systems Audit and Control Association (ISACA) and the International Organization for Standardization (ISO), ensures that IT procedures and activities align with an enterprise's strategic goals. At the same time, ITIL aims to provide best practices for IT services to its customers (Egelstaff and Wells, 2013). While IoT governance framework and during recent years, numerous methodologies and frameworks have been developed to model IoT governance. This section introduces the various methodologies suggested in previous studies. These frameworks are most appropriate to present in the context and match the scope of this study after browsing lists of IoT governance frameworks that offered in the past years. The IoT governance frameworks should protect the integrity of information transmitted by all IoT devices in the organization's network. There are several existing academic and industrial IoT governance frameworks, such as but not limited to: From cloud governance to IoT governance (Copie *et al.*, 2013), IoT smart city framework (Theodoridis *et al.*, 2013) and a principles-based approach to govern the IoT Ecosystem framework (Almeida *et al.*, 2017). Campus IoT collaboration and governance (Webb and Hume, 2018), IBM-defining IoT governance practices framework (Sedrati *et al.*, 2023), IoT-Gov: A structured framework for internet of things governance (Sedrati *et al.*, 2023), DAMA-DMBOK2 Framework (DAMA International, 2017), The Gartner Enterprise Information Management Framework (Memon *et al.*, 2020).

5.4 IoT reference models

The IoT reference model is a structured framework for comprehending IoT systems' many components and layers (Figure 3). While no single widely accepted IoT reference model exists, various models provide similar conceptualizations of IoT architectures. The International Telecommunication Union (ITU) produced the IoT Architecture Reference Model, which is widely recognized. In the domain of the IoT, various reference models consist of several layers. Notably, the Industrial Internet Reference Architecture (IIRA) (Fraile *et al.*, 2023) reference model delineates seven layers; the Industrial Internet of Things (IIoT) (Antão *et al.*, 2018) reference model has five layers, whereas reference model like Gartner reference model (Memon *et al.*, 2020), also has five layers. The IoT reference model layers offer a structured approach to building, implementing, and managing IoT systems, allowing for connectivity, scalability, and adaptability across varied IoT deployments.

5.5 IoT reference model layers

Each IoT layer defines a logical set of IoT functionalities. Any functionalities within a layer may deploy at one or more tiers. The job of the IoT architect is to determine which functionalities are necessary and where they deploy. Each of the following sections defines the functionalities of a single layer. The IoT reference model typically comprises several layers, as depicted in Figure 4. By organizing IoT systems in these layers, the reference model offers a conceptual framework for effectively designing, implementing, and managing IoT solutions. It helps stakeholders understand the various components, interactions, and dependencies within IoT architectures, enabling interoperability, scalability, security, and efficiency.

5.5.1 Perception layer

This layer depicts the physical devices or “things” in the IoT ecosystem. It is the first layer from the bottom, as shown in Figure 4 in the IoT reference model. Sensors, actuators, RFID tags, smartphones, wearables, and other endpoints that collect data or interact with the physical world are all examples of such devices. The primary job of this layer is to sense and collect data from the environment around it. Depending on the

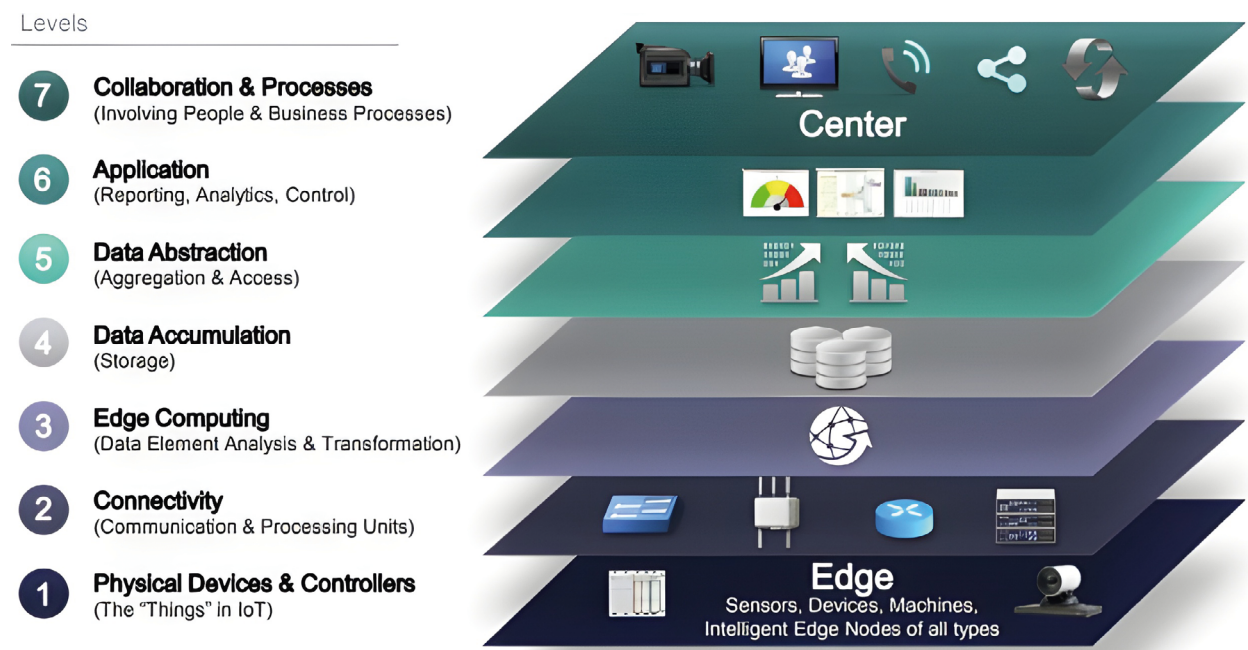


Figure 3. IoT reference model (Maraveas *et al.*, 2022).

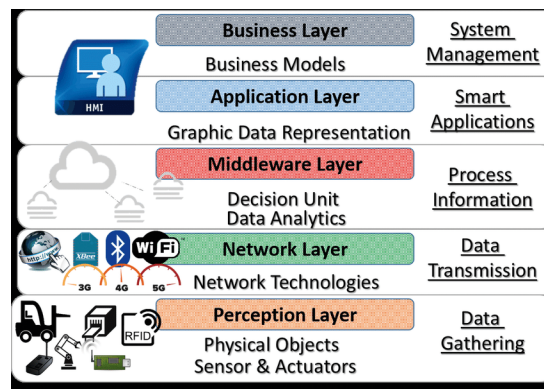


Figure 4. IoT reference model layers (Antão *et al.*, 2018).

application, data acquired at this layer could include temperature, humidity, CO₂, location, motion, sunlight intensity, and other characteristics.

5.5.2 Network layer

The network layer (the second layer) allows the perception layer to communicate with the upper layers in the IoT model layers. This layer includes various communication technologies, protocols, and standards for transferring data between devices and systems. Examples include Wi-Fi, Bluetooth, Zigbee, LoRaWAN, cellular networks (2G, 3G, 4G and 5G), Ethernet, and others. The network layer is in charge of data transfer, routing, addressing, and guaranteeing the dependability and security of the communication medium.

5.5.3 Middleware layer

The middleware layer operates as a bridge between the network and application layers. Its responsibilities include data processing, protocol translation, device management, security, and providing authentication, authorization, and access control services. Middleware components include message brokers, IoT platforms, data management systems, APIs, gateways, and edge computing devices.

5.5.4 Application layer

IoT solutions are implemented in the application layer to meet specific use cases and corporate goals. This layer contains apps, services, and platforms that use data from the perception layer to give value-added capabilities, analytics, and insights. Examples include smart home systems, smart farming, industrial automation, healthcare monitoring, predictive maintenance, and environmental monitoring applications.

5.5.5 Business layer

The business layer includes the business processes, models, and strategies that guide the implementation and operation of IoT solutions. Considerations include business models, monetization techniques, regulatory compliance, governance, privacy rules, and stakeholder relations. The business layer ensures IoT activities are consistent with organizational objectives and contribute to value creation, innovation, and competitive advantage.

5.6 Data principles

In the domain of the IoT, data principles refer to the essential rules that control gathering, managing, processing, sharing, and using data within IoT ecosystems. These guidelines ensure that data in IoT systems

meet the accuracy, consistency, and reliability throughout the data collection lifecycle. Tables 1–3 give the data principles for format, unit and data types. Table 1 includes information on sensitive General Data Privacy Regulation (GDPR) and sharable data. Growth, climate, irrigation, sap flow, and camera data are not subject to GDPR as they do not contain personal information that could be misused. Images without metadata are also exempt from GDPR, whereas images with metadata could be vulnerable to misuse. The decision to share or withhold the growth, climate, irrigation, sap flow, and camera data publicly or with others lies with the stakeholders responsible for such actions.

Table 1. Data principles, format

Data principle
(1) All data must have metadata. Apply this to images as well as numerical data.
(2) All data should be in Excel or CSV format when uploaded.
(3) Data fields with the same datatype have the same formatting and length.
(4) Maintain an original copy of data as they are received. Examine every modification.
(5) Apply common terms and definitions (points are used as decimal separators. Separating the whole part of a number from its fractional part MUST be written down as 3.5 (decimal point) and not as 3,5 (decimal comma)).
(6) Values contain no thousand separators. A separator is not needed when a number has four or more digits, i.e., 1,000 MUST be written as 1000.
(7) All Files uploaded must contain one Datetime column.
(8) Files should contain only new information. When a file is uploaded, it should not contain data already present in the database and should instead provide data following the recorded date of the relevant dataset.
(9) Annotate and augment images prior to the analysis.
(10) Use data for low- and minimal-risk AI solutions.
(11) Monitor the camera regularly to prevent it from going offline and to ensure that the memory storage capacity does not run out.
(12) Allow the images to be annotated automatically using open-sources tools.

Table 2. Data principles, units

Name	Unit, full name	Unit, abbreviation
Date Time	Day-month-year hour: min	dd/mm/yyyy hh: mm
Width	Millimeter	mm
Distance	Centimeter	cm
Leaf Surface (LAI)	Square meter leaf per square meter surface	m ² /m ²
Absolute Humidity (AH)	Gram per cubic meter	g/m ³
Temperature	Degrees Celsius	°C
Radiation	Watt per square meter	w/m ²
Photosynthetic Active Radiation (PAR)	Micromol per square meter and per second	μmol/m ² per s
CO ₂ concentration	Parts per million	ppm
Vapor pressure	KiloPascal	kPa
Precipitation	Milliliter per square meter	ml/m ²
Electrical conductivity	MilliSiemens per centimeter	mS/cm
Sap flow	Gram per hour	g/h

Table 3. Data principles, data type

Category data field	Name of the data field	Data type	Unit name	Unit	Interval length	Shareable	GDPR sensitive	Description
Growth Data	Local date	Date-time	Day, hour	h/m	7-day intervals	YES/NO	NO	Timestamp relevant to growth values.
Growth Data	Head thickness	Decimal	Width	mm	Once a week	YES/NO	NO	Tomato plant head thickness.
Growth Data	length growth	Decimal	Distance	cm	Once a week	YES/NO	NO	Tomato plant stem growth.
Growth Data	Leaf Area Index	Decimal	Surface	m ² /m ²	Once a week	YES/NO	NO	Leaf Area Index is the amount of the surface area of leaves per m ² related to the surface area of the ground per m ² .
Climate Data	Local date	Date-time	Day, hour	h/m	5-min intervals	YES/NO	NO	Timestamp relevant to climate values.
Climate Data	Absolute moisture content of greenhouse air	Decimal	Density	g/m ³	5-min intervals	YES/NO	NO	Absolute air moisture content inside the greenhouse.
Climate Data	CO ₂ greenhouse	Decimal	Parts per million	ppm	5-min intervals	YES/NO	NO	Air CO ₂ content inside the greenhouse.
Climate Data	Greenhouse temperature	Decimal	Temperature	°C	5-min intervals	YES/NO	NO	Temperature inside the greenhouse.
Climate Data	Radiation	Decimal	Radiation	W/m ²	5-min intervals	YES/NO	NO	Level of radiation that is reaching the plants measured outside.
Climate Data	Humidity deficit greenhouse	Decimal	Density	g/m ³	5-min intervals	YES/NO	NO	Saturated AH minus AH
Climate Data	Plant: PAR	Decimal	Micromol per square meter per second	μmol/m ² per s	5-min intervals	YES/NO	NO	Photosynthetically active radiation, radiation value contributing to plant growth.
Climate Data	Plant: VPD	Decimal	Pressure	kPa	5-min intervals	YES/NO	NO	Vapor pressure difference plant and vapor pressure in the greenhouse.

Table 3. Continued.

Irrigation Data	Water given - l/m ²	Decimal	Precipitation	l/m ²	5-min intervals	YES/NO	NO	Amount of water supplied to the plant.
Irrigation Data	Water given - EC	Decimal	Electrical Conductivity	mS/cm	5-min intervals	YES/NO	NO	Measurement of water's ability to conduct electricity.
Climate Data	Radiation out Pyrgeometer -	Decimal	Radiation	W/m ²	5-min intervals	YES/NO	NO	Amount of outgoing radiation outside.
Sap Flow	Local date	Date-time	Day, hour	h/m	5-min intervals	YES/NO	NO	Unique end-user identifier.
Sap Flow	Sap flow	Decimal	Day, hour	g/h	5-min intervals	YES/NO	NO	Measure of sap flow inside the plant.
Stem Diameter	Stem Diameter	Decimal	Width	mm	5-min intervals	YES/NO	NO	Measure of the stem diameter.
RGBD camera	RGBD depth camera	Pixel	Images	image	5-min intervals	YES/NO	NO	Take spot images for head thickness.
Camera metadata	Metadata	Decimal, Date-time	–	–	5-min intervals	YES/NO	YES	Includes details on the location and date, time of the image's capture; the camera may also contain information from the photographer (depending on the camera settings: name, affiliation). Then, GDPR applies.

GDPR, General Data Privacy Regulation.

6. Horti-IoT: new framework

6.1 Framework and layers

The proposed Horti-IoT framework consists of four layers. The internet business application layer, the middleware layer, the communication technologies layer and the things layer. The privacy and security trust rules consider in all four layers. In the development process, the priority of understanding the end users, specifically farmers, is to create a user-centric AI application for predicting business use cases. The study began with a user story outlining farmers' challenges and guiding feature prioritization. Collaborative discussions defined the application's structure, ensuring efficient data flow. Thus, the created model is reusable for various scenarios (Figure 5).

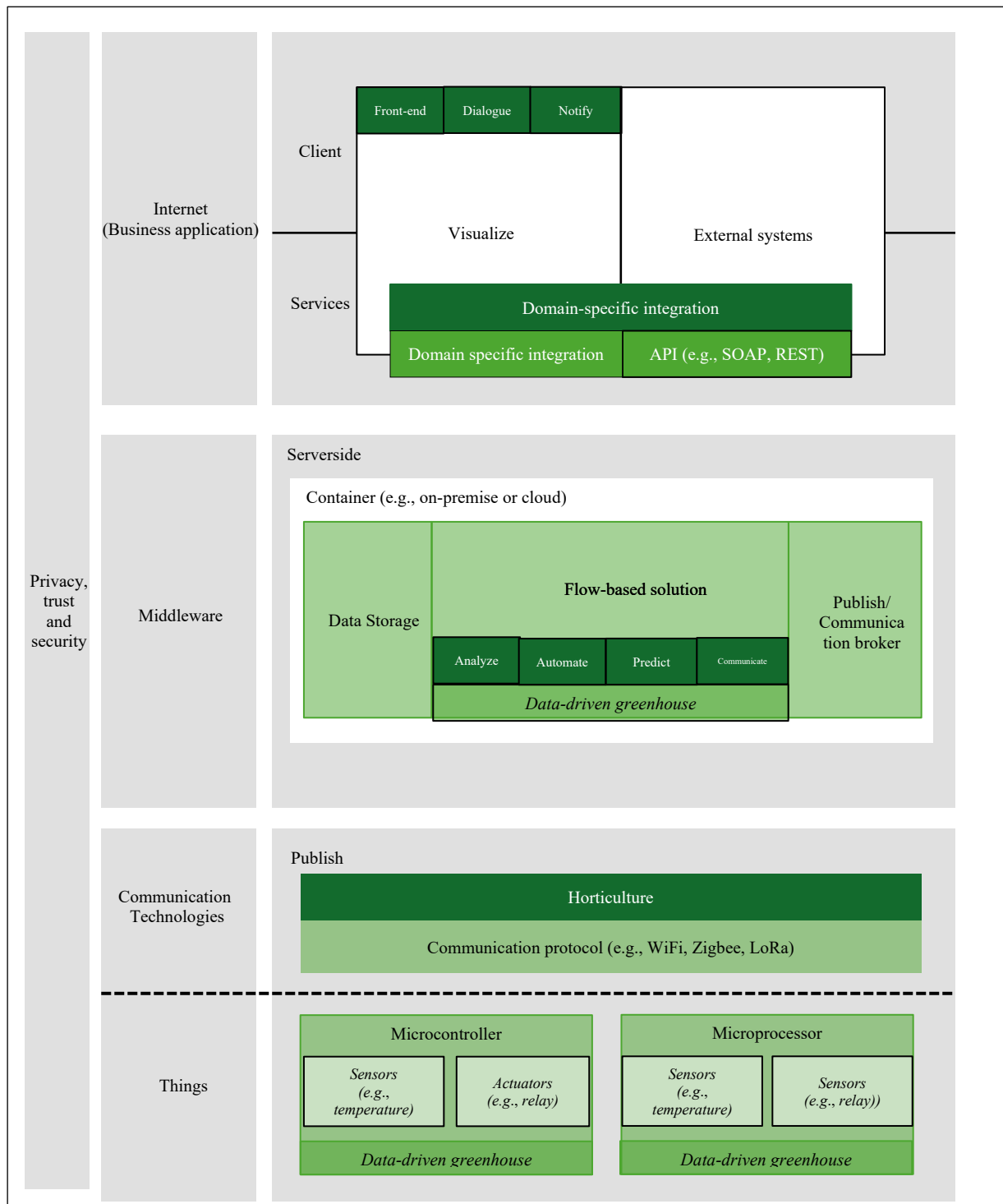


Figure 5. The proposed framework Horti-IoT.

6.1.1 Internet (business applications)

Applications that provide interfaces for managing IoT frameworks facilitate user interaction. These applications empower users to visualize and evaluate device states, facilitating informed decision-making. The Internet is a network layer, enabling connectivity among disparate IoT devices. This layer is all about APIs and integration from clients to services.

6.1.2 Middleware

Efficient storage and processing mechanisms are essential for data-driven farming to handle large volumes of diverse data, ranging from historical records to live sensor feeds. Cloud-based IoT systems offer scalable storage solutions for this purpose, necessitating the hosting of systems that oversee end-to-end IoT architecture, ensuring seamless data management and analysis. Middleware is an intermediary between operating system and application layer in IoT solutions. It abstracts the complexities of underlying technologies, simplifying the development and integration of services. Middleware solutions, including flow-based programming, streamline the implementation of new services and enhance interoperability within heterogeneous IoT ecosystems. Additionally, this layer facilitates data publishing, which is crucial for cloud computing in agriculture.

6.1.3 Communication technologies

A robust communication infrastructure forms the foundation of IoT systems. Networking technologies are categorized according to standards, spectrum allocation, and application scenarios. Short-range and long-range communication standards, including WiFi, Zigbee, and LoRa, enable efficient data exchange and publishing and are essential for real-time monitoring and control in agriculture.

6.1.4 Things

At the core of any IoT system are the IoT devices, often called sensors, essential in monitoring and analyzing various agricultural factors, such as soil nutrients and environmental conditions. These devices communicate wirelessly with sensors and actuators, requiring robust communication technology to ensure smooth data transmission. Integration things, objects, microcontrollers, and sensors is crucial to IoT framework design. Ensuring compatibility between microcontrollers and the chosen communication technology is essential. Whether utilizing Wi-Fi, Bluetooth, or cellular networks, seamless connectivity is vital for real-time data exchange and system interoperability. Additionally, microprocessors (such as Raspberry Pi ARM/x86 platforms) are also integral components of things.

6.2 Implementation scenarios

Implement a new IoT governance framework, Horti-IoT, according to the five processes depict from Sedrati *et al.* (2023):

- (1) Identify needs;
- (2) Assess on decision-making ability;
- (3) Define the governance model, stakeholders and roles;
- (4) Implement and deploy the chosen model; and
- (5) Evaluate the model.

Two scenario use-case studies in horticulture have been implemented and tested in the lab at WHC: (1) Smart climate and sap flow resource water management optimalization and (2) monitoring head thickness growth smartly using RGBD camera.

Specific business applications, things and data principles used in the two scenarios are:

Growth data (business application): The growers manually measure the growth data every week, including various values such as (not limited to) head thickness, Leaf Area Index (LAI), and length growth.

Lab Greenhouse at WHC Netherlands (Things): The research compartment lab (length 12.50 m; width 6.40 m; height 6 m), located at the World Horti Center, Naaldwijk, the Netherlands (Amir *et al.*, 2021). Axia Vegetable Seeds company provided the Xandor XR tomato seeds, which were grafted onto rootstocks (Maxifort, provided by Rijk Zwaan) at the propagator Noordam plants. The plants were planted in the research lab on September 12th, 2022. The Van der Knaap Group provides Cocopeat, Forteco Profit, and Slabs. Artificial LED light was applied between October's first week and March's last week. DLI (Daily Light Integral) was 18 mol/m² per day, the 24-h temperature inside the greenhouse was based on the RTR (Radiation Temperature Ratio) and the 24-h temperature varied between 18.5 and 23 °C, the CO₂ application was applied during the light periods on 1000 ppm, and the irrigation system applied water related to the outside conditions.

Climate and irrigation system (things): The climate and irrigation datasets collected from several sensors include the greenhouse temperature, air humidity, CO₂, outside radiation, air density, outside temperature, outside air humidity, outside air density, wind speed, stem diameter, sap flow and plant temperature. The irrigation dataset consists of given water EC, given water pH, given water/m², drained water EC, drained water amount, and absorbed water amount. All the climate data were monitored and recorded automatically via the Hoogendoorn and Priva (Amir *et al.*, 2021) climate system daily. The Priva climate system recorded the irrigation data. Stem diameter and sap flow was recorded by 2Grow (Amir *et al.*, 2021). All data were collected in the Let's Grow platform. The data stream from a wide range of sensors, such as temperature, humidity, light intensity, soil moisture, plant growth metrics, sap flow, VPR, RH and CO₂.

Sap flow system (things): The sap flow dataset was recorded using Dynagage SF sensors provided by 2GROW (Amir *et al.*, 2021). The sap flow rate was recorded every 2.5 seconds. One sensor installed on a tomato plant, and data were monitored and recorded automatically for the entire project period. The data present visually using the Phytosens software package of 2GROW (Amir *et al.*, 2021).

Depth RGBD camera system (things): The RGBD depth camera (Intel Realsense D435) positioned above tomato plants grown at the lab at the World Horti Centre in Naaldwijk (Amir *et al.*, 2021). The camera pointed towards the plant's head thickness at an angle of around 45 degrees. The camera continuously captures RGB and depth images, which are saved locally on a Raspberry Pi 4 every 150 seconds. By the Dutch protocol for vertically growing tomatoes, the plants must be moved weekly by rehanging. Consequently, the suspended camera must be relocated above the plant accordingly.

6.2.1 Scenario 1: Smart climate and sap flow resource water management optimization

Identify needs: Growers use a variety of data sources to optimize their farming practices by predicting plant water uptake based on environmental and climate conditions. Automating this procedure is critical for increasing efficiency and optimizing resource usage. To meet this demand, there is a growing interest in the development of technologies that optimize farming practices by anticipating plant water uptake based on environmental factors. The proposed solution includes a comprehensive framework for climate data integration and sap flow analysis. Transforming raw sensor data into meaningful insights enables a smooth transition from data collection to inform decision-making. This iterative method empowers growers by arguing how the application helps them optimize resource water management. This structured approach ensures that growers have access to essential information and guidance for implementing optimal sap flow management strategies. The process (Figure 6) begins with growers logging in (an internet or business application layer) to retrieve basic sap flow and climate information. In the subsequent layer, this basic information is presented to the grower, but additional insights are required. This prompts the activation of a third layer, which utilizes data

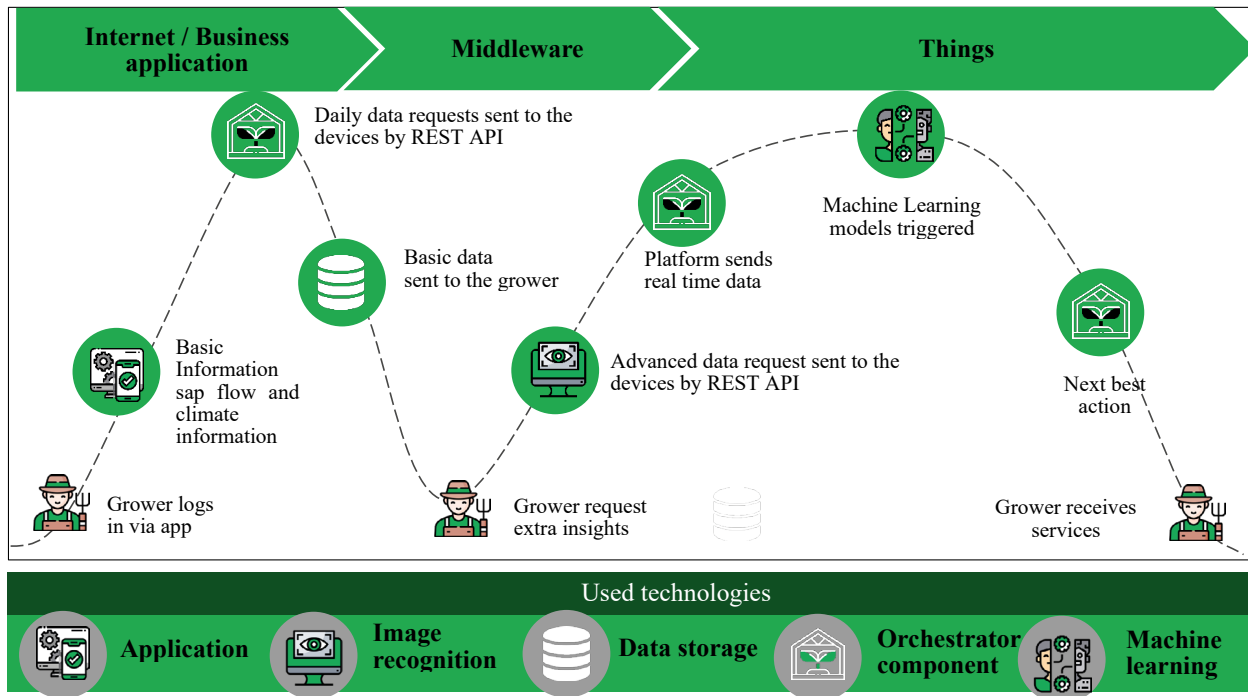


Figure 6. The Horti-IoT identify needs for smart climate and sap flow (scenario 1).

streams from various sensors. Machine learning models are then employed to provide growers with valuable information and insights. Armed with these insights, growers can determine the most effective actions to optimize the water given scheduling and make informed decisions.

Assess device and decision-making ability: Multiple data streams from various sources to the local platform at the greenhouse to the Let's Grow platform, such as growth data measured manually and ingested in an Excel sheet, sap flow data stream from 2GROW sensors to software interface (Phythosens) and imported as a txt. file, and climate and irrigation data streams from Hoogendoorn sensors to Hoogendoorn/Priva computer and imported as Excel format. All these data may present issues with consistency and the process of sharing and analyzing across multiple platforms, particularly when integrating artificial intelligence technologies. It will make it difficult for analysts to search for data, comprehend data, and transfer and merge data from different sources to create a cohesive file that combines all these separate files with varying formatting. The time complexity of unifying these various files into a single file increased considerably. The data principles format will aid in unifying and standardizing the structure of multiple data streams, enabling easier merging of data from different systems and facilitating seamless searching, analysis, and transfer between them.

Define the data principle rules, stakeholders and roles: The study adopted a pragmatic approach to address critical aspects of data consistency, quality, and usability within its scope. Utilizing data principles format (Table 1), units (Table 2) and data types (Table 3) to ensure uniformity across all sources of data from various stakeholders. This systematic approach guarantees the smooth functioning of the entire data chain, accelerates decision-making processes, and optimizes the effective utilization of collected data in agricultural design-making processes. Successful data sharing among stakeholders is key to achieving improved anticipation results and increased profitability. Therefore, stakeholders must establish agreements outlining the specific data to be shared and the protocols for sharing it.

Implement and deploy the model: The initial layer involves uploading of CSV files facilitated by a secure login mechanism. A login and password functionality strengthens data accessibility, and a dedicated dataset page

enables users to submit CSV files for predictive analysis. Frontend optimizations enhance the user experience, ensuring a visually appealing interface and seamless functionality across different devices. Transitioning to the second layer involves providing support for integrating machine learning models, processing user inputs, and projecting sap flow trends. Emphasis was placed on streamlined data processing and analysis throughout the development process, creating of a systematic data workflow for machine learning applications. In the fourth layer, sap flow data stream from 2GROW sensors to the software interface (Phythosens) by importing it as a text file (.txt). Furthermore, climate and irrigation data stream from Hoogendoorn sensors to the Hoogendoorn/Priva computer, imported in Excel format (Figure 7).

Evaluate the model: The model's performance is evaluated by executing the scenario once with using the proposed data principles and another without data principles. The climate and irrigation CSV file comprises 35 000 records with 43 attributes, while the sap flow text file (txt.) contains 43 000 records with five attributes. Each file has its formatting. By adhering to the formatting principles outlined in the Horti-IoT framework, each file is delivered with data followed by the data principles. Data analysts experience a noteworthy reduction in workload compared to processing datasets devoid of these principles. The comprehensive explanation of data principles for units, data types, and time intervals facilitated analysts' understanding of the diverse data set. The data principles for formatting aided analysts in effortlessly combining and merging diverse datasets, minimizing the time required to comprehend missing values, outliers, and interpolated data. Utilizing the Horti-IoT framework for monitoring sap flow aids in reducing water waste. However, quantifying these impacts in terms of a specific percentage is quite challenging. By monitoring sap flow and diameter measurements, gain a clearer understanding of the real-time status of the plant, including whether it is experiencing stress due to insufficient or excessive watering. As a result, appropriate countermeasures can be recommended to restore the plant's balance. These measures may involve adjusting water levels or implementing additional measures such as tube heating or venting to stimulate activity. Ultimately, the effectiveness of these measures varies depending on the specific circumstances of each case and trial greenhouse. Applying the principles outlined in the Horti-IoT framework leads to a substantial decrease in attempts to contact system administrators compared to datasets lacking these principles. This indicates enhanced data quality and a reduced necessity for manual intervention, reflecting improved system efficiency and autonomy.

6.2.2 Scenario 2: Monitoring contactless head thickness growth using a RGBD camera

Identify needs: The stakeholders, specifically growers, have been manually measuring the head thickness of tomatoes for several months during the year using calipers. They are keen on developing a tool to automate and make contactless measurements to optimize their farming practices. Head thickness is crucial indicator of plant health, with an ideal measurement target of approx. 10 mm. A thickness lower than this indicates weak plant growth, rendering them susceptible to pests and diseases. Conversely, if the thickness exceeds this threshold, the plant allocates excess sugars to its leaves rather than flowers and fruits. The correlation between head thickness and sap flow primarily reflects the plant's water uptake, essential for photosynthesis. Insufficient water intake leads to weakened plant growth. Implementation of computer vision presents significant opportunities for improving efficiency and decision-making in agriculture. Here is how deploying computer vision, open-source AI annotation tools and data anonymization can accelerate image pre-processing and enhance the overall digital growing process. Time and cost savings by adopting open-source AI annotation tools and implementing data anonymization practices, data analysts can save significant time on image pre-processing tasks. This accelerated workflow enables faster decision-making and allows growers to respond promptly to changing conditions in the growing environment. Moreover, reducing the time spent on pre-processing can lower labor costs and increase overall operational efficiency. Growers heavily rely on their observational skills to assess the physical condition of plants, a crucial aspect for maximizing efficiency and productivity in farming. The proposed solution in this study introduces a straightforward approach utilizing a depth camera system. The process (Figure 8) initiates with the growers accessing a dedicated internet or business application layer to acquire fundamental crop and climate data. Subsequently, this data is presented to the growers; however, to get deeper insights, the third layer comes

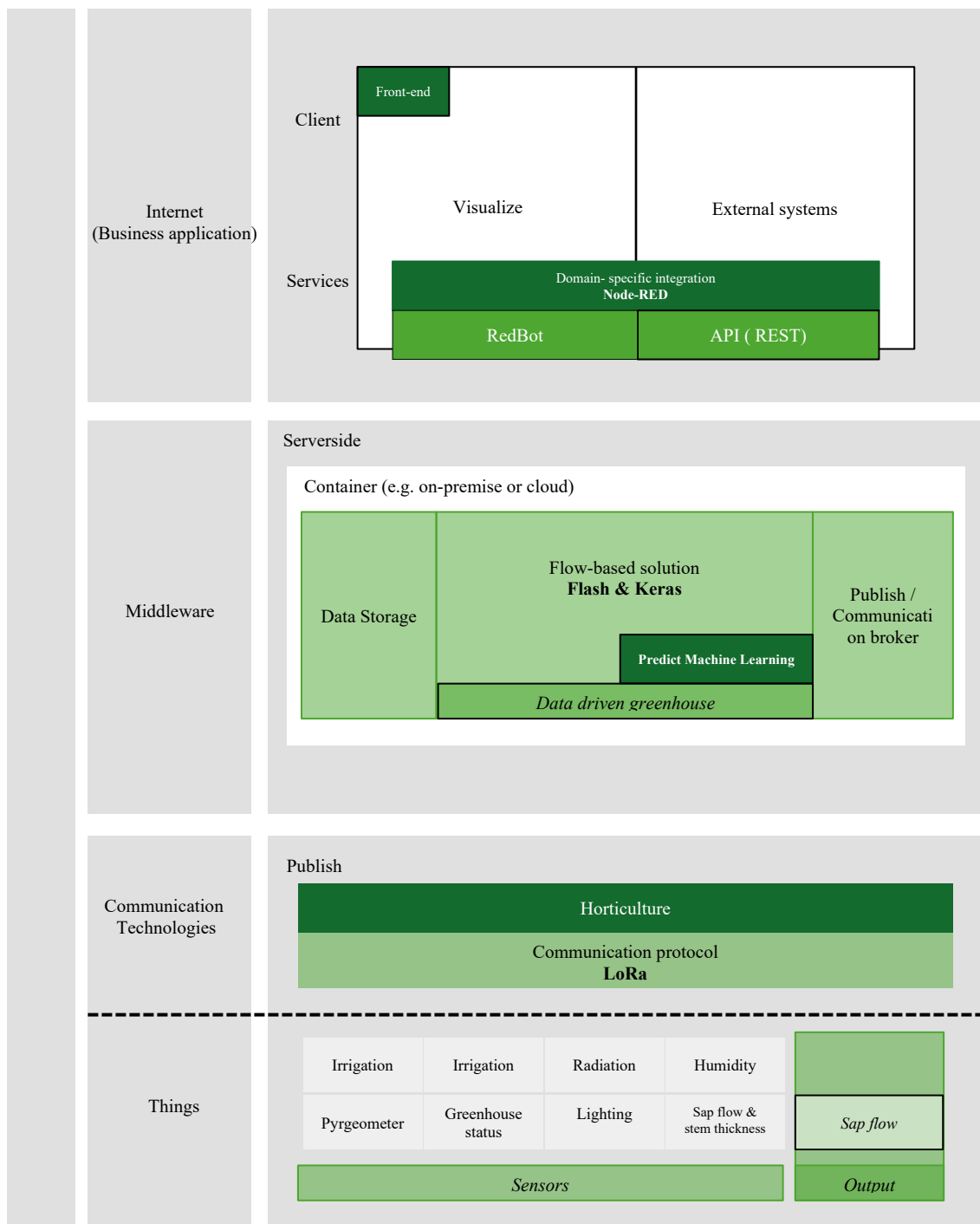


Figure 7. The Horti-IoT implemented according to Smart climate and sap flow resource water management optimization.

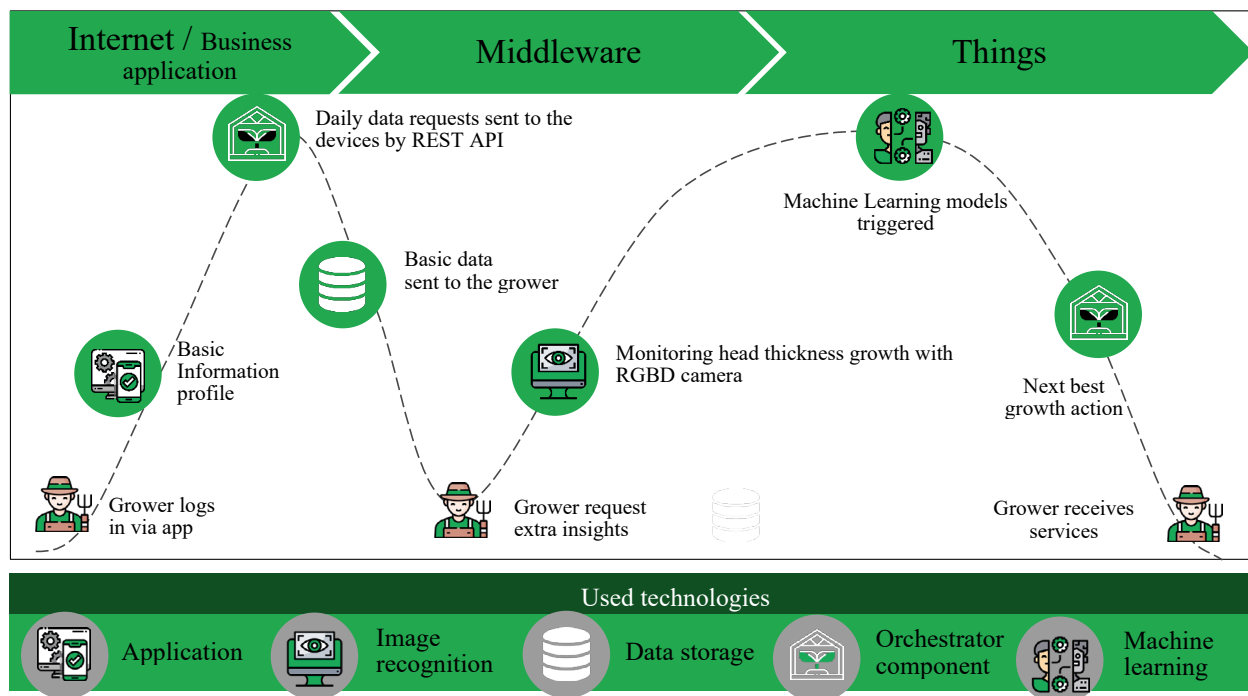


Figure 8. The Horti-IoT identify needs for monitoring head thickness growth smartly using RGBD camera (scenario 2).

into play. By utilizing data from cameras paired with machine learning algorithms, growers gain access to information and analyses, enabling them to effectively identify the most appropriate actions to optimize crop yield.

Assess device and decision-making ability: The RGBD depth camera (type 435) is installed in the ceiling above the crop. The camera points precisely at the plant's head thickness. The camera continuously takes images and streams them to the server. Images are displayed using the VNC viewer. Image pre-processing steps need to be done before training the model. Decision-making can take place after the computer vision algorithm trains the images.

Define the data principle rules, stakeholders and roles: The RGBD depth camera's configuration allows it to take images and send them to the server in less than 150 seconds. The system may run out of storage space as a result of that. Organize storage in high demand in general to prevent missing images. Maintaining internet connectivity is essential for system upkeep and proper image streaming. The source of energy suppliers is just as crucial as internet access. Generally, check the electricity and internet connectivity frequently to prevent the camera from entering offline mode. Using open-source AI software for image analysis and processing can be crucial for GDPR (General Data Privacy Regulation) sensitive data sharing. Sharing private or sensitive information should generally be avoided and private company data should be anonymized. Stakeholder roles must define a list of agreements regarding what and which data they can and will share.

Implement and deploy the model: The initial layer focused on uploading CSV files, facilitated through a secure login mechanism. A login and password functionality enriched data accessibility, while a dedicated dataset page allowed users to submit CSV files for predictive analysis. Frontend optimizations were implemented to enhance user experience and ensuring seamless functionality across various devices. Moving to the second layer, image pre-processing involves several essential tasks such as annotation, augmentation, scaling, masking, and filtering to prepare raw images for analysis by computer vision algorithms. Utilizing

open-source AI annotation tools streamlined this workflow significantly (Butt *et al.*, 2023). These tools offer automated or semi-automated annotation capabilities, enabling data analysts to annotate images more efficiently compared to manual methods. Moreover, they may include features for data augmentation, scaling, and filtering, further enhancing the pre-processing process. Establishing agreements on data anonymization practices is crucial to address concerns regarding sensitive information. By removing identifiable information and anonymizing sensitive linked data, growers can comply with privacy regulations while benefiting from insights generated by computer vision analysis. This ensures data privacy and security while facilitating efficient data analysis and decision-making. In the fourth layer, computer vision technology was deployed to analyze images captured by cameras installed in greenhouses or fields. This technology monitored various aspects of plant growth, including head thickness length, health, and environmental conditions. Tasks such as detecting pests and diseases, assessing plant growth parameters, and optimizing resource utilization can enhance agricultural practices (Figure 9).

Evaluate the model: The model's performance is evaluated by two scenarios: one incorporating the proposed data principles and the other without. The RGDB camera monitored head thickness 24 hours per week, capturing images every 2.5 minutes, which were then stored for analysis. For the evaluation of the Horti-IoT framework, 2000 images were selected. Adhering to the formatting principles of the Horti-IoT framework, each file was accompanied by metadata in accordance with the data principles. The annotation process, a crucial part of pre-processing, consumed significant time when done manually. Although open-source tools like Roboflow API (Butt *et al.*, 2023) to automate image annotation are available, they require datasets to be publicly available, such as those in the COCO (Common Objects in Context) dataset. However, due to privacy regulations and security limitations preventing the public upload of project images, manual annotation was necessary, resulting in substantial time consumption. Conversely, computer vision analyses facilitated automatic head thickness detection, saving time for labor and growers (Xu *et al.*, 2023) who would otherwise measure it weekly according to Dutch growth measurement protocols. Quantifying these impacts in terms of a specific percentage poses challenges as it varies depending on factors such as the greenhouse size and the crop type. The metadata accompanying the images, like the location, the date and the time, enabled analysts to delve deeper into further analysis, gaining valuable insights like determining the location of specific demands like disease or pest.

7. Key Findings, Recommendations and Conclusion

Some farmers are not equally able to utilize cutting-edge data tools. Enabling all agricultural stakeholders to take use of data frameworks requires bridging the digital divide.

The key findings following the implementation of the Horti-IoT framework's principles are as follows:

- (1) Reduced workload for data analysts: Applying the Horti-IoT framework's formatting principles significantly reduces data analysts' workload compared to pre-processing data sets without these principles. This indicates improved efficiency and streamlines data processing workflows.
- (2) Efficiency in plant monitoring: Utilizing camera technology and computer vision to monitor plant head thickness reduces field labor. This demonstrates the potential of IoT and AI technologies to automate agricultural monitoring tasks and improve productivity.
- (3) Time savings in image annotation: Implementing the Horti-IoT framework, particularly by leveraging open-source AI annotation tools and automation, results in time savings in pre-processing compared to manual methods. This highlights the effectiveness of AI-driven annotation processes in accelerating data preparation tasks.
- (4) Reduce water resource management: Monitoring sap flow with the Horti-IoT framework improve water resource management. This suggests IoT-enabled monitoring can contribute to more efficient water usage in agricultural operations.
- (5) Reduced system administrator contacts: Applying the principles of the Horti-IoT framework to data sets results in a significant reduction in attempts to contact system administrators compared to data

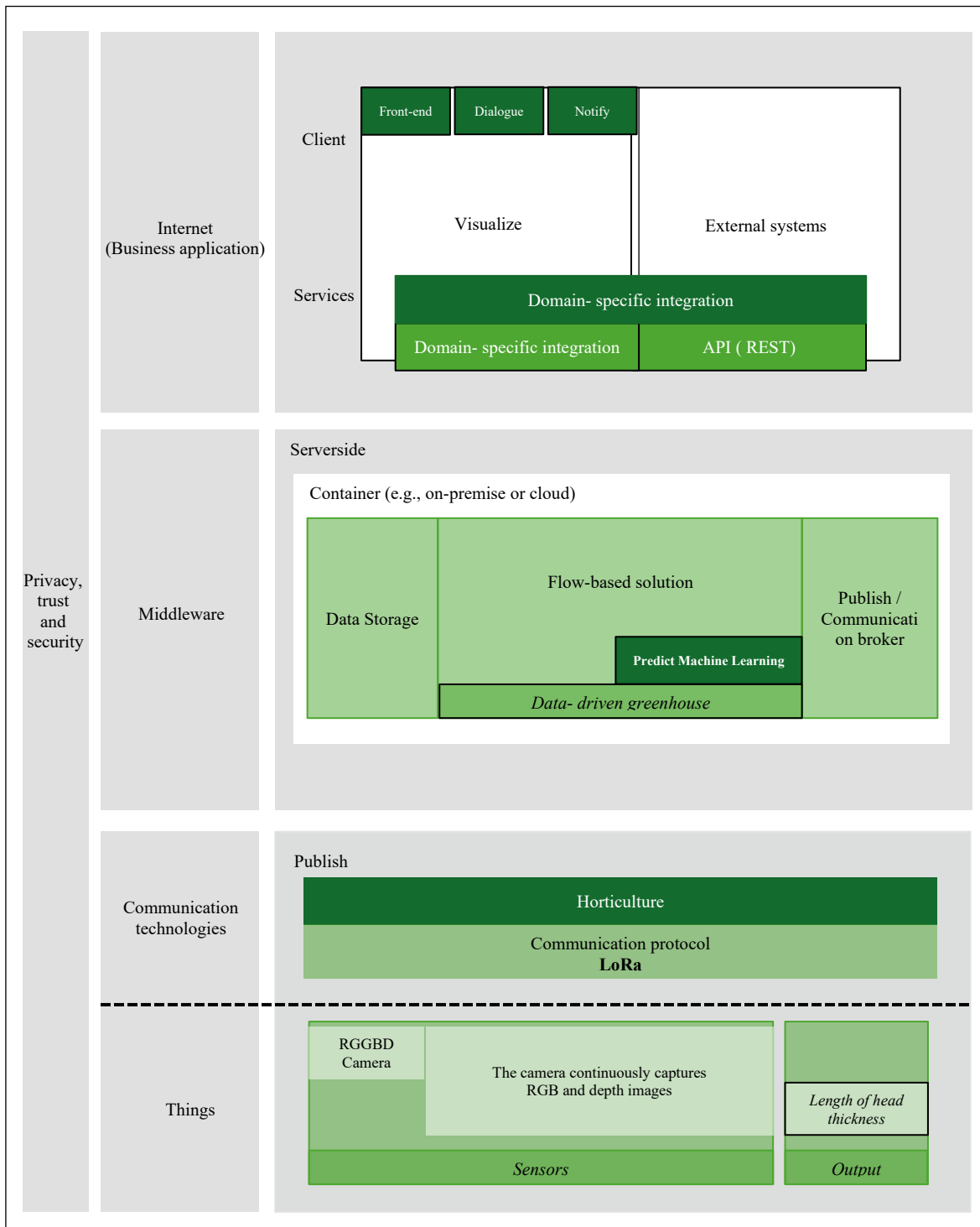


Figure 9. The Horti-IoT implemented for monitoring contactless head thickness growth using RGBD.

sets without these principles. This indicates improved data quality and reduced need for manual intervention.

- (6) Compliance with GDPR: Establishing agreements with project partners from the start is necessary to guarantee compliance with the General Data Protection Regulation (GDPR) for all layers of the framework design. This proactive approach protects the project from potential privacy breaches and legal issues.

Overall, these findings underscore the effectiveness of the Horti-IoT framework in optimizing data processing, automating monitoring tasks, improving resource management, reducing garbage-in garbage-out data, and ensuring regulatory compliance in IoT-based agricultural systems.

A significant scope that growers are currently searching for is the implementation of the concept of digital growing. Major's approach to achieve this is deploying computer vision, one of the most essential technologies. In this instance, data analysts will spend the most time on image pre-processing (annotation, augmentation, scaling, masking, and filtering). Recommendation from this study defines agreement on utilizing open-source AI annotation tools by removing any sensitive personal/ corporate information and anonymizing the sensitive linked information. This will significantly accelerate the pre-processing work for data analysts, saving time and speeding up decision-making.

Another preference scope from partners and stakeholders is having a unified plug-and-play system to connect IoT devices rather than using multiple APIs (Application Programming Interface), which is understandable and reflects a desire for simplicity, ease of use, and streamlined operations. Addressing the above preference of the partners and stakeholders will enhance the overall usability and effectiveness of the IoT ecosystem. Horti-IoT is the initial potential step solution to address this preference. Future work and recommendations for follow-up studies are significantly recommended.

The importance of cloud infrastructure must be addressed when it comes to overseeing the abundant data flow originating from Internet of Things (IoT) devices. This framework provides indispensable scalability and accessibility crucial for managing vast data volumes while upholding data security measures. Nevertheless, it is vital to recognize the considerable costs of accessing data from cloud services. Given the terabytes or more of data produced by assets, a robust data policy, efficient management, and clear vision are essential for effectiveness and cost efficiency. Facilitating the entire continuum, hastening decision-making, and optimizing the efficient utilization of amassed data within agricultural decision-making is paramount. Data exchange among stakeholders stands as the linchpin for achieving superior anticipatory outcomes and bolstering profitability. Stakeholders must delineate a comprehensive agreement framework specifying the nature and scope of shared data.

In conclusion, a solid foundation for the Horti-IoT framework is established by combining the DAMA-inspired data governance model with the IoT reference model for horticulture. By using the revolutionary power of IoT, this collaborative approach not only handles the complexities of data management but also pioneers a solution specifically designed for the horticulture sector. Combining the specialized IoT reference model with DAMA's well-established data governance principles results in a novel approach that has the potential to revolutionize data management practices within the horticulture industry. Automated decision-making for the, for example, water-given scheduling is the future work and is part of optimization for developing project digital growing.

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