

Development of a Hybrid Human-AI Personalised Learning Path for VET for Innovation in
Agriculture



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Module: Agriculture Software

Support Tools

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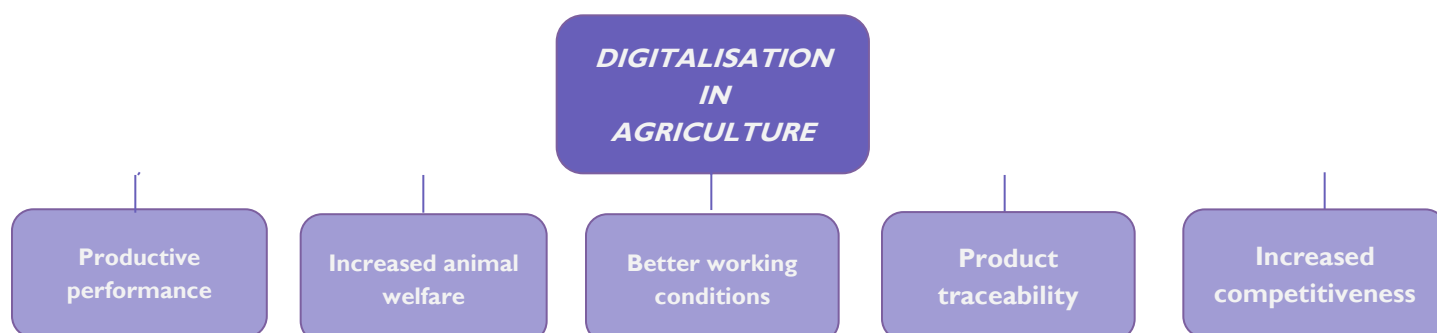
UNIT 1: INTRODUCTION TO SOFTWARE IN AGRICULTURE

Introduction

The global agricultural sector, particularly within Europe, is experiencing a transformative period as it takes on an essential role in mitigating environmental impacts amidst numerous challenges. The sector faces three primary challenges that significantly affect agricultural operations and sustainability. The first major challenge is climate change, which has fundamentally altered traditional seasonal patterns. Farmers now contend with extended periods of drought that alternate unpredictably with episodes of excessive rainfall, making traditional growing patterns less reliable. The second critical issue is the progressive degradation of soil fertility, which directly impacts crop yields and agricultural sustainability. The third challenge stems from ongoing price instability in agricultural markets, largely driven by geopolitical uncertainties that affect global trade and supply chains.

In response to these challenges, **digitalisation in agriculture** has emerged as a transformative solution, offering improvements across five key areas (Ref. 1):

Table 1: Digitalisation in agriculture: key areas



This module focuses specifically on examining the **software systems and technological tools** that farms can implement to achieve precision agriculture objectives. Precision agriculture is built upon two fundamental components:

- **Hardware:** This encompasses all physical equipment, including sensors, machinery, and monitoring devices that collect and transmit data from the field.
- **Software:** This comprises all programmes and applications that process data, control equipment, and provide decision support tools for agricultural operations.

Understanding Software in Agriculture

Before exploring how software enhances agricultural operations, it is essential to establish a clear understanding of what software encompasses in this context. At its core, software consists of organised collections of **programmes, files, and data structures** that work together to



perform specific functions. Within the agricultural sector, we focus primarily on **application software programmes** designed to help users accomplish specific tasks efficiently and precisely. Software systems can be broadly categorised into several types, ranging from operational software that enables basic system functionality (such as search engines and core applications) to specialised application software that can be installed on various devices (Ref. 2). Applications, commonly referred to as 'apps', are available in two main categories:

- For computers (such as **browsers** and **farm management systems**).
- For mobile devices (**smartphones** and **tablets**).

An important distinction exists between **traditional software systems** and **modern applications**. System software requires initial installation and configuration to enable basic device functionality. In contrast, contemporary applications can typically be acquired and installed through dedicated application stores, streamlining the deployment process. Whilst applications excel at performing specific tasks, comprehensive software systems offer more integrated and flexible functionality across multiple operations (Ref. 2). **Mobile applications** have transformed **agricultural management by enabling portable access to critical information and control systems**. These applications offer distinct advantages in modern farming operations. They provide the capability to access and input information from **any location**, provided there is **network connectivity**. Additionally, mobile applications are characterised by their **user-friendly interfaces**, making them particularly intuitive to use. Their cost-effectiveness is enhanced through cloud-based deployments and flexible licensing models, which we will examine in detail in the final unit.

Software's Critical Role in Sustainable Agriculture

Agricultural software systems are key to achieving sustainability in modern farming, **enhancing production efficiency** while **reducing environmental impact**. Through digitalisation, farming operations are guided by data-driven decisions that optimise resource use. For example, systems for monitoring soil health and crop development use sensors to create detailed field maps, allowing targeted interventions, such as pesticide application only in affected areas. This reduces waste, lowers costs, and minimizes environmental harm. These technologies also revolutionise animal husbandry by **continuously monitoring livestock health, enabling early disease detection** and **preventive measures, improving both animal welfare** and **farm productivity**. Furthermore, software automation reduces physical demands on workers, improving safety and allowing better resource allocation. **Blockchain technology enhances product traceability**, ensuring transparency in the supply chain and building consumer trust by documenting each product's journey from field to consumer. Through these innovations, digitalisation enhances environmental, social, and economic sustainability, improving resource management, working conditions, and global competitiveness.



Software in the European Vision

The **European Union** has positioned **digital technologies** and **software systems** as cornerstones in its strategy for agricultural transformation, recognising their essential role in achieving sustainable farming practices. Through a comprehensive framework of policies, funding mechanisms, and regulatory initiatives, the **EU actively supports the agricultural sector's digital evolution**. A landmark development in this strategic vision is the **Data Act** (Ref. 3), which represents a significant advancement towards establishing an integrated data market across the European Union. When this regulation comes into effect in September 2025, it will introduce fundamental changes to how agricultural data is managed and valued. The Act establishes principles for equitable distribution of data-generated value, ensuring that farmers and farms **can benefit fairly** from the information their operations generate. This legislation has been carefully crafted to promote the responsible utilisation of agricultural data whilst maintaining robust protections for privacy and individual rights within the existing regulatory framework. The Data Act is part of the **European Data Strategy**, focusing on **IoT adoption in agriculture**. It enables real-time data collection and analysis, improving resource management and emergency response. This digital transformation **supports both environmental sustainability and economic resilience** in the agricultural sector.

Data: The Foundation of Digital Agriculture

The effectiveness of agricultural technology systems relies on **high-quality data**, which supports informed decision-making. Farms generate unique, contextual data on soil, crops, climate, and machinery, which enables precise operational strategies. However, the sensitive nature of this data **requires strong protection to prevent misuse**, as it can be **commercially valuable** and **impact privacy**. Challenges include unclear data ownership and privacy protocols, causing hesitation among farmers to share data. Additionally, fragmented information systems create isolated data silos, hindering comprehensive analysis and decision-making. To address these challenges, the agricultural sector has implemented sophisticated security protocols. These include advanced encryption systems and stringent access controls that align with major regulatory frameworks such as the **Data Act**, **Data Governance Act**, and **General Data Protection Regulation** (GDPR). The adoption of security-by-design principles in agricultural software platforms has strengthened data governance practices and enhanced regulatory compliance. These combined technological and regulatory measures have significantly advanced the **AgriTech** sector's capability to innovate whilst maintaining robust security standards within the European policy framework (Ref. 5). The European Union has responded to these challenges by establishing comprehensive **regulations for agricultural data protection and sharing**. The Data Act specifically addresses the usage of information collected through IoT devices, mandating **explicit owner consent for data utilization**. This regulatory framework creates essential safeguards against unauthorized access and privacy breaches, whilst promoting responsible data sharing practices that benefit the entire agricultural sector. The European Union has responded to these challenges by establishing comprehensive regulations for agricultural data protection and sharing. The Data Act specifically addresses the usage of



information collected through IoT devices, mandating explicit owner consent for data utilization. This regulatory framework creates essential safeguards against unauthorized access and privacy breaches, whilst **promoting responsible data sharing practices** that benefit the entire agricultural sector.

GDPR plays a key role for farmers who intend to use precision farming software because it ensures that the data collected (e.g. geolocation, yields, use of agricultural inputs) are processed transparently, securely and in compliance with the privacy of farmers. In fact, since personal or farm-related data are sometimes used by third parties (e.g. software providers or insurance companies), farmers must be able to know and control how and by whom they are used (European Data Protection Board (EDPB), Guidelines on the concepts of controller and processor in the GDPR).

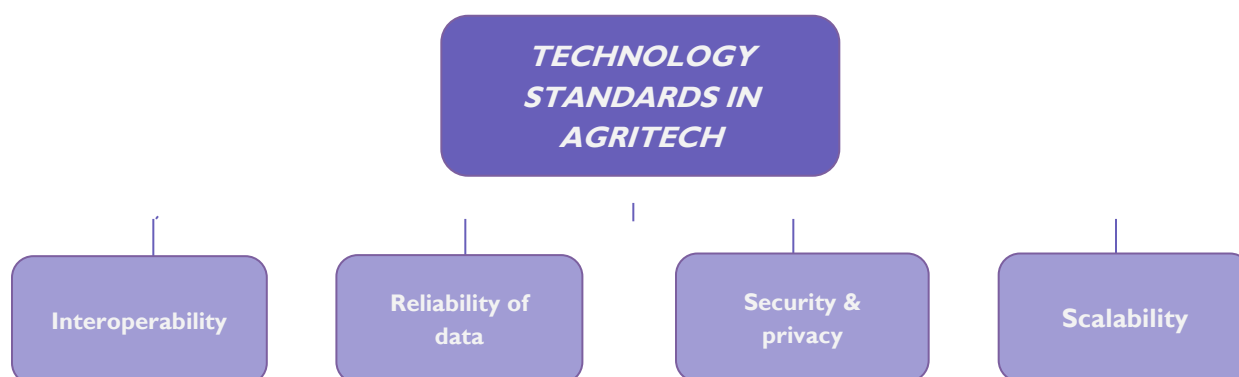
The adoption of digital technologies in agriculture requires transparency, clear definition of data ownership and trust between the actors in the supply chain (Van der Burg et Wiseman, 2021). The GDPR helps prevent inappropriate use of data, thus increasing the level of trust on the part of farmers in the use of such software. Through this structured approach to data management, modern agriculture can harness the power of information technology whilst **protecting the interests of farmers** and **maintaining the security of sensitive agricultural data**.

Technology standards

Technology standards in the Agritech sector encompass a comprehensive framework of **protocols, specifications, and methodologies** that enable seamless **integration between diverse agricultural systems and technologies**. As noted by (Ref. 5), these standards form the foundation for interoperability across the agricultural technology landscape, ensuring that various systems and equipment can communicate and function together efficiently.

In the AgriTech domain, technology standards are characterized by four essential attributes:

Table 1: Technology standards in agritech



operations. They significantly enhance data accessibility between different systems whilst **reducing the overall complexity** of the agricultural technology ecosystem. By eliminating



compatibility issues between various components, these standards improve operational efficiency for farmers. Furthermore, they facilitate greater sustainability by enabling the implementation of environmentally conscious farming techniques through software systems capable of **processing diverse data types from multiple sources**.

Within the agricultural technology landscape, several key types of technology standards have emerged as essential components:

- **GNSS (Global Navigation Satellite System);**
- **Data standards;**
- **IoT standards;**
- **ISOBUS.**

Through these standardised frameworks, agricultural technology systems can achieve the necessary integration and functionality required for modern farming operations.

Software integration and data management in agriculture

Data analysis has become a cornerstone of modern agricultural operations, driven by three fundamental imperatives. From an environmental perspective, **precise data tracking** enables farmers to **minimise product wastage and reduce negative environmental impacts**. The economic benefits emerge through the analysis of agronomic data, which enables enhanced yield optimisation whilst ensuring that **only essential technical resources** are deployed in cultivation, thereby **controlling production costs**. The operational advantages manifest in the ability to develop targeted strategies based on predictive analyses of potential crop threats (Ref. 6). However, the mere availability of diverse data streams presents challenges without proper integration tools. **Enterprise Resource Planning (ERP)** systems have emerged as a crucial solution, providing farms with **immediate access to precise**, timely information for comprehensive process management. These systems are distinguished by two primary characteristics:

- **Integrated functionality:** All data entered into the system becomes instantly available across all modules through seamless integration within the unified ERP framework;
- **Multifunctionality:** The system coordinates multiple operational processes under a single platform, encompassing crop planning, warehouse management, financial operations, sales, procurement, and other essential functions.

Whilst **ERP systems** were historically perceived as having limited applicability in the agri-food sector, contemporary solutions now effectively streamline various agriculture-specific processes (Ref. 7). These sophisticated management systems, which will be explored in detail later in this unit, represent a significant advancement in agricultural software capabilities.

The agricultural software landscape encompasses **various specialised tools** that transform raw data into actionable insights for farmers. These solutions can be categorised into four distinct types:



- **Connection software between systems:** Exemplified by ISOBUS, which facilitates seamless communication between equipment from different manufacturers;
- **Analysis and decision support software:** Including Decision Support Systems (DSS) that process complex datasets to generate operational guidance;
- **Business management software:** Designed for comprehensive planning and operational tracking;
- **Software for traceability and e-commerce:** Enhancing supply chain transparency and enabling direct market access.

In conclusion, software systems have become indispensable tools in the modernisation and sustainable development of the agricultural sector. Their integration with progressive European policies, such as the Data Act, and advanced technologies like IoT, creates unprecedented opportunities for **enhancing operational efficiency, minimising resource waste**, and addressing global agricultural challenges through sustainable practices.

Internet of Things (IoT) in agricultural systems

The **Internet of Things** represents a transformative technology that extends internet connectivity beyond traditional computing devices to everyday objects, creating **'smart' devices with unique digital identities**. These digitally enhanced objects **establish a network of interconnected devices** capable of autonomous communication and data exchange. The implementation of IoT in agriculture has yielded significant **improvements in both product quality and quantity**, whilst simultaneously optimising operational costs and enhancing farm profitability (Ref. 8). A particularly significant development has been the creation of a seamless human-machine-object interconnection framework, enabling farmers to exercise swift and dynamic control over their agricultural equipment and devices. This **advanced level of control** is achieved through stable, wireless data transmission networks that **connect various digital identities** across the farm. In practical applications, IoT manifests through physical objects equipped with digital capabilities, such as field sensors or machinery-mounted monitoring devices. These systems collect cultivation data and transmit it to centralised management systems for analysis and action.

Agricultural IoT systems serve three primary functions:

- **Data collection and transmission from cultivation devices**, including critical measurements such as soil moisture levels;
- **Implementation of automated cultivation systems**, encompassing irrigation management and livestock feeding operations;
- **Comprehensive tracking of agricultural operations and processes.**

A notable advancement in IoT communication technology is the **Long Range Wide Area Network (LoRaWAN) protocol**. This protocol has gained widespread adoption due to its capability to maintain reliable information exchange across substantial distances and through



various physical obstacles, making it particularly suited to agricultural applications (Ref. 9). The ability to track operations in real time has become **increasingly vital in modern farming**. This capability ensures farmers maintain continuous awareness of all farm activities and operational status. Such tracking proves especially valuable in specialised agricultural operations, such as livestock transport or the movement of products that must comply with specific regulatory standards. Through IoT systems, farmers can monitor these operations continuously, ensuring compliance and maintaining product quality throughout the transportation process.

Practical Cases

To illustrate the practical implementation of IoT systems in agriculture, let us examine two representative case studies that **demonstrate how this technology addresses specific operational challenges**. The first case study involves a fruit and vegetable farm managing the distribution of perishable produce to retailers and trade fairs. The critical challenge in this operation is maintaining an unbroken cold chain throughout the transportation process. IoT technology provides a comprehensive solution through a network of sensors installed throughout cold storage facilities and transport vehicles. These sensors enable farmers to monitor temperature conditions remotely and continuously, ensuring product freshness and quality. Beyond temperature monitoring, the IoT system collects data on various transportation parameters. The system tracks fuel consumption, vehicle performance, and route efficiency, providing insights into both environmental impact and operational costs. This comprehensive data collection enables the farm to conduct comparative analyses of different transportation methods and routes, facilitating informed decisions about the most cost-effective and environmentally sustainable logistics solutions. The second case study examines bulk grain storage operations, specifically focusing on safety systems for large-scale silo facilities storing wheat or barley. These operations face two significant safety risks: mechanical blockages in conveyor systems and potential fire hazards in storage areas. To address these challenges, an innovative IoT-based monitoring system has been developed (Ref. 10). This safety system employs a network of wireless sensors strategically positioned throughout the storage and transport equipment. These sensors continuously monitor various parameters, including equipment performance, temperature levels, and material flow rates. The data collected is processed through intelligent monitoring systems that can detect early warning signs of potential problems. When the system identifies concerning patterns or conditions that might indicate an impending blockage or safety risk, it automatically triggers alerts to facility operators, enabling preventive intervention before incidents can occur. These case studies demonstrate how IoT technology transforms agricultural operations by providing real-time monitoring capabilities, enhancing safety measures, and enabling data-driven decision-making across various aspects of agricultural production and distribution.



UNIT 2: SOFTWARE FOR PRECISION AGRICULTURE

Introduction

Modern agriculture stands at the threshold of a technological revolution through precision farming methods, which transform traditional agricultural practices into data-driven, resource-efficient operations. This unit explores the essential software systems that enable this transformation and examines how they work together to create comprehensive farming management solutions. Precision agriculture represents a sophisticated approach to farm management that harnesses advanced technologies, such as positioning systems, semi-automated guidance, robotic and data acquisition sensors, to achieve optimal resource utilisation whilst enhancing productivity through sustainable methods (Ref. 11). At its core, this approach relies on the seamless integration of several key technological systems that work in concert to provide farmers with unprecedented control over their operations.

The foundation of precision agriculture rests upon **Global Navigation Satellite System (GNSS)** technology. These positioning systems serve as **the cornerstone for precise agricultural operations** by providing exact location data for farm machinery. This capability proves invaluable across numerous farming activities, from initial soil preparation to final harvest. When a tractor moves across a field, GNSS technology enables it **to maintain precise positioning**, ensuring that operations such as **seeding, fertiliser application, and crop protection measures** are executed with remarkable accuracy. Working in tandem with GNSS, **Geographic Information System (GIS)** technology **transforms raw location data into meaningful agricultural insights**. By integrating GNSS positioning with detailed spatial analysis capabilities, GIS creates sophisticated **field maps** that **reveal variations in soil conditions, crop health**, and other crucial agricultural parameters.

These detailed visualisations enable farmers to identify specific areas within their fields that require particular attention or different management approaches. Understanding these fundamental technologies – GNSS and GIS – establishes the necessary foundation for exploring more **advanced precision farming software systems**. These include sophisticated satellite guidance systems that automate machinery operation, variable rate application technologies that adjust input application based on field conditions, and **ISOBUS systems (ISO 11783)** that enable seamless communication between different agricultural machines and implements. The integration of these three core technologies – GNSS, GIS, and ISOBUS – creates a powerful framework for agricultural management. This unified system enables farmers to execute farming operations with unprecedented precision, significantly reducing waste and operational costs while minimising environmental impact. As global agriculture faces increasing challenges from climate change, resource scarcity, and growing food demand, these precision farming tools become not merely beneficial but essential for sustainable agricultural production.



Understanding Global Navigation Satellite Systems (GNSS)

Global positioning systems, collectively known as GNSS (Global Navigation Satellite System), originated from military technology developed by the United States. What began as the **Navastar** system has evolved into several global positioning networks, each operated by different nations or entities:

1. **GPS (Global Position System)**: Operational since 1995, this **United States system** remains the most widely used positioning network worldwide;
2. **GALILEO**: The **European Union's** contribution to global navigation, operational since 2016;
3. **GLONASS**: **Russia's** Global Navigation Satellite System;
4. **BEIDOU**: **China's** satellite navigation system.

Given its widespread adoption, the GPS system serves as an excellent model for understanding how these positioning systems function. GPS operates through the **coordinated interaction** of three distinct segments:

- **Spatial segment;**
- **Control segment;**
- **User segment.**

These segments work in continuous harmony, exchanging data in a carefully orchestrated process. The spatial segment **receives information from the control segment, measures temporal data, and transmits positioning signals to the user segment.** This intricate dance of data relies on sophisticated mathematical models that, through careful calibration by the control segment, calculate precise satellite positions and velocities. The control segment consists of six strategically positioned stations along the Earth's equatorial belt. These stations serve two critical functions: **analysing satellite positions** and **maintaining data backups.** When satellites pass overhead, the stations measure several crucial parameters:

- **Satellite velocity;**
- **Trajectory patterns;**
- **Orbital height;**
- **Additional relevant metrics.**

These measurements undergo processing through sophisticated mathematical models at each station. The user segment encompasses all equipment capable of receiving, storing, and processing GPS signals. These signals contain two fundamental elements: code and phase. The code manifests as a recognisable square wave, while the phase appears as a sine wave. Satellites transmit these signals via two carrier frequencies, designated L1 and L2, each with distinct wavelengths. Individual satellites generate unique codes, enabling position determination with **accuracies of 5-10 metres. GPS determines position by measuring the transmission time of bit sequences sent from satellites to Earth.**



This process requires precise synchronization between two atomic clocks – one aboard the satellite and another in the receiver. However, since equipping GPS receivers with atomic clocks proves impractical, time calculations rely on mathematical processing systems. Additional analysis and coordinate conversions then yield the final position. Phase measurements offer an alternative method for position determination, though they require different processing approaches due to uncertainties in calculating cycle numbers between satellites and receivers. **Positioning accuracy depends** on several factors, including **receiver characteristics** (measurement duration and detection method) and **satellite geometry**. In precision farming applications, where GPS monitors moving equipment, inherent system limitations mean no receiver can achieve accuracy better than 5-10 metres without correction. Farmers can improve accuracy through both differential and non-differential correction techniques, which help mitigate these positioning errors. This sophisticated system of global positioning has transformed modern agriculture, enabling precise field operations and resource management that would have been impossible just decades ago.

GIS and Prescription Maps

Understanding soil variability presents one of the fundamental challenges in modern agriculture. Agricultural land rarely maintains uniform properties across its entirety; instead, it typically exhibits significant **variations in nutrient availability** from one area to another within the same field. This inherent variability creates a critical challenge in agricultural management. Traditional farming methods that apply uniform rates of fertiliser across an entire field fail to account for this natural variation. Such approaches inevitably result in some areas receiving excess nutrients while others remain undernourished. This inefficiency not only wastes resources but can also lead to environmental issues in over-fertilised areas while reducing yield potential in undernourished sections. The solution lies in adopting a more nuanced approach to cultivation operations, one that acknowledges and responds to **the heterogeneity within individual plots**. Farmers can now access various sophisticated tools **to create detailed soil maps**, including topographical surveys, electromagnetic induction, electrical conductivity and resistivity measurements, gamma ray analysis, ground-penetrating radar, production sensor data, and spectroscopic analysis (Ref. 12). Modern software systems have revolutionised this mapping process **by generating comprehensive terrain maps and associated data essential for planning precise cultivation operations**. At the heart of this technological **advancement lies the Geographic Information System (GIS)**. While GIS has found applications across numerous sectors, its adoption in agriculture has grown significantly in recent years. GIS functions as an integrated system that **collects, stores, and processes spatial data**, enabling sophisticated analysis, transformation, and visualisation of agricultural landscapes (Ref. 13). The system relies on georeferenced spatial imagery that can provide detailed data about soil conditions at various depths. **In precision agriculture, GIS is valuable for creating multi-layered digital maps** representing soil nutrients, moisture, pest levels, and crop yields. Integrating these layers helps farmers identify field areas needing specific management.



Prescription maps generated via GIS are essential for advanced farming technologies like Crop Technology, allowing precise planning that leads to:

- **Optimised resource use and better economic returns;**
- **Greater environmental sustainability;**
- **Reduced use of pesticides;**
- **More efficient fertiliser application.**



Figure 1: Digital field map

Satellite guidance systems in precision agriculture

Modern precision farming relies heavily on **satellite guidance systems** to achieve **exceptional accuracy in field operations**. These systems enable farm machinery operators to maintain **precise parallel paths during various agricultural tasks**, from initial soil preparation to final harvest. This precision proves invaluable across the full spectrum of farming operations, including **tillage, seeding, fertiliser application, crop protection measures, and harvesting**. The primary advantage of satellite guidance lies in its **ability to minimise pass overlaps and eliminate gaps in field coverage**. This precision delivers significant **benefits in both economic and environmental terms**. By reducing overlaps, farmers achieve meaningful **reductions in fuel consumption**, decrease the usage of agricultural inputs, and minimise equipment wear.

Additional benefits include **reduced soil compaction** and the ability to continue operations even in conditions of poor visibility, such as dust, fog, or darkness. While current technology cannot completely eliminate pass overlaps, modern systems have reduced them significantly. Today's systems typically **maintain overlap rates around 10%**, though this figure **may increase to 30%** when working with **irregular or smaller field configurations**. Understanding how these guidance systems function requires examining the three primary types of satellite guidance technology available to farmers. Assisted driving represents the entry-level solution, offering a cost-effective approach to precision guidance. This system employs sensors mounted on agricultural machinery to determine the equipment's position and calculate optimal trajectories that **minimise surface overlap**.



The system communicates guidance information to the operator through either a light bar or **digital display**, showing the recommended path, areas already covered, and remaining work zones (Ref. 14). **Semi-automatic driving**, also known as parallel driving, incorporates more sophisticated technology into the vehicle's control systems. This advanced setup includes **real-time trajectory correction capabilities** that eliminate delays associated with operator response times, thereby reducing positioning errors. Semi-automatic systems offer two primary steering control options: **electric steering** and **hydraulic steering**. Electric steering systems employ mechanical control devices that eliminate the inconsistencies typically associated with manual steering inputs. The more advanced hydraulic steering systems replace mechanical controls with sophisticated hydraulic systems, **offering superior performance albeit at a higher cost**. To achieve precise positioning, these guidance systems rely on three main correction technologies:

- **GPS (Global Positioning System)** provides basic positioning with accuracy within 30 centimetres, though performance can vary based on satellite availability and vehicle speed;
- **DGPS (Differential Global Positioning System)** achieves improved accuracy of approximately 10 centimetres by incorporating correction signals from geostationary satellites;
- **RTK (Real Time Kinematic)** represents the pinnacle of precision, maintaining accuracy within 2 centimetres through correction signals transmitted via radio waves or UMTS networks.

The economic viability of satellite guidance systems varies with farm size and operation type. These systems prove particularly valuable for **medium to large-scale arable operations and agricultural contractors**. However, the substantial initial investment, particularly for semi-automatic systems, may prove challenging for smaller farming operations. For operations where traditional GPS-based systems might prove cost-prohibitive, alternative guidance technologies exist. These include mechanical sensors, optical systems, and 3D cameras. These more affordable solutions use existing crop rows as reference points for real-time trajectory corrections, offering a cost-effective approach to precision guidance. Through this sophisticated integration of satellite technology and agricultural machinery, modern farming achieves levels of precision that significantly improve both operational efficiency and environmental sustainability.

Variable Rate Technology (VRT) distribution systems

Variable Rate Technology (VRT) distribution systems represent an advanced solution to address the **natural variability present in agricultural fields**. These sophisticated systems enable farm machinery to adjust the application **rates of agricultural inputs automatically**, responding to **specific soil conditions and crop requirements across different areas** of the field. This precise control over input distribution marks a significant advancement from traditional uniform application methods. These versatile systems **can be integrated into a wide range of agricultural equipment**, including seeders, transplanters, sprayers for pests



treatments, fertiliser spreaders, and irrigation systems. However, effective implementation of VRT requires a comprehensive suite of supporting technologies. The system relies on the coordinated operation of several key components: precision sensors, sophisticated control units, satellite receivers, and automated actuators. At the heart of the system, typically housed in the machine cabin, sits a central control unit. This unit processes **incoming data about various field locations in real time**, continuously adjusting the flow rate of agricultural inputs during operation. VRT systems can operate through two distinct approaches: **using pre-prepared prescription maps** or **relying on real-time sensor data** (Ref. 15). The prescription map approach requires careful preparation of detailed field maps that document various soil characteristics and crop requirements. This method depends heavily on precise machine localisation, as the system must constantly relate the equipment's current position to the corresponding zone on the prescription map. The operating machine then varies its distribution rate based on its location and the requirements specified in the prescription map. To implement this approach effectively, the machinery must be equipped with advanced tracking systems. The field must be divided into homogeneous zones, each with specified distribution rates. As the machine moves across the field, it automatically adjusts product application rates between these zones. This adjustment occurs through an actuator that controls the implement's **opening mechanism or volumetric control system**, responding to commands from the onboard computer based on position data from the satellite receiver.

The sensor-based approach offers an alternative method for variable-rate distribution. This system employs indicators derived from real-time data about soil characteristics or crop conditions, collected through an array of sensors. Optical sensors play a particularly crucial role in this approach. These sensors continuously gather data and transmit it to the processing unit, which then instructs the actuator about appropriate application rates. Since this method primarily **relies on immediate crop condition data**, it can often operate without the need for precise position tracking (Ref. 16). VRT systems have proven particularly valuable in several key agricultural operations, including **precision seeding** and the **application of granular fertilisers**. Through their ability to adjust input rates automatically based on field conditions, these systems help farmers **optimise resource use** while **maintaining crop productivity**. This technology represents a significant step forward in precision agriculture, enabling farmers to apply exactly what is needed, where it is needed, thereby improving both economic efficiency and environmental sustainability.

Production Mapping in Modern Agriculture

Data analysis is essential in modern farm management, and production mapping is a key tool for **understanding field performance** and **planning strategies**. By capturing and analyzing detailed production data, farmers can identify patterns, assess seasonal variations, and make informed decisions. Precision agriculture software has evolved to capture real-time harvest data, allowing farmers to measure yields by specific areas within fields and simplifying data management. **Production mapping** helps farmers understand **field variability**, enabling effective precision



farming techniques and contributing to both economic and environmental sustainability. It aligns with Green Deal and Farm to Fork objectives and enhances product traceability throughout the supply chain. Modern software also quantifies by-product production, supporting sustainable farming practices and circular economy principles. Today's mapping systems use advanced sensor networks installed on harvesting machinery, providing real-time yield data, moisture levels, and quality parameters. The system **georeferences data** with high accuracy using **GNSS satellite receivers** and **RTK correction**, ensuring precise yield measurements and optimized resource management. Production detection typically employs ultrasonic sensors mounted on the harvesting bar, though placement varies by machinery type. These sensors measure grain flow through two primary methods:

- **Impact measurement:** Sensors detect individual grain impacts, converting them into quantity measurements;
- **Volume measurement:** Systems calculate yield by measuring the time required to collect specific quantities (Ref. 17).

Proper sensor calibration remains crucial for **maintaining accuracy**. The system must also account for a 10-20 second delay between crop cutting and sensor detection. **Advanced software compensates for these delays** and other variables, such as **external moisture conditions** that might affect readings, to provide accurate yield data. To illustrate this technology in practice, consider cereal harvesting, where this technology finds widespread application. A modern combine harvester takes yield measurements nearly every second, with **each measurement precisely georeferenced**. The system calculates area-specific yields by dividing the measured production by the harvested area, determined through working width sensors and speed measurements. The mapping software then generates detailed "**areal yield**" values for each field point, with the option to convert measurements to dry matter basis using moisture sensor data.

Through this sophisticated integration of sensors, satellite technology, and data processing, production mapping provides farmers with unprecedented insight into their field performance, enabling more precise and efficient agricultural management practices.

ISOBUS

Modern farming operations often involve multiple pieces of sophisticated equipment working in concert. **ISOBUS** represents a groundbreaking **standardised communication protocol** that enables these various agricultural machines and implements to communicate effectively **using a shared language**. This international standard, formally known as ISO 11783 'Tractors and machinery for agriculture and forestry - Serial control and data networks for communication', emerged in the mid-1990s as a response to the growing complexity of agricultural equipment integration (Ref. 18). The development of ISOBUS technology addressed a significant practical challenge faced by farmers as agricultural equipment became increasingly digitalised. Before



ISOBUS, operators needed separate control devices for each piece of electronic equipment in their tractor cab, creating a cluttered and inefficient working environment. ISOBUS revolutionised this situation by introducing a **unified system capable of managing various electronic machinery** and implements through a **single interface**. At the heart of this system lies the 'Universal Terminal', which serves as a **centralised control centre**, automatically managing all signals detected by **working implements during operation**. This unified control becomes possible when all implements are **ISOBUS-compatible**, enabling simultaneous communication between implements and the primary machine. This level of integration provides farmers with unprecedented automation capabilities while **optimising both agronomic performance and environmental sustainability** by allowing precision farming systems to operate synergistically.

An ISOBUS system comprises four essential components, three of which are fundamental to its operation:

- **Implement ECU** (Electronic Control Unit) manages individual implements;
- **Tractor-ECU coordinates** overall system operation;
- **Universal Terminal** (UT) provides the operator interface;
- **Joystick**, while optional, enhances system usability.

The **Agricultural Industry Electronics Foundation** (AEF) has established **standardised functionalities** within ISOBUS systems, complete with **specific symbology**. This standardisation ensures that electronic equipment can communicate through common language elements, making it crucial for farmers to select products with compatible AEF functionality (Ref. 19).

Key ISOBUS functionalities include:

- **Universal Terminal (UT)**: Enables centralised control of all equipment or distributed control through multiple terminals;
- **Task Controller Basic (TC-BAS)**: Facilitates import of work performance data from equipment;
- **Auxiliary Control systems (AUX-O and AUX-N)**: Provide additional control options for complex devices, with 'O' indicating older systems and 'N' representing newer ones;
- **Geo-based Task Controller (TC-GEO)**: Captures position-related data;
- **Basic Tractor ECU (TECU)**: Monitors essential parameters like speed and power take-off;
- **Task Controller Section Control (TC-SC)**: Manages automatic section control based on GPS positioning (Ref. 19).

One of ISOBUS's most valuable features is its modularity, allowing farmers to expand their systems over time as needs evolve. When components connect, individual **ECUs transmit**



their operational requirements to the **tractor's central bus**. Regardless of manufacturer or model, operating machines send standardised commands to the tractor cab monitor, ensuring consistent operator interface across different equipment types. This sophisticated integration of agricultural machinery through ISOBUS represents a significant advancement in farming technology, enabling **more efficient** and **precise agricultural operations** while **simplifying** equipment management for operators. The system's standardised approach ensures compatibility across manufacturers, making it easier for farmers to build integrated, efficient farming systems that can evolve with their needs.

UNIT 3: SIMULATION MODELS AND DSS AGRICULTURE

Introduction

This unit examines the integration of **simulation models** and **Decision Support Systems (DSS)** within modern agricultural management frameworks. Precision agriculture fundamentally depends upon the synergy between advanced computational technologies and spatial data analytics to optimise agricultural resource allocation, enhance productive efficiency, and minimise environmental impacts. Within this technical framework, simulation models and DSS serve as essential computational tools for analysing and forecasting complex agricultural scenarios with statistical rigour. Simulation models systematically **replicate the interactions between agronomic variables, climatic parameters** and **management decisions**, enabling quantitative analysis of their effects on crop development and yield. Through the integration of these models with real-time data streams, DSS generate evidence-based operational recommendations, facilitating precise resource management across critical inputs such as irrigation water, fertiliser applications, and pest control measures. These computational systems **transform raw agricultural data into actionable intelligence**, enabling farm managers to implement decisions based on robust analytical frameworks whilst promoting sustainable resource utilisation.

Simulation Models

Agricultural crop simulation models represent sophisticated computational frameworks that **reproduce crop physiological processes** in response to environmental variables. These models process complex environmental inputs including thermal gradients, atmospheric humidity, and edaphic characteristics **to simulate crop development and yield responses** (Ref. 20). **The integration** of diverse sensor networks, encompassing meteorological monitoring systems and soil analysis sensors, enables these models to process multidimensional data streams, providing farmers with comprehensive analytical insights. Effective model implementation **requires extensive environmental data collection**, including detailed soil



physicochemical properties, meteorological parameters, and potential pathogenic pressures that may impact crop development (Ref. 21).

Simulation models in agriculture can be categorised based on their computational approach to variable processing and temporal dynamics:

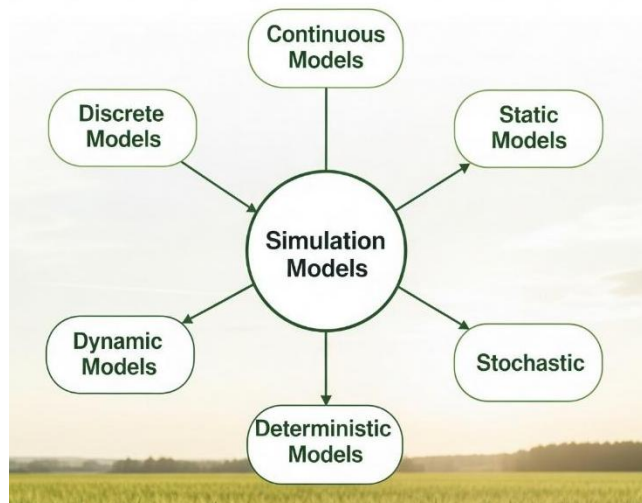


Figure 2: Simulation models

The selection and implementation of appropriate simulation models requires careful consideration of **multiple factors**. Model selection depends primarily on the specific analytical requirements and crop characteristics under investigation. **Crop-specific models** offer enhanced **precision through detailed parameterisation** for particular species. Implementation follows a systematic process: initial model calibration establishes precise parameter estimates, followed by rigorous validation procedures. Validation methodologies encompass both

expert-based subjective assessment and statistical validation using quantitative indices.

To illustrate this framework, consider a nitrogen fertilisation model. Such a model must incorporate **multiple parameters** to accurately simulate nitrogen dynamics. For example, these parameters include:

Table 2: types of multiple parameters

Parameters	Description
Soil N concentration	Quantitative measurement of available nitrogen in different soil horizons
Organic matter concentration (OM)	Assessment of soil organic content affecting nitrogen mineralisation rates
Mineral N distribution	Spatial analysis of nitrogen compounds throughout the soil profile
Soil hydrological constants	Key parameters including field capacity, wilting point, and hydraulic conductivity.
Evaporation	Measurement of water loss from soil surface and water bodies
Air and soil temperature	Continuous monitoring of thermal gradients affecting biological processes
Mineralisation index	Rate of organic nitrogen conversion to plant-available forms



Crop N absorption	Temporal patterns of nitrogen uptake by specific crop varieties
Crop water absorption	Water uptake patterns affecting nutrient transport and availability

Example of simulation model realisation

Having explained how this works, in order to better understand how factors play a role in the application of the simulation model, let us now give an example of how a simulation model for fungal diseases is developed. Simulation models for early detection of fungal diseases provide significant agricultural benefits through **optimised timing** and **reduced pesticide applications**, ultimately protecting seasonal yields (Ref. 22). The development process begins with clear problem definition, considering both **economic parameters** and **integrated production (IPM) requirements**. The next phase involves creating a detailed flow chart through systems analysis, examining each stage of the infectious process. This approach enables precise definition of system states and identification of transition factors between states (Ref. 21). The development of a simulation model for managing fungal diseases in agriculture involves several key phases. Initially, the problem is clearly defined by analyzing the disease's biological cycle and the key variables influencing infection dynamics, such as environmental conditions, infection stages, and spread. This phase includes creating detailed flowcharts to represent the interactions among system components. Next, this information is translated into precise mathematical equations that drive the computerized model, enabling accurate quantitative simulations. **Model validation** involves comparing predictions with historical data and meteorological observations, while field verification ensures simulations reflect real agricultural conditions. Once completed, the model can be used as a standalone tool or integrated into more complex decision support systems, providing valuable assistance to farmers in effectively predicting and managing fungal disease outbreaks, optimizing pesticide use, and protecting yields. Integration into decision systems also allows combining multiple models and data sources, enhancing analysis capabilities and prediction accuracy. This systematic approach ensures more sustainable and targeted disease management, reducing costs and environmental impact. Finally, **continuous updating and adaptation of the model** to new data and conditions guarantee its long-term effectiveness.

Decision Support Systems (DSS)

The capabilities of a simulation model can be enhanced by integrating it into an advanced **Decision Support System (DSS)**, which facilitates strategic decision-making in agriculture. These systems provide more comprehensive analysis within the agricultural management context, addressing modern challenges like climate change. The agricultural sector is particularly vulnerable to the effects of climate change, such as droughts alternating with heavy rainfall that



damage crops and threaten food security. Environmental challenges include precipitation anomalies, thermal stress, increased pest and disease pressure, and extreme weather events.

DSS implementation offers key advantages, including:

- **Preventive management:** Early identification of diseases, pests, and adverse weather conditions;
- **Resource optimization:** Precise management of fertilizers, pesticides, and water for more efficient use;
- **Increased productivity:** Aligning operations with crop needs to improve quality;
- **Sustainability:** Efficient resource use, reducing environmental impacts.

DSS platforms are particularly useful in **Integrated Pest Management (IPM)** programs, optimizing pesticide application and costs while improving crop productivity, in line with the **Green Deal** objectives and the **Farm to Fork strategy** in the **2023-2027 CAP**. Additionally, they enable precise fertilizer management, reducing water contamination and atmospheric emissions. The DSS system is particularly relevant for organic farming, where **preventive strategies** are key to avoiding diseases and pests. DSS platforms support this preventive management with early warning systems and integrated monitoring.

DSS platforms are based on three main components:

- **Knowledge base:** Formalized agricultural knowledge, including crop-specific parameters and disease models;
- **Inferential engine:** Analyzes incoming data and provides management recommendations;
- **User interface:** Allows interaction with the system, presenting analytical results in an understandable way.

DSS platforms integrate multiple information sources, such as sensor networks and agricultural databases, generating useful insights for critical decisions, like phytosanitary treatments.

The operational framework of a DSS consists of three phases:

- **Data collection:** Monitoring critical variables through sensors;
- **Data analysis:** Cloud-based algorithmic analysis to identify trends;
- **Decision support:** Customized recommendations to optimize agricultural operations.

DSS platforms provide decision support, not prescribed solutions, allowing farmers to make informed choices through comprehensive data analysis. DSS implementation enhances efficiency in operations such as irrigation, fertilization, and phytosanitary treatments.

Structure of a DSS

The operational framework of a Decision Support System relies on **dynamic interaction between the computational system and the agricultural decision-maker**. This interaction forms the foundation for effective agricultural management support.

The DSS architecture integrates two fundamental computational systems working together:



- **Electronic Data Processing (EDP):** This system transforms raw agricultural data into structured information through sophisticated processing algorithms. For example, it might convert raw sensor readings of soil moisture into meaningful irrigation requirements;
- **Management Information System (MIS):** Building upon the EDP output, this system processes information to generate actionable reference points for agricultural decision-making. It might, for instance, translate processed soil moisture data into specific irrigation scheduling recommendations.

These systems work symbiotically within the DSS framework **to process potential decision scenarios** available to the agricultural practitioner.

Agricultural DSS platforms can be categorised into three distinct technological classifications based on their hardware and software capabilities:

1. **Specific DSS:** These systems are tailored to address particular agricultural challenges for individual farmers. For instance, a system might focus exclusively on vineyard disease management for a specific geographical region;
2. **DSS Generators:** These represent more versatile platforms capable of rapidly generating specific DSS applications to address emerging agricultural challenges. They offer the flexibility to create customised decision support tools as new management needs arise;
3. **DSS Tools:** These fundamental components enable the development and enhancement of both specific DSS and DSS Generators, forming the technological foundation of agricultural decision support.

The functional architecture of a DSS comprises five essential elements:

1. **Routine packages:** These consist of optimisation algorithms written in high-level programming languages, enabling query processing through keyword selection. Modern implementations increasingly incorporate artificial intelligence to enhance query interpretation and routine selection;
2. **Graphical interface:** This critical component transforms processed data into visually accessible formats such as graphs and diagrams, significantly reducing the time required for data interpretation compared to raw numerical analysis;
3. **System multimedia interface:** This encompasses the human-computer interaction mechanisms, including touch screen interfaces and voice command systems, enabling intuitive system operation;
4. **Database:** This serves as the information repository, with networked databases offering particular advantages through their capacity to support multiple models and facilitate computer network integration;
5. **Modeller:** This component generates problem scenarios and identifies potential solutions through mathematical rule-based information management, enabling systematic approach to agricultural challenges (Ref. 23).



DSS Application in Agriculture

The practical implementation of Decision Support Systems in agriculture requires understanding how these systems process and integrate various data streams to generate meaningful management recommendations. To effectively utilise a DSS, practitioners must first understand the diverse data sources that inform these systems. The sources from which DSS draw to advise the farmer are of a different nature. They range from modelling, instrumentation and even field observations. Bringing together data from such diverse sources ensures a more complete end result. Specifically, specific forecast models are taken into account: in relation to the specific case, forecast models will be taken, for example, on the prediction of attacks by pathogens, rather than on the phenology of the crop concerned. Among the instruments, on the other hand, meteorological columns are often taken into consideration, which are able to provide data describing wind, temperature, humidity, etc. Observations by the farmer are also important elements to get a more complete picture. Field monitoring by the operator can provide different data than those obtained by instruments; these are also processed. This **integration of multiple data sources** enables agricultural practitioners to make **more informed decisions** about crop management interventions, resource allocation, and timing of agricultural operations. Understanding these data sources and their integration within the DSS framework enables practitioners to more effectively utilise these systems for improved crop management outcomes. The system's ability to process complex, **multi-source data streams** and **generate practical management recommendations** represents a significant advancement in agricultural decision support technology.

Application for Nutrient Management

Agricultural fields exhibit significant internal heterogeneity in both their structural characteristics and nutrient distribution patterns. This spatial variability creates complex challenges for nutrient management, as individual plants within the same field may experience markedly different growing conditions and nutrient availability. The sophisticated nutrient management capabilities of modern DSS address this variability by **supporting precise, location-specific fertilisation strategies**. These systems help agricultural practitioners **optimise nutrient applications** across heterogeneous field conditions, simultaneously maximising production efficiency while minimising input costs. Nitrogen management serves as an exemplary case of DSS application in nutrient management. As nitrogen typically represents the nutrient required in largest quantities by most crops, its management proves particularly critical for agricultural success. A nitrogen-focused DSS integrates multiple data streams to create a comprehensive analysis of nitrogen dynamics within the agricultural system. The system processes soil nitrogen content, crop nitrogen requirements, meteorological data, and soil characteristics to model potential nitrogen losses under current conditions. This integrated analysis enables agricultural practitioners to make informed decisions regarding fertiliser selection, application rates, and timing (Ref. 24). More advanced DSS platforms extend beyond single-nutrient analysis to provide comprehensive nutrient management support. These systems integrate data on multiple nutrients and organic matter content, enabling more sophisticated fertility management strategies. Such



Figure 3: Precision fertilization using prescription maps

comprehensive nutrient management systems prove particularly valuable for organic agricultural operations, where understanding complex interactions between organic matter dynamics and nutrient availability becomes essential for successful crop production. For example, in an organic farming system, a comprehensive DSS might analyse soil organic matter levels, mineralisation rates, and nutrient cycling patterns to recommend appropriate organic

fertiliser applications. The system could account for factors such as green manure contributions, composting dynamics, and seasonal nutrient release patterns, providing organic producers with detailed guidance for maintaining optimal soil fertility while adhering to organic certification requirements. This approach to nutrient management through DSS enables practitioners to implement more precise and efficient fertilisation strategies, ultimately supporting both production goals and environmental sustainability objectives.

Application for Plant Support

The economic sustainability of agricultural operations depends fundamentally on effective plant disease management. Healthy crops demonstrate enhanced potential for achieving superior production standards in both qualitative and quantitative dimensions. Within this context, modern disease control strategies increasingly emphasise the principles of **Integrated Pest Management (IPM)**. IPM represents a sophisticated approach to pest control that integrates multiple management techniques while balancing economic, environmental, and social sustainability parameters. This methodology prioritises ecosystem protection, human health preservation, and agricultural profitability through sustainable pest control strategies (Ref. 25). Key objectives include optimising phytosanitary product application efficiency, enhancing ecosystem services, and expanding agricultural practitioners' knowledge base. Precision agriculture, particularly through DSS implementation, serves as a crucial enabler for **advanced IPM practices**. Contemporary DSS platforms integrate meteorological data and plant phenological information to support sophisticated pest management strategies. The ability to analyse meteorological forecasts proves particularly valuable for predicting potential insect or pathogen pressures. Advanced systems incorporate yield loss simulation capabilities, enabling agricultural practitioners to assess potential economic impacts of specific pest pressures on crop production (Ref. 24). There are crop-specific DSS that provide information to solve various problems like defense strategies and irrigation. For example, vine DSS help combat diseases such



as downy mildew and pests like moths using forecasting models, field surveys, and satellite images. Similarly, tobacco DSS suggest strategies against pathogens to promote sustainable cultivation. Another case is DSS for controlling the olive fly, which combines data from models, instruments, and farmer observations crucial for detecting information instruments may miss. These systems convert complex data into practical recommendations, supporting more effective and sustainable pest management through integration of multiple data sources and advanced analysis.

Application for Irrigation Support

In modern agriculture, efficient water management is increasingly important due to climate change. Precision irrigation—providing water “when, where, and how much needed”—is a key strategy to address water scarcity. Irrigation Decision Support Systems (DSS) integrate data on soil, moisture, plant growth, and weather, along with hydraulic models and satellite images, to deliver precise, customized recommendations, even for specific cultivars. These systems help farmers balance productivity with water conservation, promoting more sustainable irrigation practices in increasingly water-stressed environments.

Application For Market Support

Decision Support Systems (DSS) go beyond field agronomic management to include crucial market intelligence functions. In modern agriculture, production quality must be paired with sophisticated market awareness to ensure economic sustainability. Market-oriented DSS, through Market Information Systems (MIS), provide comprehensive data to bridge the gap between production and commercial success, essential for obtaining fair value for agricultural products. MIS analyze various market data, such as current and future prices, wholesale and retail dynamics, and supply-demand trends, offering insights for effective marketing strategies. These systems help farmers make informed decisions on product positioning, market entry timing, distribution channel selection, price negotiation, and strategic inventory management. By integrating market intelligence with production data, producers can align their agricultural operations more effectively with market demands (Ref. 24). This alignment proves particularly crucial in today's agricultural economy, where market responsiveness often determines an operation's economic sustainability. The implementation of market-focused DSS represents a strategic approach to ensuring that superior agricultural production translates into appropriate market value. These systems help bridge the critical gap between production excellence and market success, supporting the overall economic sustainability of agricultural operations.



UNIT 4: PLATFORM FOR AGRICULTURE

Introduction

Digital platforms are transforming agriculture through advanced data processing capabilities that enable integrated resource management. They allow real-time crop monitoring, optimization of water and fertilizer use, and improve product traceability. The integration of sensors, specialized software, and decision support systems supports more precise and sustainable agricultural decisions. Automation and artificial intelligence adoption make advanced productivity and waste reduction strategies accessible. However, the agricultural sector faces challenges such as operational complexity, data security, and limited interoperability between platforms, which must be addressed to develop efficient and competitive digital systems.

Digital Platforms in Agriculture

Digital platforms serve as **fundamental components in the AgriTech sector**, enabling agricultural practitioners **to manage data rationally, rapidly, and securely**. The agricultural environment generates data from an extensive array of sources, including tractors, operational machinery, and specialised equipment. Additional data streams originate from meteorological sensors, satellite systems, and taxation documentation, alongside the technologies explored in the ["Robotics in Agriculture" module](#). Furthermore, agricultural practitioners contribute valuable observational data based on their direct field experience (Ref. 26). This diverse data landscape necessitates **an integrated management system founded on interoperability principles**.

Interoperability represents "the ability of two or more systems to exchange and utilise information, enabling different domain-specific digital structures to be connected in a larger workflow" (Ref. 27). This capability proves essential for integrating varied data sources, including IoT devices, satellite imagery, and farm management software. Such integration facilitates seamless data sharing whilst supporting regulatory initiatives such as the Data Act. The maintenance of reliable, standardised data proves crucial for analytical processes, research activities, and compliance requirements, with technology standards playing a vital role in ensuring data consistency (Ref. 28). Agricultural business management platforms enhance operational efficiency through interoperability systems integration. These platforms mark a significant step towards farm computerisation, enabling practitioners to consolidate available data and systematically integrate it with external databases and satellite imagery. This comprehensive approach facilitates advanced management of diverse information categories, spanning fiscal, agronomic, real estate, commercial, and operational domains. Furthermore, these platforms enable automation of specific operations, including quality certificate generation, documentation processing, supply chain monitoring, and information traceability (Chiodini, 2024). The software **processes vast quantities of heterogeneous data**, systematising it to generate readily



comprehensible information for agricultural practitioners. The operational framework of agricultural digital platforms centres on the management of big data - extensive datasets collected **from multiple sources**. These include weather stations, environmental monitoring systems, external climate and soil sensor networks, satellite imagery, computational algorithms (DSS), and specialised sensor arrays. The platforms maintain bidirectional communication with positioning systems (such as GPS) and precision farming instruments used in phytosanitary treatments, fertilisation, and irrigation operations. This **connectivity enables both data acquisition and transfer**, providing comprehensive support for agricultural decision-making. The platforms also facilitate marketing operations and business management functions. They automatically generate regulatory compliance documentation required at European, national, and regional levels based on integrated data analysis.

The marketing support capabilities of these platforms process big data to generate valuable insights for:

- **Agricultural product processing and marketing operations.**
- **Product traceability and tracking systems.**
- **SMART contract** implementation.
- **Environmental and ethical certification processes.**

This integrated approach to data management and analysis enables agricultural practitioners to make informed decisions across all aspects of their operations whilst maintaining regulatory compliance and market competitiveness.

Advantages of Digital Platforms in Agriculture

Digital platforms in agriculture demonstrate sophisticated **interoperability capabilities**, enabling **integration across diverse agricultural systems** whilst **processing complex data streams into readily accessible insights for agricultural practitioners**.

These platforms deliver multiple concurrent functionalities, creating a unified framework that encompasses operational management, resource optimisation, and decision support capabilities. The primary functional domains include:



Figure 4: Functionalities of digital platforms in agriculture



The continuous evolution of agricultural software systems enables progressive integration of emerging technologies, particularly artificial intelligence, further enhancing platform capabilities and operational effectiveness.

Management and Monitoring of Agricultural Resources

Agricultural platforms provide integrated management and monitoring capabilities, enabling comprehensive control of resources through digital systems. Using **Geographic Information Systems (GIS)**, these platforms transform geospatial data into detailed maps, allowing the monitoring of critical parameters. The **integration of real-time data from IoT networks** enables continuous monitoring of soil conditions, microclimatic variations, and crop development, reducing the need for physical inspections and optimizing costs. Additionally, equipment management includes performance analysis and maintenance scheduling, which is essential for large-scale operations. **Centralized monitoring systems** allow for proactive maintenance, ensuring equipment readiness for precision farming operations, optimizing resource use, and improving operational efficiency.

Planning and Optimising Operations

Precision agriculture relies on systematic operational planning supported by forecasting models and optimized resource allocation. Digital platforms assist these processes with advanced analytical capabilities, enabling structured planning across critical operations like crop rotation, soil cultivation, seeding, treatments, fertilization, and irrigation management. Using historical data and predictive models, platforms generate prescription maps that **optimize resource allocation** across field variations. Some advanced platforms also integrate automated control of operations through machinery compatible with **ISOBUS**, enabling precise operations based on the platform's analytical recommendations. This approach **optimizes operational efficiency** and **resource conservation**.

Decision Support

Modern agricultural platforms integrate multiple Decision Support Systems (DSS) into a unified operational framework, improving management efficiency and simplifying the decision-making process. These platforms consolidate complex data streams into clear management recommendations. For example, they may combine disease prediction models, irrigation scheduling systems, and nutrient management tools into a single interface. Integration occurs through forecasting models and DSS that analyze real-time and historical data to provide contextualized guidance. This approach reduces data analysis complexity and helps farmers make more informed decisions.

Irrigation Management

Agricultural management platforms are increasingly integrating advanced precision irrigation features through specialized modules. These extensions significantly enhance the digital management capabilities of agricultural operations. The irrigation management interface enables



comprehensive remote monitoring through **mobile apps and web portals**, using data from weather networks, primarily from on-site field stations. In the absence of local stations, data from nearby **meteorological stations** is used, though with lower accuracy. Through systematic integration of data collection, processing, and interpretation systems, these platforms enable sophisticated control of irrigation infrastructure. **The software interfaces directly with irrigation control units to manage multiple system components.** This includes automated control of valve operations, pump activation sequences, filter cleaning cycles for sediment management, and precise fertigation applications in designated zones (Ref. 31).

Agricultural practitioners can execute these management functions through various digital interfaces, including desktop computers, tablets, and smartphones. Advanced platforms incorporate diagnostic capabilities that automatically detect irrigation system anomalies, alerting operators to issues such as water leakage, supply interruptions, or consumption irregularities. This comprehensive management capability relies on integrated communication technologies, including **Wi-Fi networks, 4G-5G cellular systems, and Bluetooth connectivity.** The platforms **interface with Global Navigation Satellite System (GNSS)** enabled irrigation equipment, including automated roller systems and irrigation robots. Implementation of these advanced irrigation management systems enables significant improvements in agricultural competitiveness through enhanced production quality and quantity, ensuring **optimal timing of water applications.** The systems demonstrate substantial efficiency gains, with documented **water consumption reductions of up to 30% whilst maintaining crop productivity** (Ref. 30).

Fertilisation Management

Modern digital platforms incorporate **specialised fertilisation management** modules that enable agricultural practitioners **to implement precise nutrient management strategies.** These systems support rational fertiliser application by integrating multiple data streams to match nutrient applications with actual crop requirements, **considering critical factors** such as phenological development stages, meteorological conditions, and soil characteristics.

The platforms demonstrate versatility across diverse cultivation systems, supporting fertilisation management for **traditional open field operations, fertigation systems,** controlled environment agriculture in greenhouses, and **advanced hydroponic installations** (Ref. 31). Through sophisticated analytical tools, these systems enable practitioners to develop detailed fertilisation plans tailored **to specific crops and growing conditions.** The software analyses comprehensive datasets stored within the system database **to generate precise nutrient management recommendations.**

This digital approach to fertilisation scheduling improves both the economic and environmental efficiency of nutrient management. It enables more precise applications, reducing costs and minimizing environmental impacts caused by fertiliser overuse. Accurate nitrogen management is especially important to prevent greenhouse gas emissions from volatilisation and nitrate leaching



that contaminates water, particularly during heavy rainfall. With this digital precision, farmers can ensure optimal crop nutrition while avoiding environmental issues.

Management of Phytosanitary Treatments

Contemporary digital platforms serve as essential tools for implementing rational phytosanitary management strategies. These sophisticated software systems incorporate **dedicated modules for treatment planning and execution**, though this represents a more complex challenge than other agricultural operations due to the multiple variables requiring simultaneous consideration. Within the integrated pest management framework, these platforms **synthesise data** regarding **crop status, pathogen presence, weed populations, and meteorological conditions**. This comprehensive approach enables agricultural practitioners **to optimise phytosanitary interventions** whilst achieving multiple objectives: reducing production costs, enhancing crop yield and quality, and protecting the broader ecosystem's biodiversity. In precision agriculture applications, these platforms enable **remote management of sophisticated treatment technologies** through integration with sensor-equipped machinery. This technological framework supports two primary approaches to product application:

1. **Targeted distribution:** Rather than applying treatments uniformly across entire plots, the system enables precise application only where required. This selective approach significantly reduces chemical usage while maintaining treatment efficacy;
2. **Sensor-driven application:** Treatment decisions and application rates are determined through real-time analysis of field sensor data, ensuring interventions respond to actual field conditions.

The platforms support two principal methods for **localised product distribution**. The first utilises georeferenced mapping, where treatments are applied according to prescription maps generated through GIS integration. The second relies on real-time field sensor data to guide application decisions. The software processes **data from diverse sources** including field monitoring stations, satellite imagery, operational machinery, soil probes, and pest monitoring traps, complemented by manual observations from agricultural practitioners. Advanced platforms additionally provide regulatory compliance support, informing practitioners about treatment product eligibility within specific production systems. This feature ensures treatments align with relevant agricultural regulations while maintaining effective pest and disease control.

Documentation and Machinery Management

Digital agricultural platforms integrate administrative functions to support regulatory compliance, which varies across European regions. For example, in Umbria, farms must meet specific requirements linked to production methods and certifications, such as organic farming or Integrated Production, to access CAP subsidies. These platforms simplify documentation by automating mandatory registers like those for plant protection products, reducing administrative burden and improving accuracy. Integrated compliance tools enable “smart” administration by embedding documentation into daily operations. They also store and track certifications, licenses, and professional qualifications, sending alerts for renewals to help farmers stay up to date with



regulations. Platforms also manage personnel by monitoring qualifications, training, and regulatory compliance, facilitating task assignments and streamlining administrative procedures. On the operational side, connection to farm machinery with integrated sensors allows real-time monitoring of field conditions and equipment performance. The system detects needed maintenance and regulatory deadlines, sending alerts for actions such as calibrations, ensuring efficiency, compliance, and preventing breakdowns.

Traceability

Product traceability is essential in modern agri-food systems. Farmers implement traceability systems for two main reasons:

- **Process Monitoring:** Detailed traceability allows for precise interventions when issues arise, improving production efficiency and quality management
- **Consumer Confidence:** Transparent systems increase consumer trust, as they demand clear information about product origins and production methods. Traceability is also a powerful marketing tool



Figure 5: blockchain

Some agricultural platforms now **incorporate blockchain technology**, providing secure and immutable records, ensuring transparency and verification throughout the supply chain. These systems enhance operational efficiency and market competitiveness, meeting the growing demand for supply chain transparency.



Limitations of Digital Platforms

Despite their significant contributions to agricultural efficiency, productivity, and sustainability, digital platforms face several notable constraints that affect their widespread adoption and optimal utilisation. These limitations require careful consideration when implementing digital solutions in agricultural operations:

Table 3:: Limitations of digital platform

Limitation	Description
Interoperability Constrains	Many agricultural platforms have limited compatibility with existing technologies due to a lack of standardization (beyond ISOBUS), making data integration and system coordination difficult and hindering the simultaneous operation of multiple equipment systems
Data access restrictions	Farmers struggle to access and exchange operational data due to providers retaining data ownership, raising concerns about control and utilization
Interface complexity	Agricultural platform interfaces are often complex, especially for those with low digital literacy, limiting adoption and the benefits of digital management.
Economic considerations	Agricultural platform costs are often prohibitive, especially for small farms, as the cost-benefit ratio favors larger operations with greater economies of scale.
Data security concerns	Handling sensitive agricultural data raises privacy and security concerns, impacting platform adoption despite regulations like GDPR
Infrastructure requirements	In rural agricultural areas, stable internet dependence is a challenge; poor digital infrastructure limits the use of cloud platforms and systems needing updates.
Knowledge gaps	Limited understanding of platform capabilities by farmers leads to suboptimal utilization, reducing the benefits of digital agricultural systems.
Localisation challenges	The variety of agricultural operations, especially in mountainous areas, makes it difficult to adapt global platforms to local needs

While these limitations present significant challenges for digital platform implementation, continuous development efforts by platform providers aim to address these constraints and



enhance system effectiveness. Understanding these limitations enables agricultural practitioners to make informed decisions about platform adoption while considering their specific operational context and requirements. However, it should be specified that different manufacturers are continuously developing and improving their products. As a result, some of the limitations described may be resolved over time.

Supplementary Packages

Digital platform providers increasingly offer crop-specific modules, usually via subscription. These tailored tools help farmers manage the unique needs of their crops by integrating specific data to deliver targeted recommendations throughout the cultivation cycle.

Crop-Specific Packages

For instance, a **crop-specific package** might integrate soil analysis data, local climate patterns, and crop development models to generate precise management recommendations. These recommendations span the **complete production cycle**, from pre-sowing preparations through to harvest operations. The system **considers critical factors** such as:

- Pre-sowing field preparation requirements specific to the crop;
- Optimal sowing dates based on local environmental conditions;
- Customised fertilisation schedules aligned with crop nutrient demands;
- Targeted phytosanitary monitoring and intervention protocols;
- Harvest timing optimisation based on crop maturity indicators.

Each crop-specific package incorporates distinct functionalities that address the unique requirements of that particular crop. For example, a package designed for viticulture might emphasise canopy management and disease monitoring, while a cereal package might focus on nitrogen management and harvest moisture optimization. Through this targeted approach, agricultural practitioners can access precisely calibrated management tools that align with their specific crop requirements, enabling more effective and efficient crop management across their operations.

Olive Growing-Specific Packages

Digital platforms offer specialised management packages for olive cultivation that enable comprehensive oversight of olive grove operations in real-time. For farms implementing high-performance precision farming systems in olive production, these specialised management tools have become essential for optimising the entire olive-oil production chain. A comprehensive olive cultivation platform typically incorporates multiple integrated management functions that span the complete production cycle. These platforms synthesise data from multiple sources, including sensor networks, satellite systems, and meteorological stations, to provide sophisticated analytical capabilities.



The core functionalities of an olive-specific digital platform include:

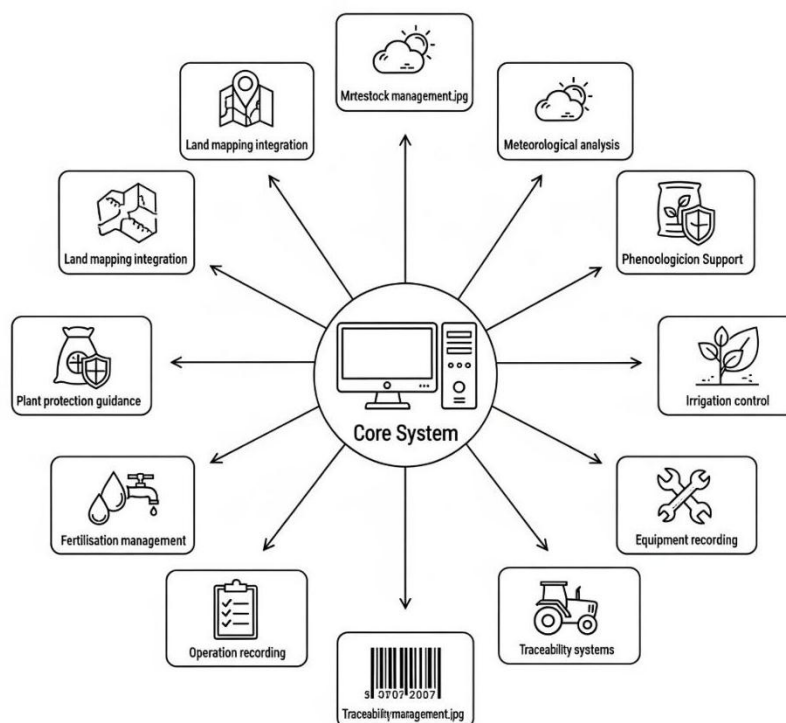


Figure 6: digital platform functionalities

These systems process extensive datasets from diverse sources including sensor networks, satellite systems, and meteorological stations, enabling precise management of olive cultivation operations through integrated digital solutions.

Practical Case Studies

Application for Olive Fly Management

The practical value of digital platforms in olive cultivation becomes particularly evident when examining their application in **managing *Bactrocera oleae* (olive fly) infestations**. This significant pest poses considerable challenges to both yield quantity and quality in olive production systems. Understanding the olive fly's biological cycle proves crucial for effective management. The female fly oviposits in olives once they reach suitable ripeness, when the drupe's skin becomes penetrable. Upon successful fertilisation, the developing larva feeds within the fruit, creating tunnels through the olive flesh. This internal feeding activity not only reduces fruit quality directly but also creates conditions conducive to rot and fungal development, leading to irreversible damage that affects both oil quantity and quality.

Implementing effective integrated pest management requires a **preventive approach** focused on limiting adult fly reproduction. This strategy fundamentally **depends upon comprehensive**



monitoring systems that track infestation progression and inform management decisions. Digital platforms support this monitoring by integrating key environmental parameters:

- **Meteorological conditions:** The system tracks temperature thresholds that influence fly behaviour and survival. Adult flies demonstrate optimal activity between 24-28°C with adequate humidity, showing increased mating and infestation rates. However, when temperatures exceed 35°C, juvenile mortality rates increase significantly;
- **Fruit development status:** The platform monitors drupe ripening levels to predict susceptibility to infestation.

Modern digital platforms synthesise these parameters with field observations **to generate predictive models of infestation risk**. Agricultural practitioners must initiate monitoring before drupes become susceptible to oviposition, combining technological insights with regular field assessments throughout the ripening cycle.

The Decision Support System (DSS) processes meteorological data, field observations, and fruit maturity indicators to generate infestation predictions. These predictions enable agricultural practitioners **to develop targeted management strategies** and **evaluate intervention effectiveness in real-time**.

Application for Maize Cultivation Management

Digital platforms offer specialised management packages for **maize cultivation** that address the unique challenges of this spring-summer cereal crop. While many cereals share common management requirements, maize presents distinct characteristics that necessitate **specific management approaches**, making it an instructive example of specialised crop management systems.

As a macro-terrestrial cereal with a spring-summer biological cycle, maize cultivation requires precise management, particularly during critical growth stages. The crop faces several significant challenges:

- **Germination requirements;**
- **Water management;**
- **Pest and weed control.**

Specialised maize management packages integrate multiple data streams to support sustainable, high-yield production systems. While maintaining core platform functionalities like **documentation management, equipment tracking** and **compliance recording**, these packages incorporate maize-specific analytical capabilities that process environmental and crop data. The system supports environmentally sustainable practices by integrating: **forecasting models, vegetation indices, manual observations, pest pressure analysis**. These data streams guide precise decisions on: **sowing timing, resource management, irrigation scheduling**. This integrated approach allows practitioners to improve yield and sustainability in maize production.



Application For Livestock Management

Modern digital platforms extend beyond crop management to encompass comprehensive **livestock operation management systems**. These specialised packages address critical requirements in contemporary animal welfare, including **animal welfare monitoring**, **environmental impact reduction**, **livestock performance optimisation**, and **personnel management** in an increasingly specialised labour environment. These livestock management platforms enable agricultural practitioners to maintain detailed digital records of facility specifications, animal characteristics, and operational machinery. The systems process multiple data streams to generate actionable insights across all aspects of livestock operations. The platform's integrated management capabilities typically encompass:



Figure 7: digital platform functionalities

These functionalities vary among specific manufacturer packages, but the fundamental objective remains consistent: enabling **remote digital management of livestock operations** to enhance overall stable efficiency. Through systematic integration of these management tools, agricultural practitioners can implement more precise and efficient livestock management strategies while **maintaining high standards of animal welfare and production quality**.



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