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Review

Digital Twins in greenhouse horticulture: A review

Natasja Ariesen-Verschuur [a,*], Cor Verdouw [a,b], Bedir Tekinerdogan [a]

[a] *Information Technology Group, Wageningen University & Research, Hollandseweg 1, 6706 KN Wageningen, The Netherlands*
[b] *Mprise Agriware, Mprise, P.O. Box 598, 3900 AN Veenendaal, The Netherlands*

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ABSTRACT

Digital Twins can be considered as a new phase in smart and data-driven greenhouse horticulture. A Digital Twin is a digital equivalent to a real-life object of which it mirrors its behaviour and states over its lifetime in a virtual space. Research indicates that they can substantially enhance productivity and sustainability, and are able to deal with the increasing scarcity of green labour in greenhouse horticulture. This paper presents the results of a systematic literature review on Digital Twin applications in greenhouse horticulture. The review identifies 8 articles that explicitly address Digital Twins in greenhouse horticulture and 115 studies that implicitly apply the Digital Twin concept in smart IoT-based systems. Findings indicate that the concept of the Digital Twin is in a seminal phase in greenhouse horticulture, but there are existing applications that are not yet framed as Digital Twins. In the reviewed papers, there is a dominant focus on the cultivation process at the greenhouse level, among others for climate control, energy management and lighting. About 9% of the articles are virtualizing plants themselves, which indicates that the granularity level addressed is still rather limited. Only 7 % of the articles look beyond plants or single greenhouses. None of the reviewed articles consider the company level. Furthermore, most applications address monitoring and control of the state and behaviour of real-life objects. More advanced applications, including predictive and prescriptive capabilities across the complete lifecycle, are still in an early stage of development, although predictive Digital Twins are gaining prominence.

1. Introduction

Due to critical challenges in food security, food safety, sustainability, and health, greenhouse horticulture production processes are becoming increasingly industrialised. Greenhouses are developing towards high-tech factories characterised by large-scale production and heavy use of technology (Oliveira et al., 2017; van Henten, 2019). Business and production processes are intensively monitored and controlled, enabled by advanced systems and sensors, e.g. for climate management, irrigation, fertigation, lighting, crop monitoring, disease scouting, harvesting, internal transportation, sorting and packaging. As a result, greenhouse horticulture is becoming increasingly smart and data-driven (Zude-Sasse et al., 2016). This trend has accelerated recently, driven by the fast pace of developments in ICT, such as cloud computing, Internet of Things, big data, machine learning, augmented reality and robotics (Kamilaris and Prenafeta-Boldú, 2018; Tzounis et al., 2017; Zhai et al., 2020).

In smart and data-driven greenhouse horticulture, growers are able to monitor and control operations remotely, based on (near) real-time digital information instead of direct observation and manual tasks on-site. They receive alerts, in case of any (expected) issues, and can inspect the greenhouse situation behind their desk or smartphone by viewing a rich digital image of the plants or equipment concerned. Simultaneously, growers can simulate the effects of corrective and preventive actions on the digital representation. Finally, the grower can execute the chosen interventions remotely, and the digital representation can again be used to verify whether the (expected) problem is solved. This intelligent management cycle will become increasingly autonomous without the manual intervention of the grower (Hemming et al., 2020). In conclusion, we could state that every object in the greenhouse (such as plants, containers, greenhouse sections, and equipment) can, in principle, be virtualised and remotely controlled. A Digital Twin is a powerful enabler of this development (Pylianidis et al., 2021; Verdouw et al., 2021).

A Digital Twin mirrors the real-life object's state and behaviour over its lifetime in a virtual space (Boschert and Rosen, 2016; Grieves and Vickers, 2017). Digital Twins allow simulating changes of its physical counterparts by adding advanced data analytics such as machine learning and prediction models. Depending on the purpose of usage, the

* Corresponding author.
E-mail address: Natasja.Ariesen@wur.nl (N. Ariesen-Verschuur).

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virtualised objects in greenhouse horticulture may range from individual plants' genetics to a greenhouse or the complete value chain.

Digital Twins have the potential to substantially enhance greenhouse horticulture productivity and sustainability (Defraeye et al., 2021; Howard et al., 2021; Qi et al., 2021). Although the Digital Twin concept is relatively young, it can be considered a further development of smart greenhouse horticulture. Yet, it is unclear currently to what extent Digital Twins are applied in greenhouse horticulture. The application of Digital Twins in greenhouse horticulture remains an idea, whereas there is a lack of knowledge about how to design and implement Digital Twin based systems in the greenhouse horticulture domain. This paper contributes to overcoming this situation by conducting a systematic literature review. This review's main objective is to provide insight into the state-of-the-art of Digital Twin applications in greenhouse horticulture.

The remainder of the paper is organised as follows. Section 2 introduces the concept of Digital Twins and provides an overview of related work. Section 3 describes our review protocol in detail. Section 4 presents the results of the literature review. Section 5 presents the discussion and section 6 the conclusion.

2. Background and related work

2.1. Digital Twin concept

The Digital Twin concept originates from the Product Management context (Grieves, 2014). In this domain, there was a need for a product management system that incorporates all product information throughout the product lifecycle stages, accessible for all users. For this reason, a digital copy of the physical product was envisioned to hold all relevant data used in the design, manufacturing, and maintenance phases (Schleich et al., 2017).

While originating from Product Lifecycle literature, a key technology for realizing Digital Twins is the Internet of Things (IoT) (Marr, 2017). The interaction between real/physical and digital/virtual objects is an essential concept behind the IoT. Each physical object is accompanied by a rich, globally accessible virtual object, which contains both current and historical information on that object's physical properties, origin, ownership, and sensory context (Welbourne et al. 2009, Sundmaeker et al., 2010). With the maturing of IoT-based systems, these virtual objects are more and more used as a basis of smart systems, including increasingly advanced control capabilities, such as monitoring and prediction capabilities. Such smart systems are actually Digital Twins, although they are often not framed as such, among others due to the novelty of the concept. Consequently, Digital Twins can be considered as a further development of smart IoT-based systems (see Fig. 1).

The emergence of Digital Twins in literature has resulted in various

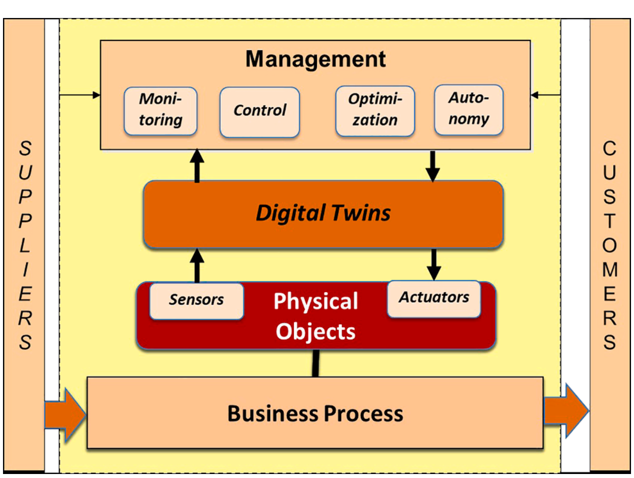

Fig. 1. Digital Twins in Smart Systems.

definitions both from a Product Life Cycle (PLC) and an Internet of Things (IoT) perspective. In the IoT literature, the digital representation of physical objects using sensing technologies is highlighted. In the PLC literature, the emphasis is on mirroring real-life objects across their lifecycle, including simulation of expected object behaviour. In this paper we combine both perspectives and use the following definition: "A Digital Twin is a dynamic representation of a real-life object that mirrors its states and behaviour across its lifecycle and that can be used to monitor, analyse and simulate current and future states of and interventions on these objects, using data integration, artificial intelligence and machine learning" (based on a literature review by Verdouw et al., 2021). More specifically, the following essential characteristics of Digital Twins can be addressed:

- *Timeliness*: a Digital Twin represents its physical twin in (near) real-time, state changes of the physical object are (immediately) identified and synchronized and vice versa (Verdouw et al., 2015; Durão et al., 2018; Mikell and Clark, 2018; Tao et al., 2018; Knibbe et al., 2019; Park et al., 2019);
- *Fidelity*: the reliability and security of a Digital Twin must be unquestionable, allowing to blindly trust Digital Twins for decision making (Verdouw et al., 2015; Durão et al., 2018; Tao et al., 2018);
- *Integration*: a Digital Twin combines data from all facets of the physical object and merges the data in a uniform format (Schleich et al., 2017; Kritzinger et al., 2018; Tao et al., 2018; Park et al., 2019);
- *Intelligence*: Digital Twins do not only reflect object data but also use algorithms for describing, analysing and predicting the behaviour of the physical counterpart (Glaessgen and Stargel, 2012; Schleich et al., 2017; Durão et al., 2018; Kritzinger et al., 2018; Knibbe et al., 2019; Park et al., 2019; Shaw and Fruhlinger, 2019, Lenfers et al., 2021);
- *Complexity*: Digital Twins can mirror various physical objects, such as products, living and non-living resources, components and processes (Marr, 2017; Saddik, 2018). Also, the Digital Twin can depict multiple interdependent objects as well as sub systems at different levels of granularity (Glaessgen and Stargel, 2012; Verdouw et al., 2016; Grieves and Vickers, 2017).

2.2. Digital Twin typology

A Digital Twin can readily be created in the design phase of an object's lifecycle, enhancing the creative phase of inventing new products and elaborating it into a detailed product model (see Fig. 2). In this stage, a Digital Twin allows early and efficient assessment of the consequences of design decisions on products' quality and function, reducing the need to develop costly physical prototypes (Grieves and Vickers, 2017; Schleich et al., 2017). After the design phase, a physical stage is entered, in which the Digital Twin comes into existence. A physical object is produced based on the designed Digital Twin, which is updated in case of any deviations. During operational usage, the current and historical state and conditions of a physical product are monitored by using sensors and AutoID devices. Moreover, the Digital Twin can be used to control remotely an object by using actuators. Finally, the disposal phase takes place, in which the physical object is disposed, but the conceptual object may remain for some period e.g. for traceability, compliance and learning.

Based on the role in the Product Life Cycle and the supported capabilities of smart systems, different types of Digital Twins can be identified. In this study, we adopt the typology of Verdouw et al. (2021), which identifies six different Digital Twin types (based on Porter and Heppelmann, 2014; Verdouw et al., 2015; Hagerty, 2016; Grieves and Vickers, 2017; Redelinghuys et al., 2019; Lepenioti et al., 2020):

- *Imaginary Digital Twin*: a digital object that represents an object that is not yet in existence. Imaginary twins can aid in designing the

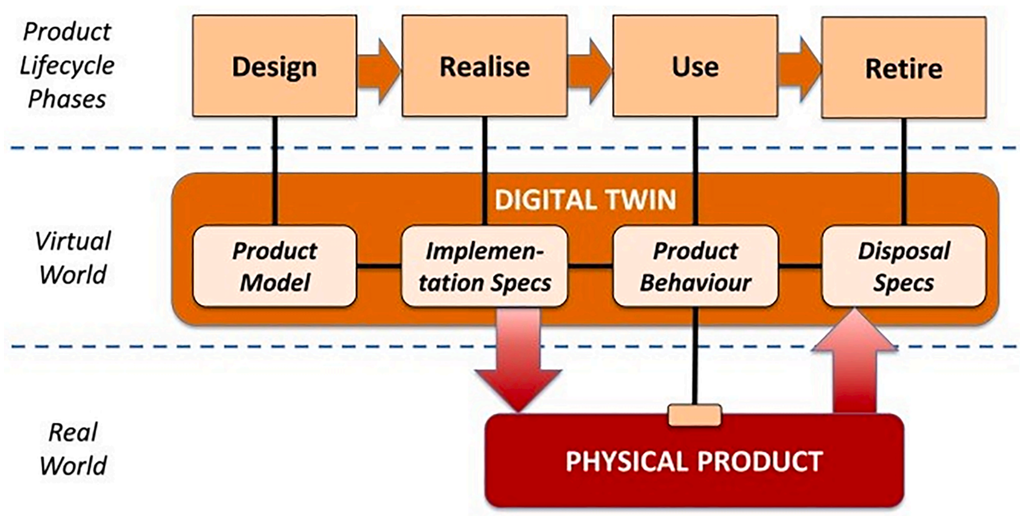

Fig. 2. Role of Digital Twins during the Product Life Cycle (Verdouw et al., 2021).

physical twin and simulate expected behaviour of the designed objects.

- *Monitoring Digital Twin*: a digital representation of the current condition, behaviour and environment of its physical twin, including its trajectory. Monitoring twins can be either provide insight in what happens or happened with the connected physical object (descriptive) or explain why it happens or happened by relating the object to contextual data (diagnostic).
- *Predictive Digital Twin*: a digital projection of the future state and behaviour of its physical twin. Prediction is done dynamically based on (near) real-time data of the physical object.
- *Prescriptive Digital Twin*: an intelligent object that proposes corrective or preventive interventions on the real-life object, usually based on optimization algorithms or heuristics. The decisions on the recommended actions still are taken by humans, who also trigger the remote or on-site execution of interventions.
- *Autonomous Digital Twin*: operates independently and fully controls the real-life object without human intervention. Autonomous twins also can become self-learning and self-adaptive systems.
- *Recollection Digital Twin*: records a complete history of the physical counterpart that no longer exists in real life. They serve as a digital memory that can be used to reconstruct past behaviour of physical objects, trace its origin, manage disposals and optimize next generation objects.

A Digital Twin does not necessarily belong to one category but usually combines features of different types. Each support control capability builds on the preceding one: prediction requires monitoring, optimization requires control and monitoring, and autonomy requires all three. Digital Twins during the usage phase apply virtual models that are already created before the existence of the physical objects. Furthermore, Digital Twins build upon each other's control capabilities. Predictive twins require monitoring capabilities, prescriptive twins require predictive capabilities and autonomous twins requires all three.

2.3. Architecture for Digital Twins

At the time of writing this article, several architecture design approaches for Digital Twins have been introduced in recent studies. For example, Schleich et al. (2017) proposed an abstract reference architecture that addresses some basic modelling principles for 'twinning' between the physical and virtual world properties, such as model scalability, interoperability, expansibility, and fidelity. Alam and Saddik (2017) developed a specific a Digital Twin architecture, that analytically describes key properties of cloud-based cyber-physical systems. Redelinghuys et al. (2019) designed an architecture for Digital Twins of manufacturing cells comprising six layers, including local data, gateways, cloud-based databases and a layer for emulations and simulations.

These architectures are similar to reference architectures developed in the IoT domain, in which virtual representation of objects have an important role.

Thus, these systems are comprised of four layers (Atzori et al., 2010; Ma, 2011; Verdouw et al., 2021):

1. *Device layer*, provides the hardware components that are attached to and directly interact with physical objects, especially: i) sensors to measure the dynamic properties of physical things including climate conditions, and ii) actuators to remotely operate objects such as climate control, irrigation, vans and lights; this layer also monitors and controls the devices and its interaction with the network layer.
2. *Network layer*, for communication of object information in an efficient and secure way, including connectivity, communication and data transport capabilities; the data are mainly first sent to intermediary platforms (internet gateways or cloud proxy machines) using wired and wireless local area networks.
3. *Integration layer*, for processing and integrating object data; in this layer the Digital Twins are managed, starting with creating virtual representations (i.e object abstractions) from diverse data from sensor devices, internal databases or external applications; furthermore, it controls the synchronization with the physical objects and continuously monitors the validity of Digital Twins; the information integration layer also includes basic data management capabilities, such as cloud storage and security.
4. *Application layer*, provide specific functionalities for different users based on the Digital Twin information that is accessible via the integration layer; the different categories of Digital Twins are enabled by diverse intelligence capabilities, including big data analytics and Machine Learning (neural networks, fuzzy logic, and regression models); this application layer also includes the user interface for interacting with Digital Twins.

2.4. Digital twins in greenhouse horticulture

Horticulture is characterised by a great variety and variability of production because living, perishable products are involved, and production depends on natural conditions such as weather, diseases, soil condition, seasons and climate. Indoor production in greenhouses is a strategy to cope with these uncertainties, resulting in a more controlled production environment to optimise climate conditions, fertigation, light and moisture. Due to the remaining uncertainties resulting from the weather, pests and quality decay, and new challenges, especially concerning energy management, growers continuously have to reassess cultivation strategies and reschedule planned activities based on the timely monitoring of greenhouse operations to achieve their goals (Stanghellini et al., 2019). Digital Twins can significantly enhance the needed control capabilities by allowing growers to act immediately in case of (expected) deviations and simulating interventions based on real-life data. Moreover, the scale of greenhouse horticulture has increased in recent years. In large-volume production, it is no longer possible to keep track of the cultivation process manually. This is reinforced by the increasing scarcity of green labour, i.e. experienced employees with horticultural knowledge.

Digital Twins can be a suitable enabler to deal with these challenges because they remove fundamental constraints concerning place, time, and human observation (Verdouw et al. 2021). Greenhouse horticulture would no longer require physical proximity, enabling remote and automated execution, monitoring, control, and coordination of greenhouse operations by different stakeholders (Fig. 3). This caters for the decoupling of physical flows from information aspects of horticultural processes. Digital Twins can also be enriched with information that cannot be observed (or not accurately) by the human senses (e.g. sensor and energy data) or data that other information owners provide (e.g. weather data).

Moreover, Digital Twins in greenhouse horticulture not only represent the actual states of objects like plants and greenhouses, but can also analyse historical states and simulate future behaviour, e.g. crop growth or expected yields. Consequently, if properly synchronised, Digital Twins applications can assist growers and other stakeholders with decision-making and enable them to act immediately in case of (expected) deviations and remotely control greenhouse operations accordingly. Adding intelligence also allows to capture the tacit "green" knowledge of experienced horticultural experts in Digital Twins and to learn continuously from data. This will reduce the need for skilled employees while further improving production performances, including yields and quality needed at the optimal time.

3. Research method

The review method followed the guidelines of Kitchenham et al. (Kitchenham et al., 2009) for a systematic literature review (SLR) specific to Software Engineering. We have applied this protocol to identify and synthesize the key results related to digital twins in horticulture. First, a framework for analysis and the research questions were defined. Based on these questions, the search strategy and search strings were elaborated. Next, we defined the selection criteria and we applied the criteria to the retrieved papers. We then narrowed the selection to a final subset of 123 articles. In the sixth and last step, we defined analysed the data synthesis and presentation of the data. The remainder of this section further describes the research methods of these steps.

3.1. Conceptual framework for analysis

The review started with the definition of a novel conceptual framework, based on a synthesis of literature about Digital Twins literature (section 2) and previous research of the authors (especially Tekinerdogan and Verdouw 2020; Verdouw et al., 2021). In Fig. 4, the conceptual framework used for this systematic literature is shown.

The starting point of the framework concerns the purposes for developing a Digital Twin based system (why?). For this, we adopted the widely-used Balanced Scorecard of Kaplan & Norton (1996) for classification. This, we surmise that Digital Twins can be developed to improve:

1. Financial performance of a horticultural company, including cost efficiency or revenue growth;
2. Customer value including product quality and service levels such as on-time-delivery and fill rates; also sustainability is considered to be part of this category because it provides societal value;
3. Internal business processes regarding operational performance such as production cycle times, yields, consumption of inputs, and capacity utilization.
4. Innovation in order to learn and grow, and as such to ensure continuity and long-term performance improvement.

The second part of the framework addresses the real-life objects that are virtualized in Digital Twins (where applied?). These objects can be defined in multiple levels of granularity (Verdouw et al. 2016). In greenhouse horticulture, this may vary from single plants to the complete supply chain. Digital Twins of individual plant include both visible characteristics (e.g. shape, colour, flowers, or leave area), and invisible characteristics (e.g. stress, sap flows, photosynthesis, or genetics) as well as its ambient environment (micro climate, soil moisture, pathogens, etc.) A Digital Twin of a greenhouse is a view on the complete greenhouse system and its sub systems, including the energy system climate, crop growth and expected yield in a greenhouse compartments, etc. A Digital Twin of a horticultural company represents the organization including the business processes and its (near) real-time performance (quality, costs and profits, lead times, etc.). A Digital Twin of a

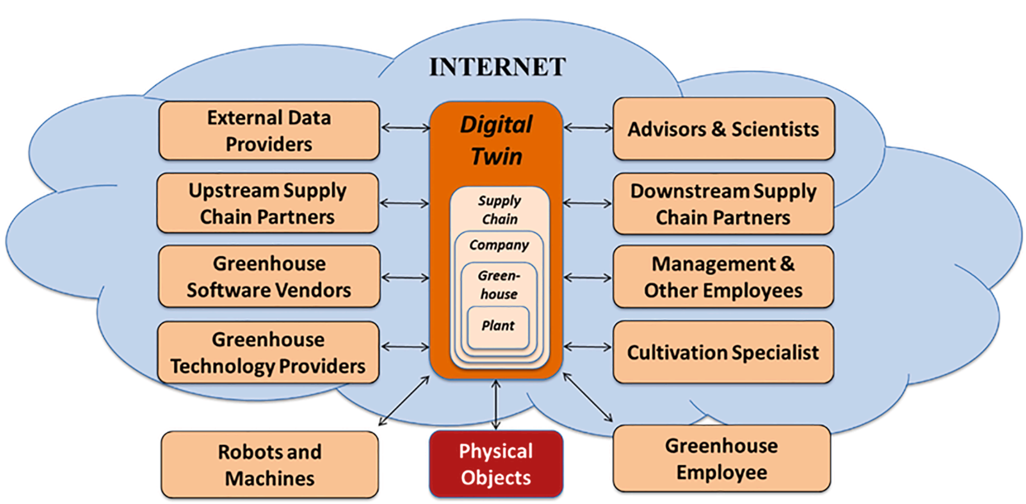

Fig. 3. Digital Twin concept in greenhouse horticulture.

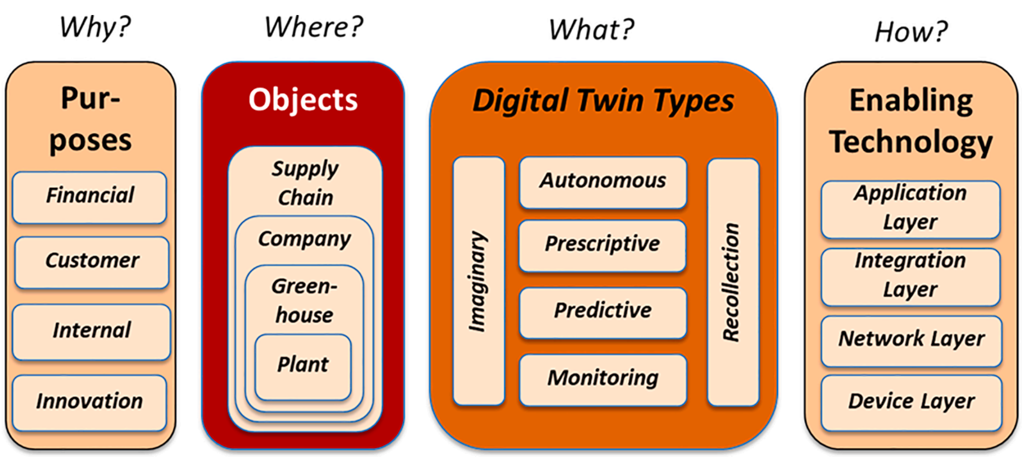

Fig. 4. Framework for analysis of Digital Twins in greenhouse horticulture.

horticultural supply chain extends this to the value chain, including (end) customers and suppliers.

The third part of the framework is a typology of six Digital Twin categories (what type?), which is adopted from Verdouw et al. (2021): imaginary, monitoring, predictive, prescriptive, autonomous and recollection digital twins (as introduced section 2.2).

Finally, the enabling technology (how?) of a Digital Twin-based system is described by adopting the architecture of smart IoT-based systems, which basically comprise device, network, integration and application layer (as introduced section 2.3).

3.2. Research questions

The goal of this research is to provide insight into the state-of-the-art of Digital Twin applications in greenhouse horticulture. Based on the conceptual framework of the previous section we defined the following research questions for this systematic literature review.

a) What is the purpose of the Digital Twin, what is the problem that it aims to solve?
b) What 'objects' are virtualised with the Digital Twin?
c) What type of Digital Twin is described?
d) How is it technically implemented (devices, network, integration and application interface)?

3.3. Search processes

We performed a systematic automated search through the available papers on Web of Science, Scopus and Google Scholar. The start year of our search was set in 2012, two years before the year the concept was first mentioned in Grieves' paper (Grieves, 2014) to account for articles discussing the topic without use of the Digital Twin terminology. The search string consisted of the following query: "(digital AND twin) AND (horticulture OR greenhouse)".

This query led to the results of the initial search. After applying the selection criteria and a quality assessment, only eight articles were selected.

As discussed in section 2.1, Digital Twins can be considered as a further development of especially the IoT, that increasingly use virtual representations of real things as a basis of smart systems. For this reason, we broadened the scope of our review to include papers on smart IoT-based systems in greenhouse horticulture. We then checked if these papers implicitly address a Digital Twin. To include these implicit Digital Twins in the search, a new query was formulated:

"TITLE-ABS-KEY((internet AND of AND things) AND (horticulture or greenhouse))"

This query led to the 2040 results of the initial search. After applying the selection criteria, in total 157 articles remained, and after the quality assessment, 115 articles were added to the review.

3.4. Selection and quality assessment

The search strings were set up as broad searches to ensure no relevant articles were excluded. We filtered the most relevant papers from these broad searches by using the selection criteria (Table 1).

The quality of the articles was assessed using the questions in Table 2 as a checklist. The articles are ranked on the quality criteria with a yes (1), partial (0.5) or no (0) answer.

The reviewed papers are listed in appendix A.

3.5. Data collection and synthesis

Data extraction was performed by reading all the selected articles for answering each research question. A data extraction form was designed for retrieving all the information needed based on the conceptual framework for analysis. First, some general information about the articles, such as title, date, author, paper type and focal country was. Second, we extracted the elements of the conceptual framework, i.e. the purposes, the virtualised objects, the Digital Twin types addressed, and the enabling technologies used.

The data synthesis started with synthesising synonyms and checking the applicable concepts as defined in the framework for analysis. Next, the data were analysed and visualised in order define the results, which are described in the following section.

4. Results

4.1. Analysis papers that explicitly address Digital Twins in greenhouse horticulture

In our review, eight articles were identified that explicitly address the Digital Twin concept within the greenhouse horticulture domain.

Table 1
Selection Criteria.

ID	Criterion
1	Full text is accessible
2	Paper is not a duplicate from multiple sources
3	Paper is written in English
4	Paper is not a secondary study paper
5	Paper relates to greenhouse horticulture
6	Content is on virtualising objects
7	Article describes an (IoT) Digital Twin

Table 2
Assessment questions.

No	Question
Q1	Are the aims of the study clearly stated?
Q2	Are the scope and context of the study clearly defined?
Q3	Is the proposed solution clearly explained and validated?
Q4	Is the research process documented adequately?
Q5	Are all study questions answered?
Q6	Are the main findings stated clearly in terms of credibility, validity and reliability?

Table 3 provides a partial set of the identified Digital Twin properties described in these papers.

[1] The first paper found in this review was published in 2018 (Monteiro et al., 2018). The research proposed a model to implement Digital Twins for vertical farming and also developed an IoT-based prototype that uses data retrieved from sensors (temperature, humidity, luminosity, CO2 concentration) to monitor operations and actuators to control farming conditions. The collected data is stored in a cloud infrastructure for intelligent data analysis. Data from other sources of information, such as weather or market information, is included. A dashboard interaction provides the visualisation of the Digital Twin. The model proposed is a high-level IoT architecture that specified the goals, tasks and technical resources especially on the device and application layer and does not Digital Twin-specific elements such as Digital Twin abstraction and synchronization.

[2] Howard et al. (2020) is the first article from a four-year project, which aims to create integrated Digital Twins of three greenhouse sub systems: production flows, climate compartments and energy systems. This article addresses the first: a Digital Twin that allows to optimize the greenhouse production process and communicate with other digital twins representing essential areas in the greenhouse (climate and energy). This digital twin can estimate future states of the greenhouse production batches by using past and real-time data inputs from databases, sensors, and spot markets. This paper, together with paper [5] of the same author, are thus far the only ones that acknowledge the possibility of coupling multiple Digital Twins to get a more holistic view of the business processes in greenhouses, although the research focusses on production, climate and energy systems. For integration of these systems, the SIAM (Smart Industry Architecture Model) is proposed and the production-related data is analysed based on this model.

[3] Wang et al. (2020) aim to develop a simulation Digital Twin to enhance the development of a safe, efficient, reliable and automated supply chain. The authors propose a blockchain system for supply chain traceability and compliance, and a Digital Twin that utilizes the information from the blockchain for risk management, learning and process surveillance assistance. The object virtualised is an entire Supply Chain from seed to product. Through simulation modelling, the Digital Twin can quantify the output variability from random input factors. Throughout the supply chain processes, these outputs will guide dynamic decision making. The simulation Digital Twin will conduct a process risk analysis.

[4] Cumo et al. (2020) designs a hydroponic greenhouse for crop cultivation and event location. Based on the Building Information Model (BIM), they developed a virtual model that integrates multiple dimensions including energy management. The authors mention that the energy analysis was carried out through a Digital Twin made in the BIM environment. This is an example of an Imaginary Digital Twin, a virtual model of a product that does not exist yet in the physical world.

[5] Howard et al. (2021) introduce their ongoing research into the optimisation of greenhouse production using multi-agent systems and Digital Twin technology. The envisioned Digital Twin of the greenhouse production flow consists of an artificial intelligence (AI) based simulation model. This model investigates the effects of co-optimising a production schedule, plant growth, energy consumption and cost. The Digital Twin considers the influential factors, including production deadlines, quality assessment, heating demand, gas and electricity prices and weather forecasts.

[6] Hemming et al. (2020) describe and analyse the results of the autonomous greenhouse challenge, organised by Wageningen University. In this challenge, an experiment was conducted in six high-tech greenhouse compartments during a period of six months of cherry tomato growing. Five international teams competed for the best production performance by remotely operating their compartment. They

Table 3
Overview of papers that explicitly address Digital Twins in greenhouse horticulture.

Authors	Title	Paper type	Object	DT type	Sensors used	Actuators used
Monteiro et al., 2018	Towards Sustainable Digital Twins for Vertical Farming	conference paper	greenhouse	Monitoring and control	Temperature, humidity, CO2, illuminance	Air conditioning, air extraction, lighting, misting
Howard et al., 2020	Data Architecture for Digital Twin of Commercial Greenhouse Production	conference paper	plant	Prediction	Location	Not specified
Wang et al., 2020	Simulation-Based Digital Twin Development for Blockchain Enabled End-to-End Industrial Hemp Supply Chain Risk Management	conference paper	network	Prediction	Data on Blocks (added to blockchain)	Not specified
Cumo et al., 2020	Optimisation of Design and Management of a Hydroponic Greenhouse by Using BIM Application Software	journal	greenhouse	Imaginary	Temperature, humidity, illuminance, solar radiation	Heater, fan
Howard et al., 2021	Digital twin framework for energy efficient greenhouse industry 4.0	journal	greenhouse	Prescription	Location	Not specified
Hemming et al., 2020	Cherry Tomato Production in Intelligent Greenhouses—Sensors and AI for Control of Climate, Irrigation, Crop Yield, and Quality	journal	greenhouse	Prediction	temperature, humidity, illuminance, CO2 & Actuator: lighting, shade, heater, opener ventilation, cooling, CO2 dosing, fogger, dehumidifier, irrigation, and fertilisation	Lighting, shade, heater, opener ventilation, cooling, CO2 dosing, fogger, dehumidifier, irrigation, and fertilisation
Chaux et al., 2021	A Digital Twin Architecture to Optimize Productivity within Controlled Environment Agriculture	journal	greenhouse	Prediction, prescription	indoor and outdoor temperature and relative humidity	Fans and mini submersible pump
Martin et al., 2021	AI-TWILIGHT: AI-digital TWIn for LIGHTing - A new European project	conference paper	lighting system	Prescription	Light sensors	LED-based lighting system

developed intelligent AI algorithms and used sensor data to determine climate setpoints and management strategies for climate, irrigation, and crop management. During the experiment, the results of the participating teams were compared with a greenhouse crop production Digital Twin to analyse various growth factors (light, temperature, CO2, etc.). This Digital Twin combines a dynamic greenhouse climate model with a tomato crop model. It was used to calculate each compartment's predicted yield and the effects of changes in light, air temperature, and CO2 control strategies. The simulated results of the Digital Twin were compared with the realised crop production for calibration and for analysis of the effects of the different climate-crop strategies.

[7] Chaux et al. (2021) propose an architecture of Digital Twins for controlled environment agricultural systems (such as greenhouses), and apply it to a case study. The architecture comprises six technology layers: the greenhouse as the physical object, a controller, gateway, data storage, intelligence and the Digital Twin layer. The Digital Twins addressed, utilize current and historical data to assess the different crop treatments and climate control strategies received from the intelligence layer. As such, they combine prediction of future climate conditions, energy consumption and expected crop growth and yields, with prescription of optimal crop treatment and climate control strategies.

[8] Finally, Martin et al. (2021) introduce a new European project that will develop prescriptive digital twins for the lighting industry, including the application area of horticulture. The envisioned Digital Twins will virtualize LED-based lighting systems across a large part of the lifecycle. The ambition is to create self-learning models using Artificial intelligence (AI) and analytics techniques.

4.2. Overview including IoT papers that implicitly address Digital Twins in greenhouse horticulture

Digital Twins are building upon existing technologies, especially for the aforementioned IoT in section 2.1. Therefore, we included IoT papers in our review that apply Digital Twins in greenhouse horticulture domains but do not explicitly frame the Digital Twin concept. As previously discussed, this extension of the search scope resulted in the addition of 115 articles.

Fig. 5 shows that Digital Twins are already implicitly applied to greenhouse horticulture in the IoT literature from 2012. However, we only found a limited number of articles until 2016 and see a sharp increase from 2018. This year, the first published paper explicitly mentions Digital Twins' concept in greenhouse horticulture. The rapid rise in the number of papers shows that IoT literature increasingly addresses IoT technologies' usage to virtualise operations in greenhouse horticulture, which indicates that IoT literature is maturing. The relatively large number of journal articles (41%) also indicates this (Fig. 6). However, labelling this IoT development as Digital Twins is yet in a seminal phase.

Concerning the region, almost half of the articles are written with a focal country in mind, mostly from Asia (of which 21 papers from China), whereas Europe, Africa and America's fall behind (Fig. 7). Though 65 articles had no focal country specified.

The following sections will further analyse the papers based on the framework as introduced previously. After that, the Digital Twin's purpose, the virtualised object, applied typology and enabling technologies are described.

4.3. Purposes of Digital Twins (why?)

The majority (59%) of the Digital Twin applications developed in the reviewed articles mainly aims to improve financial results, namely cost-efficiency. Also the improvement of customer value is a notable purpose. For this category the papers focus on addressing the enhancement of production quality (16%) and improving sustainability (11%). Papers that address the improvement of operational process performance, specifically aim to increase production yields (6%). Furthermore, a relatively small part of the papers (9%) do not mention direct business benefits, but solely focus on innovation by exploring technological advances. Fig. 8 shows that other reasons than financial purposes gain importance during the last three years. Remarkably, in 2020 there is a substantial increase in papers that were aiming for innovation and technological advances. This increase can be explained by the novelty of the concept of Digital Twins in the greenhouse horticulture domain.

4.4. Virtualised objects (where?)

In the data collection, we assumed to find four granularity levels of the virtualised object: plants, greenhouse, company and supply chain. In the analysis of the papers, we discovered a fifth level, multiple greenhouses. The Digital Twin of multiple greenhouses couples the data on and states of more than one greenhouse.

The dominant focus of Digital Twins in the papers reviewed is on the cultivation process itself. In most articles, the virtualised object is a greenhouse (Fig. 9). Climate management is the most important

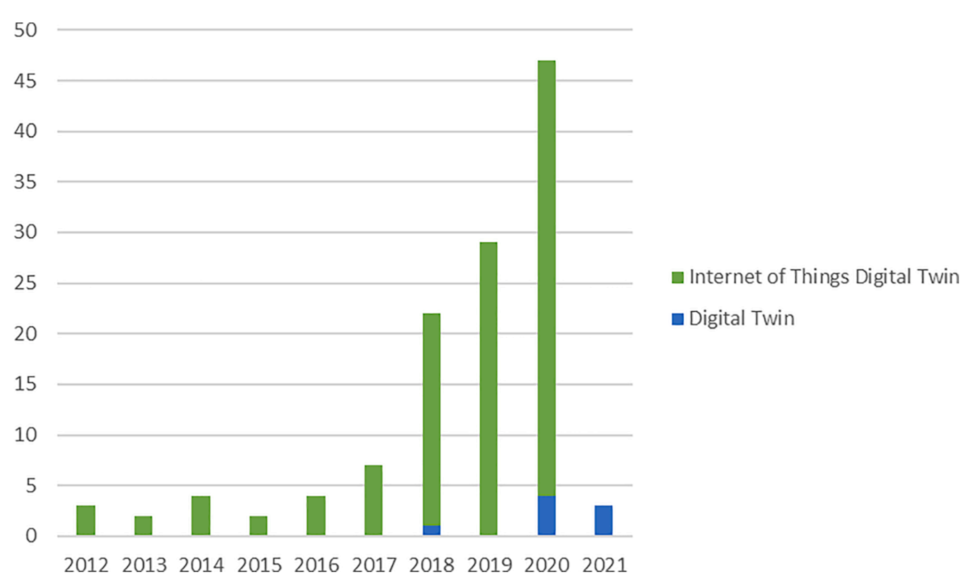

Fig. 5. Number of articles published per year, categorized into papers that explicitly (Digital Twin) or implicitly (Internet of Things Digital Twin) address Digital Twins in greenhouse horticulture.

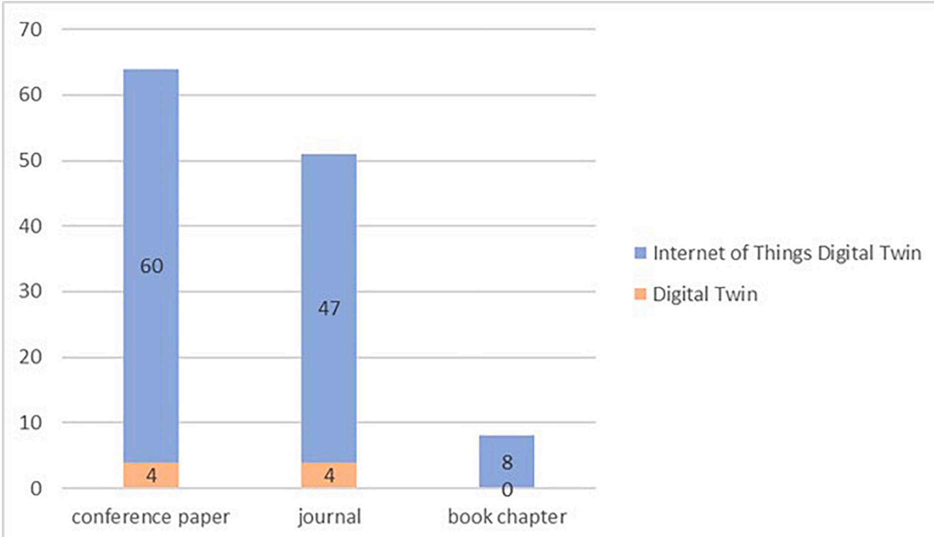

Fig. 6. Type of publications of reviewed papers that explicitly (Digital Twin) or implicitly (Internet of Things Digital Twin) address Digital Twins (number of papers per category) in greenhouse horticulture..

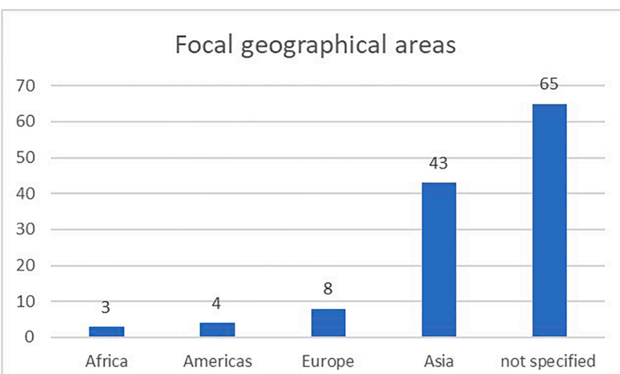

Fig. 7. Focal geographical areas (number of papers per region).

application of these Digital Twins. They use a wide range of sensors measuring the climatic conditions, including temperature and humidity and visualise this in virtual representations of the greenhouse. Other applications on this granularity level are Digital Twins for energy management, optimisation of lighting, irrigation, CO2 monitoring, fertilisation, and yield prediction.

About 9% of the articles are virtualising the plants themselves. For example, sensors on the leaves or at different heights of the stem return the state of the plant to its virtual representation. Here a grower can detect diseases or plant growth deviations. One paper specifically describes a smart pot that contains several sensors (Hadabas et al., 2019).

There is only a small proportion (nine) of the articles that have a focus that goes beyond a single greenhouse, seven on multiple greenhouses and two that visualise the supply chain. The papers virtualising multiple greenhouses aim to connect the input, throughput and output of single greenhouses and combine this in a Digital Twin of the network of greenhouses. A grower checks the current status per greenhouse and uses this data to optimise the overall output or productivity. Similar to the Digital Twin of a single greenhouse, the focus is mostly on cultivation and greenhouse climate. One could say a Digital Twin of multiple

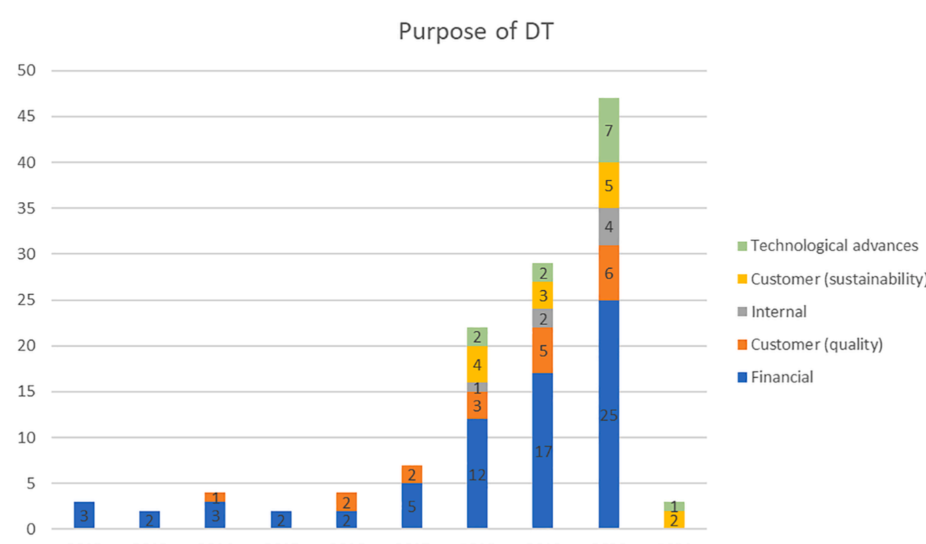

Fig. 8. Purposes of Digital Twins, mentioned by the number of reviewed papers throughout the years.

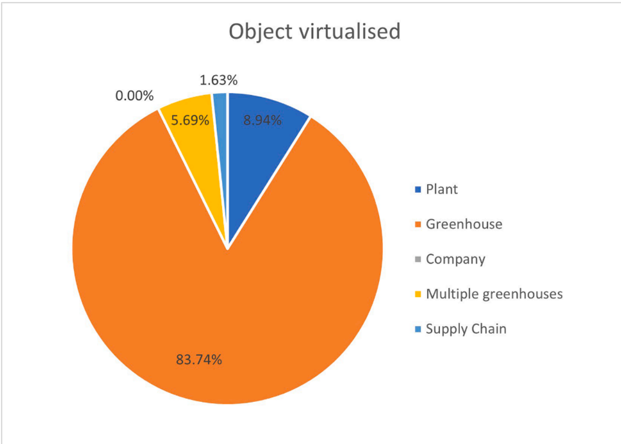

Fig. 9. Object virtualised (percentage of reviewed papers per object), multiple granularity levels possible per paper.

greenhouses is a combined Digital Twin of single greenhouses.

The two articles on Supply Chain Digital Twins describe how supply chain management can be managed without physical proximity. Verdouw et al. (2013) conceptualise the decoupling of coordination and control in floricultural supply chains by using virtual objects (i.e. Digital Twins) of real objects like a product, box, container or truck. The other article describes a simulation-based Digital Twin in Industrial Hemp Supply Chains (Wang et al., 2020).

Finally, we did not find papers that virtualise business processes at the company level. The management aspects of using Digital Twins to plan, monitor, control, and optimise horticultural companies' business processes are not yet addressed.

If we consider the reviewed paper's publication year, no prominent trends emerge (Fig. 10). Articles that virtualise multiple greenhouses are published over the last few years, but the sharp increase of studies since 2018 might also be the reason for that. This is also the case for virtualisation of individual plants.

4.5. Digital Twin types (what?)

The majority of the reviewed papers (73%) describe a monitoring type of a Digital Twin, i.e. digital representations of the (near) real-time condition, behaviour and environment, including its trajectory (Fig. 11). In addition to the typology as introduced in section 2.2, these monitoring Digital Twins can be further classified into Digital Twins that are only used monitor real-life objects (25% of the reviewed papers), and Digital Twins that are also used for automated control of the real-life objects (48% of the reviewed papers). For the latter, humans still analyse the sensed objects, decide on the required interventions and trigger execution. However, the execution itself is automated by actuators that are connected to the Digital Twin. For instance, Digital Twin shows a deviation of the plant growth in a particular greenhouse compartment. The grower decides on the action needed, for example changing the temperature, and remotely triggers an actuator to switch on the heater or open a window.

In addition to monitoring and control, 19% of the reviewed articles also use a Prediction Digital Twins that project future state and behaviour. In these Digital Twins, simulation becomes more apparent, as a grower predicts yield or quality when changing parameters (temperature, humidity, nutrition, etc.). Prediction is also used for risk analysis in the hemp supply chain in the United States (Wang et al., 2020) and for calculating production deadlines and quality (Howard et al., 2020).

Some papers (6%) also use a Prescriptive Digital Twin, which proposes recommended interventions. For example, Liu et al. (2020) use such a Digital Twin to advise about the application of nutrients to improve productivity after a yield simulation. Subahi and Bouazza (2020) use IoT data to predict production and growth rate, and subsequently advise on actions for reducing energy consumption. Finally, Howard et al. (2021) apply a prescriptive Digital Twin to optimise a production schedule while considering the energy consumption and costs.

The only paper about Autonomous Digital Twins is using a mobile robot that collects data through image processing, soil samples and onboard sensors for the ambient climate data. A fuzzy interference system then processes the data to obtain the most appropriate decision for the actuators to control the greenhouse climate (Dharmasena et al., 2019).

One paper refers to an Imaginary Digital Twin, a Digital Twin of a physical product that does not yet exist. In this case, the Digital Twin is used to design a sustainable greenhouse with added functionality as an event location (Cumo et al., 2020). More specifically, it models the greenhouse in 3D, visualises the building process, calculates the costs, manages energy efficiency performance, and measures its environmental impacts throughout its life cycle (LCA approach).

The Recollection Digital Twin keeps the physical counterpart's complete history, while the physical object no longer exists in real-life. None of the papers mentioned this type of Digital Twin.

Fig. 12 shows that predictive Digital Twins are emerging recently. Before 2018 all the described Digital Twins are used to monitor their real-life siblings and partly also include automated control. This can be

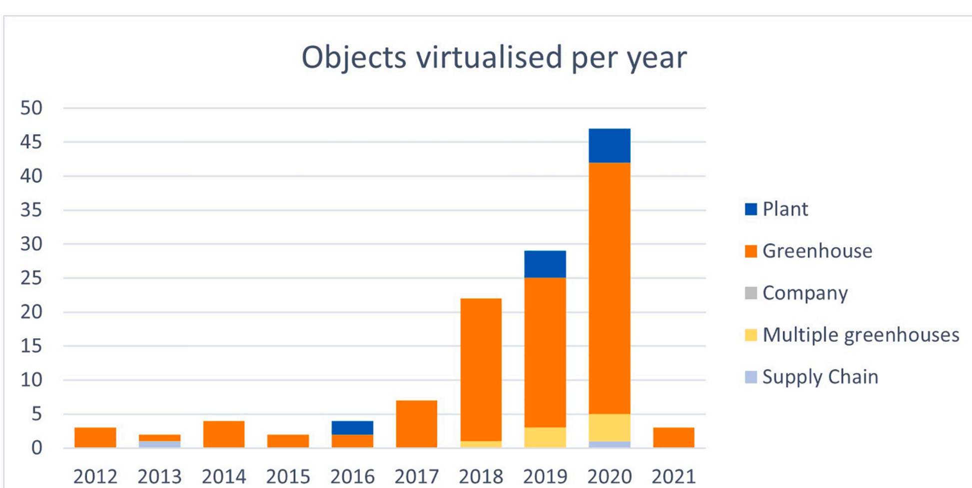

Fig. 10. Overview of the objects addressed per year (number of papers per object addressed).

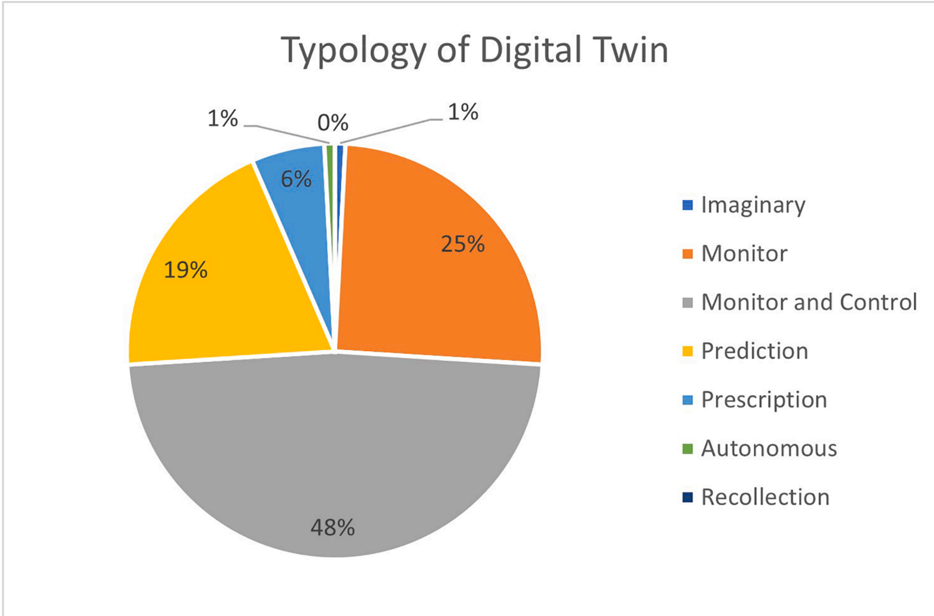

Fig. 11. Typology of Digital Twin (percentage of papers per DT type).

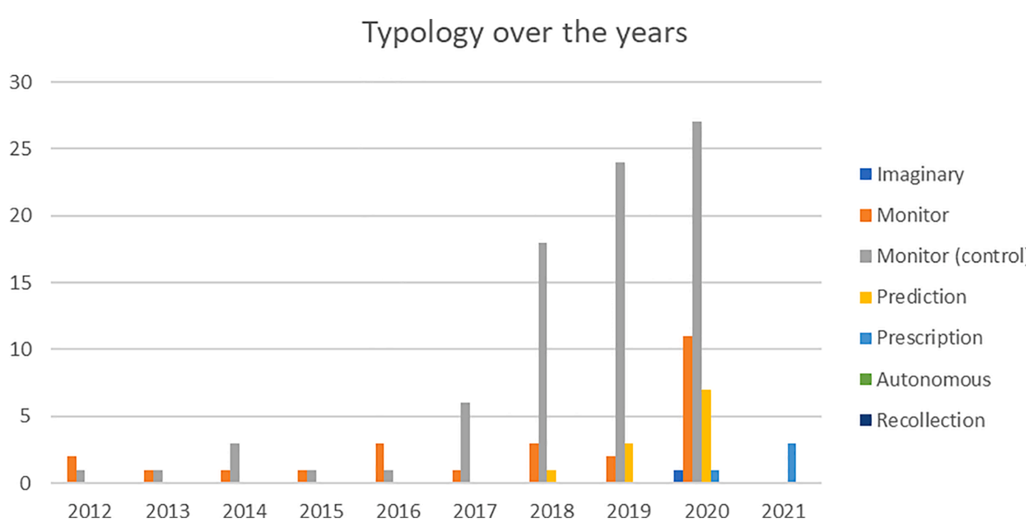

Fig. 12. Overview of the Digital Twin types addressed over the years (number of papers per DT type).

explained because predictive Digital Twins build on the capabilities of Monitoring Digital Twins and they have to use more advanced analytics techniques, including machine learning, and therefore require more in-depth knowledge. A similar explanation might hold for the few recent papers on prescriptive twins, which build on the capabilities of predictive twins.

4.6. Enabling technologies (how?)

Most of the papers analysed apply a layered model, that ranges from a physical layer of objects and devices, to an application layer that interacts with users. However, not all papers do explicitly describe the underlying architecture, especially conceptual studies, reviews and explorative pilots. Furthermore, research that include architectural designs often define more layers. For example, Chaux et al. (2021) divide the integrational layer into a storage and a Digital Twin layer, while Howard et al. (2020) split-up the application layer into a function and business layer.

Concerning the *device layer*, a broad range of sensors is used, depending on the purpose and the sensed objects (Fig. 13). The most commonly used sensors are air temperature and humidity sensors). Also sensors for illuminance and soil moisture are often used, as well as CO2 sensors.

In greenhouse horticulture also actuators are widely applied (Fig. 14). The actuators to control (drip) irrigation, ventilation fans and lighting are most commonly used. However, actuators for heating and shading are mentioned less often. This might be explained by the fact these systems are automated in regular climate computers that are not controlled remotely via Digital Twins. Some papers also apply actuators for (de)humidification, creating fog and opening doors or windows.

For the *network layer*, generic technologies are applied. Wired connections are still broadly used in greenhouses to send data to gateways, because wireless connectivity is often challenging, especially in case of heavy metal constructions and tall crops. The main wireless communication technologies found in the papers are Wi-Fi, Zigbee, LoRa, NB-IoT, networked RFID and dedicated, customised protocols. Also, direct communication in wide area networks such as GPRS is used (Aafreen et al., 2019).

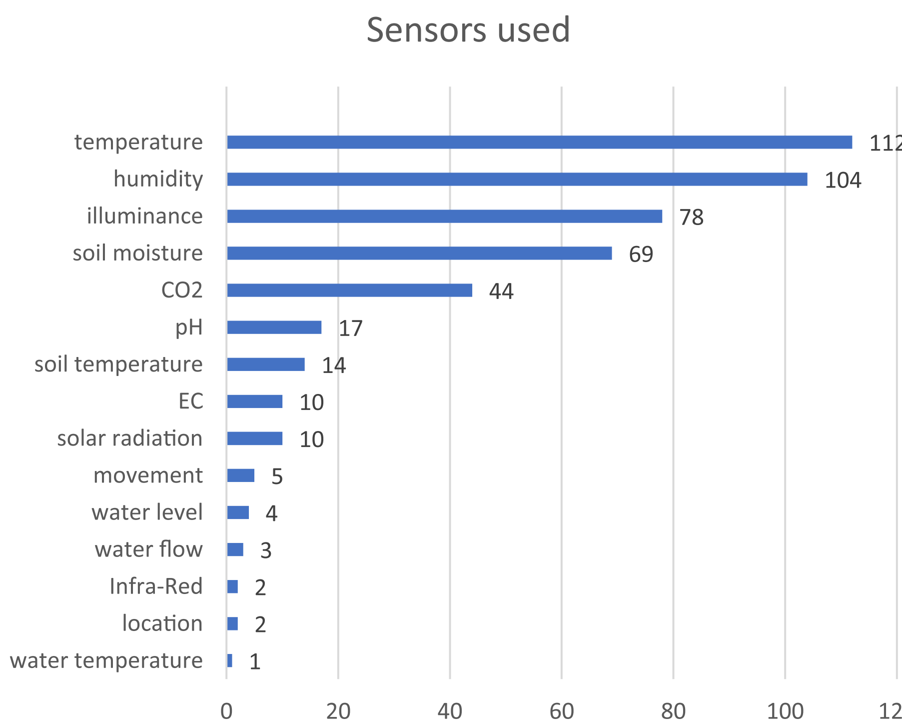

Fig. 13. Overview of the sensors used (number of papers per sensor category).

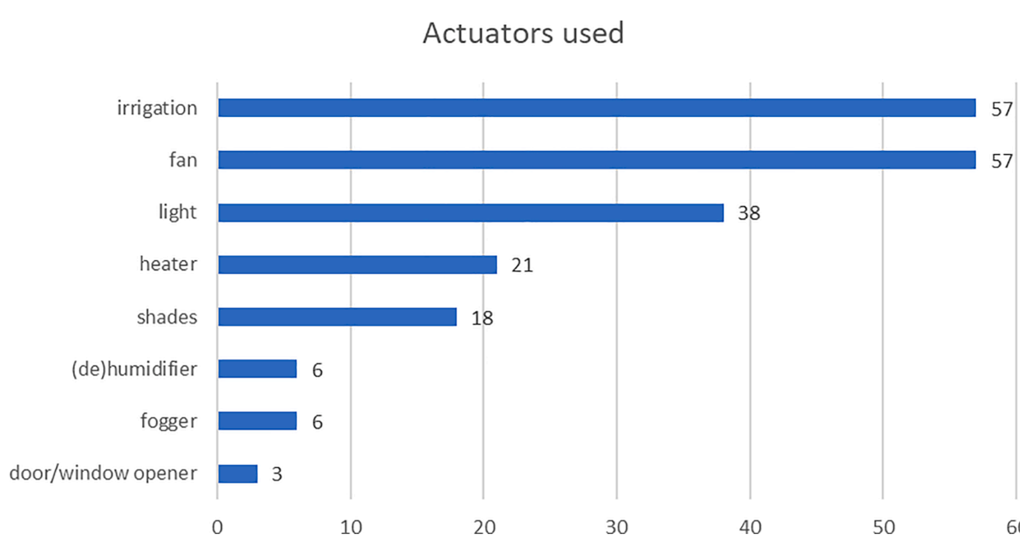

Fig. 14. Overview of the actuators used (number of papers per actuator category).

Also the successive integration layer generic technologies are applied (Pawar and Pagare, 2018; Sofwan et al., 2020; Howard et al., 2020; Escamilla-García et al., 2020). In the reviewed papers, mostly a cloud platform is used to process data and to create and manage the digital twin abstractions, e.g. the Google Platform or ThingSpeak (Drakulić and Mujčić, 2020; Jaiswal et al., 2019; Dedeepya et al., 2018). Also, Blockchain networks are applied, for example in the paper on hemp supply chains (Wang et al., 2020).

The technologies applied in the *application layer* are very dependent on the Digital Twin types addressed. Monitor Digital Twins mostly use dashboards and norms based on heuristics. Predictive and prescriptive Digital Twins mainly integrate expert-based Decision Support Models, for example for crop growth and yield prediction. Also machine learning models are increasingly applied. Autonomous Digital Twins are heavily based on Machine Learning intelligence. Furthermore, the types of user interfaces applied in the reviewed papers vary from 2D graphical user interfaces, as commonly used in personal computers, smartphones and tablets, to advanced 3D interfaces for Virtual and Augmented Reality glasses (Ren et al., 2020; Xiao et al., 2019; Howard et al., 2020).

From the articles that specified how they represented the Digital Twin, we found that the vast majority of the papers uses a dashboard with a graphical representation of the collected data (Fig. 15). Only a few articles used Simulation (Hemming et al., 2020; Howard et al., 2021; Wang et al., 2020; Shamshiri et al., 2020; Burchi et al., 2018), Virtual Reality (Ren et al., 2020) or 3D-visualisation (Cumo et al., 2020; Verdouw et al., 2013). The papers representing the Digital Twin with simulation or Virtual Reality are mainly published in the last two years.

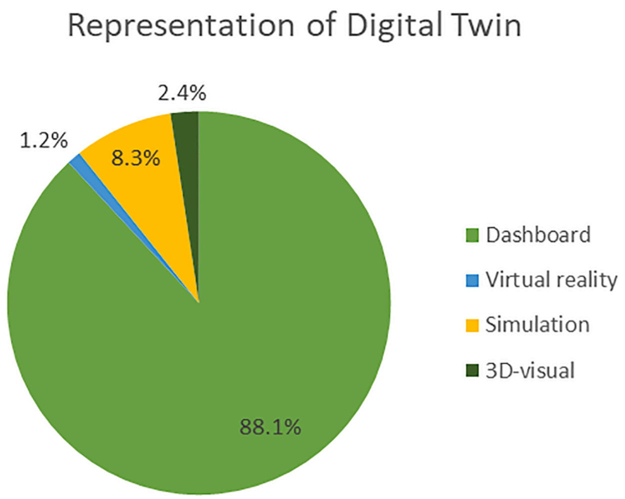

Fig. 15. Representation of Digital Twin (percentage of papers per category).

5. Discussion

Digital Twins can be seen as a new phase in smart and data-driven greenhouse horticulture. Using Digital Twins as central means for greenhouse management enables the decoupling of physical flows from its management. Growers can plan, monitor and control greenhouse operations remotely, based on (near) real-time digital information instead of direct observation and manual tasks on-site. Moreover, Digital Twins can capture the tacit 'green' knowledge of experienced horticultural experts using advanced analytics, such as machine learning, and they allow to continuously learn from data. As a consequence, Digital Twins have the potential to enhance productivity and sustainability, and to deal with the increasing scarcity of green labour, i.e. experienced employees with horticultural knowledge.

The main contribution of this paper is the provision of insight into the state-of-the-art of Digital Twin applications in greenhouse horticulture. Our systematic literature review (SLR) has applied a well-known and proven protocol to identify and synthesize the key results related to Digital Twins in greenhouse horticulture. To the best of our knowledge, this is the first SLR in this domain. Another novelty is that our SLR is based on a new conceptual framework for analysis, which is also useful for research on Digital Twins in other domains.

The results demonstrate that the concept of Digital Twins is in a seminal phase in greenhouse horticulture. Only eight articles are found that explicitly use the term Digital Twins in this domain. This is logical, as it is a relatively young concept, which was only recently introduced into the horticulture domain. At the same time, Digital Twins can be considered as a further development of especially the IoT, that increasingly uses virtual representations of real things as a basis of smart systems. For this reason, we broadened the scope of our review to include papers on smart IoT-based systems in greenhouse horticulture. We then checked if these papers implicitly address a Digital Twin. As a result, 115 additional papers were included in our review. This shows that there are already applications of Digital Twins in the greenhouse horticulture domain that are not framed as Digital Twins due to the novelty of the concept.

Digital Twins in greenhouse horticulture may range from the genetics of individual plants to a company or value chain. However, the review shows that currently there is a dominant focus on the cultivation process at the level of a greenhouse (including compartments), among other for climate control, energy management and lighting. About 9% of the articles are virtualising plants themselves, which indicates that the granularity level addressed is still rather limited. Including digital twins on a fine granularity level adds more value, but might also be more difficult and costly to implement. However, we expect that the share of digital twin applications for plants will increase, among other due to the growing availability and affordability of plant sensors and due to the rapid technology developments in the field of digital phenotyping and genotyping.

Nine papers look beyond plants or single greenhouse. Most of these few articles address the monitoring of multiple greenhouses and some focus on a supply chain. None of the reviewed papers do consider the company level. In other words, no Digital Twins are found that represent an organization, including the business processes and its (near) real-time performance. This research niche is remarkable, because the vast majority of the papers acknowledge that Digital Twins are not a goal in itself but should result in business benefits. Most articles aim to improve financial results, especially cost efficiency, or customer value including product quality and sustainability. We also expected to find more papers on virtualising supply chains, among others because of the importance of cooled and quality-controlled supply chains in horticulture. However, the limited number of supply chain papers can be explained because the focus of this review is on greenhouse horticulture, i.e. the grower's part, excluding search terms specifically for the supply chain.

Furthermore, the review shows that existing Digital Twin-based systems in greenhouse horticulture focus on monitoring the state and behaviour of real-life objects. Due to the highly automated production systems in greenhouse horticulture, also the automated execution of control based on a Digital Twin is often included. For example: if a Digital Twin notifies a growth deviation in a particular greenhouse compartment, the grower can adjust the temperature via the Digital Twin, which is integrated with the climate control system. More advanced applications, including e.g. predictive and prescriptive capabilities across the lifecycle, are still in an early stage of development. However, predictive Digital Twins are emerging as from 2018 and 18% of the reviewed papers do include predictive capabilities, e.g. for growth simulation and yield prediction. Many of the papers are also rather explorative and do not include explicit architectures or technical designs. For this reason an in-depth technical comparison was not possible.

There are many opportunities for future research to further develop the novel and compelling concept of Digital Twins in greenhouse horticulture. More knowledge is needed about how to design and implement Digital Twin based systems for taking their full advantage in this domain. So far, the Digital Twin concept is either implicitly applied or it remains a vision. More specifically, the research gaps as discussed above need to be addressed, in particular: i) including the company level of Digital Twins, ii) increasing the granularity of Digital Twins and iii) advancing the capabilities of Digital Twin concerning prediction, prescription, autonomous control and application in the complete lifecycle. Especially the diversity and dynamics of Digital Twins, as apparent in the horticultural domain, should be further studied. It is really challenging to manage interdependent Digital Twins on different levels of granularity, that continuously change and that represent very heterogenous objects, e.g. every plant is unique.

Furthermore, our framework for analysis did not take into account organisational and behavioural issues, such as the impact on supply chain collaboration, data ownership and governance, the potential emergence of disruptive business models based on Digital Twins, ethical considerations, and so forth. For example, Digital Twins would change the way how growers manage their greenhouse and their business, which requires new digital and data management competences. It is also might change supply chain collaboration, for example by enabling shorter more responsive routes from grower to end consumer or by the entrance of new tech-driven companies that specialize in virtual orchestration. We would like to encourage researchers in these disciplines to also study Digital Twins in greenhouse horticulture, since these non-technical issues might be decisive for its success.

6. Conclusions

This article presents the results of a systematic literature review on

Digital Twin technology in greenhouse horticulture. The review identifies 8 articles that explicitly address Digital Twins in greenhouse horticulture and 115 studies that implicitly apply the Digital Twin concept in smart IoT-based systems. These papers are analysed with respect to the purposes of developing a Digital Twin-based system, the real-life objects that are virtualized, the types of Digital Twins addressed, and the enabling technology.

The *purposes* addressed by the reviewed papers are to improve financial results, especially cost efficiency, and to improve customer value, especially regarding product quality and sustainability and to improve operational process performance. A minority of the papers solely focus on innovation by exploring technological advances.

Concerning the *virtualized objects*, there is a dominant focus on the cultivation at the level of a greenhouse (including compartments), among others for climate control, energy management and lighting. About 9% of the articles are virtualising plants themselves, which indicates that the granularity level addressed is still rather limited. Only nine papers look beyond plants or a single greenhouse. Most of these few articles address the monitoring multiple greenhouses and some focus on the supply chain. None of the reviewed paper do consider the company level.

Furthermore, most of the reviewed papers describe a monitoring *type of a Digital Twin*, i.e. digital representations of the (near) real-time state and real-life physical objects' behaviour. The majority of these papers also include automated control by integration of the Digital Twin with greenhouse control systems. About 18% of the reviewed papers do include predictive capabilities, e.g. for growth simulation and yield prediction. There is a sharp increase of these papers since 2018. Prescriptive, autonomous, imaginary and recollection Digital Twins are not or occasionally applied.

The *enabling technologies* used are in line with the purposes, objects and types addressed. The most commonly used sensors are air temperature and humidity sensors. Also sensors for illuminance and soil moisture are often used, as well as CO2 sensors. Moreover, actuators are widely applied, especially to control (drip) irrigation, ventilation and lighting. For communication, both wireless and wired technologies are applied, since wireless connectivity is often challenging, especially in case of heavy metal constructions and tall crops. Cloud-based systems are broadly used to store, process and share data. Finally, most applications use a dashboard with a graphical representation of the collected data. Only a few recent articles address more advanced user interfaces for simulation and virtual/mixed reality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

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