Conceptual Modelling of Digital Twin for Smart Agriculture

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Abstract

Complexity in changing objects of physical entities, processes, and applied technological solutions is the key obstacle to smart agriculture's fast development. As the representation, the digital twin serves many purposes: automating processes, improving decision-making for particular processes, and facilitating the simulation of various scenarios. The identified approach reduces complexity and concentrates on essential subjects, objects, and processes from a stakeholder perspective. The authors of this paper propose a Viewpoint Oriented Subject-Object Meta-Model (ViPOSOM) that can provide initial requirements for digital twin solution development for smart agriculture. The main idea is to identify the main objects with characteristics and relationships within their development phases for the life cycle. This approach's novelty lies in identifying the sensing requirements of the object/entity. The approach targets an agricultural physical entity changing its structure and behavior over time. By 'physical entity', the authors mean artifacts such as crops and vegetables. The paper also describes the real-life application of the proposed approach with the Living Lab of potato plants in a small-scale experimental field. Unlike the digital twin in manufacturing or civil engineering, agricultural objects face significant uncertainties regarding the internal changes of the physical entity (object), which defines the necessity to apply a method that uses time scale and development phase as the main characteristics of the physical entity in the digital object.

Keywords

Meta-modelling, Digital Twin, Smart Agriculture, Internet of Things

1. Introduction

Development time and precision are challenging factors for simulation modeling software solutions in the agricultural field. Traditionally, simulation models are designed within the communities of researchers from a particular field and are based on large data sets of historical data and knowledge. The digital transformation area provides new horizons for ambient simulations in all sectors. The development of real-time simulation modeling environments in agriculture, the environment, and medicine is challenging because of the timely changes in objects such as living organisms or human beings. Information systems design and simulation modeling were separate disciplines before the Internet of Things (IoT) and new sensing technologies became available for various applications in research, production, and people's everyday lives. Conceptual modeling has been discussed, and the model has been applied for quite a long time. Many results have been reached, and artifacts have been found. For digital twins (DT), conceptual modeling gathers new insights and perspectives regarding system engineering. Thanks to pervasive and uninterrupted connectivity provided by new technologies, a digital twin eliminates essential limitations related to location, time, and human oversight [1]. For smart agriculture, a digital twin is a concept that aligns with changing behavior over time, rendering the initial model of the object invalid when measurement data capturing this change becomes available [2]. However, with new freedom come challenges for the design development of digital twin (DT)

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technological solutions. The main challenge lies in the complexity of the physical objects and the level of abstraction required for their representation. The authors propose a Viewpoint Oriented Subject-Object Meta-Model (ViPOSOM) to tackle the mentioned challenges. The method incorporates design principles within the timeline of the proposed artifact, based on its lifecycle and from the viewpoint of the stakeholder of a particular simulation environment.

2. Research Design and Methodology for Conceptual Modeling for Smart Agriculture

The main difference in DT development within the field lies in the characteristics and uncertainties associated with the changes of the object over time. For example, there is industrial DT, where changes are predefined or based on data from industrial processes. Environmental or agriculture cases need special attention for modeling purposes because of the changing nature of objects over time. For example, in DT modeling for potatoes, it is necessary to account for changes in the main object due to its biology and genetics. The particular step in the modeling process can capture these specific challenges. The authors propose applying the LivingLab approach for interdisciplinary research to build DT in agriculture. Object life cycle and development stages are the most significant aspects of creating accurate models and technological solutions for agricultural purposes. This aspect is not emphasized in research on domain-specific conceptual modeling. Sensing and data interpretation need special attention from a meta-modeling point of view. An example of considering the object life cycle for building a digital twin (DT) is described in the authors' previous research on developing a simulation model for organic potato production [3] and [4]. Figure 1 shows the concept of research design for the conceptual modeling of DT. The concept proposes four main steps: 1) Sense (sensing the object); 2) Interpret (interpreting the gathered data); 3) Integrate (integrating the data into a single software solution); and 4) Visualise (visualising the data and simulation).

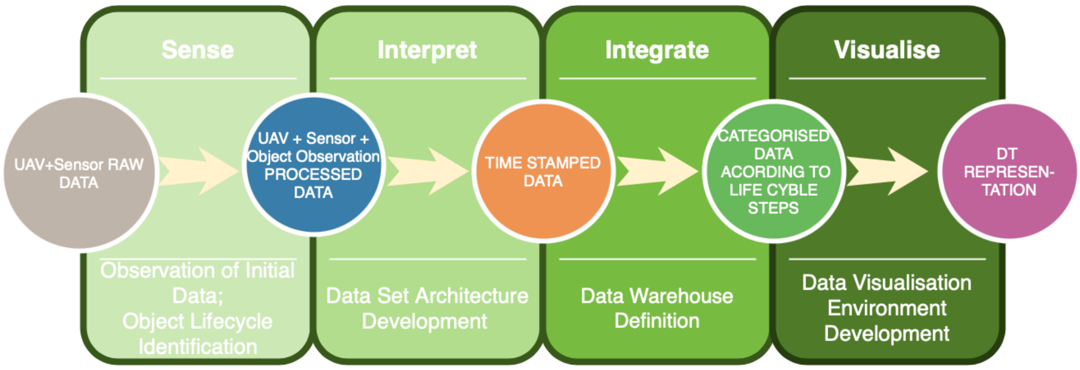

Figure 1: General Concept of Research Desing for DT Conceptual Model

There are challenges for each step where conceptual modeling can contribute to more sophisticated solutions. For Step 1, the challenge lies in determining what is being sensed. Engineers install soil moisture in the field and integrate data for simulation or potato growth. However, interpreting this data is necessary to make predictions based on the potato development cycle. For Step 2, the challenge lies in interpreting data according to time series and appropriate algorithms needs to be applied. For Step 3 the challenge is integrating data into the data warehouse. This involves handling various data types and characteristics while ensuring the original data is not lost during necessary transformations. Step 4 focuses on visualisation. The challenge lies in the visualization of processes and outcomes and DT visual representation.

The general concept of research design for the DT conceptual model proposes the agricultural LivingLab as the primary source of data from real-life objects. This approach allows stakeholders, modeling facili-

tators, and project leaders to access and contribute to the digital twin model. This paper discusses the development of digital twins (DT) in the organic production of potatoes (Solanum tuberosum). The DT model is designed to offer technological solutions during the growth stage and make harvest predictions, factoring in climate conditions and the specific traits of the potato variety. Implementing DT in crop production promises more informed decision-making regarding the precise timing and application of plant protection products, ultimately improving plant health and crop yield. In agricultural contexts, DT represents a simultaneous digital representation of real-world objects, incorporating real-time data and the variables influencing plant growth.
During the research, we identified four necessary steps, including DT conceptual modeling and incorporating steps according to the concepts shown in Figure 1. The outcome of the steps is shown in Figure 2. Figure 2 represents sensor data captured and analyzed before setting up measurement frequency. A new database was created within Oracle to interpret the data. A simulation model was created and

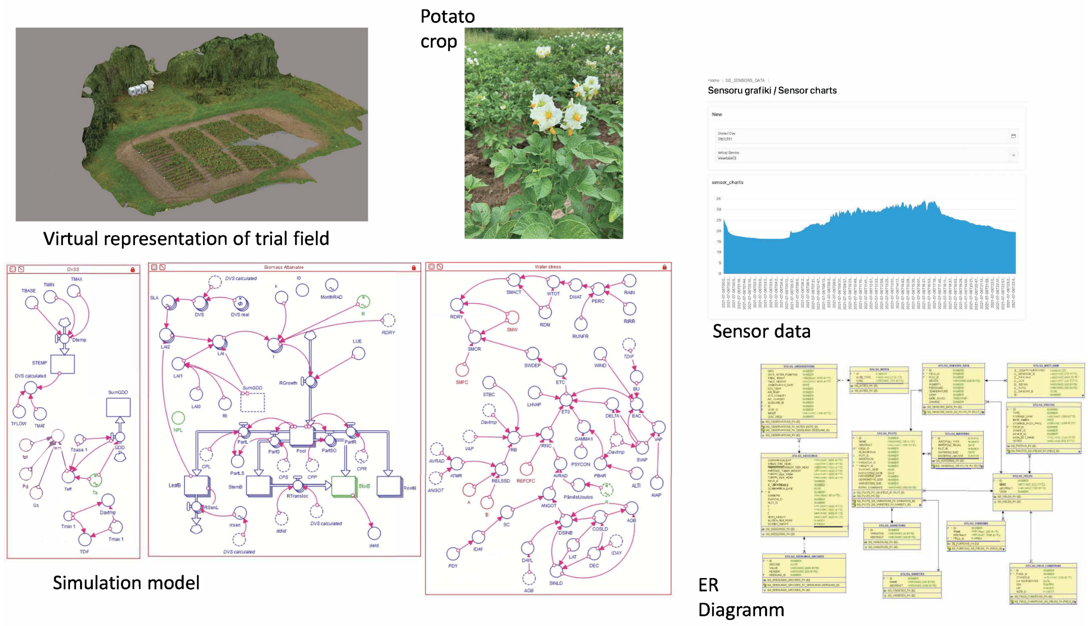

Figure 2: Outcome of Performed Steps according to Conceptual Modeling Methodology [3]

tested to understand the whole process of potato growth. Finally, an unmanned aerial vehicle (drone) was applied to capture the growing stages of the potato plant. As a result of the sensing, interpretation, and integration phases, a new conceptual model was developed. This model serves as a basis for discussions on new improvements and the incorporation of a viewpoint-oriented method for developing a digital twin (DT) for potato plant growth and production calculation. Figure 3 represents the conceptual model that serves as a basis for Viewpoint Oriented Subject-Object Meta-Model (ViPOSOM). The main challenge and research direction for conceptual design is identifying and reflecting an object's changes over time. The next section reflects and discusses the proposed approach.

3. Viewpoint Oriented Subject-Object Conceptual Model (ViPOSOM)

TThe idea of the Viewpoint Oriented Subject-Object Meta-Model (ViPOSOM) originates from two sources and has been combined by the authors. The first part of the methodology is derived from the Viewpoint Oriented Method (VORD) [5], which is defined as "a software requirements engineering approach used to organize both the elicitation process and the requirements themselves into viewpoints " [6]. The second part comes from studying and analyzing use cases in various fields [7]. The authors proposed a modeling approach that integrates a viewpoint-oriented architecture with visual representations of subjects, objects, and their relationships within specific models [8]], incorporating the time

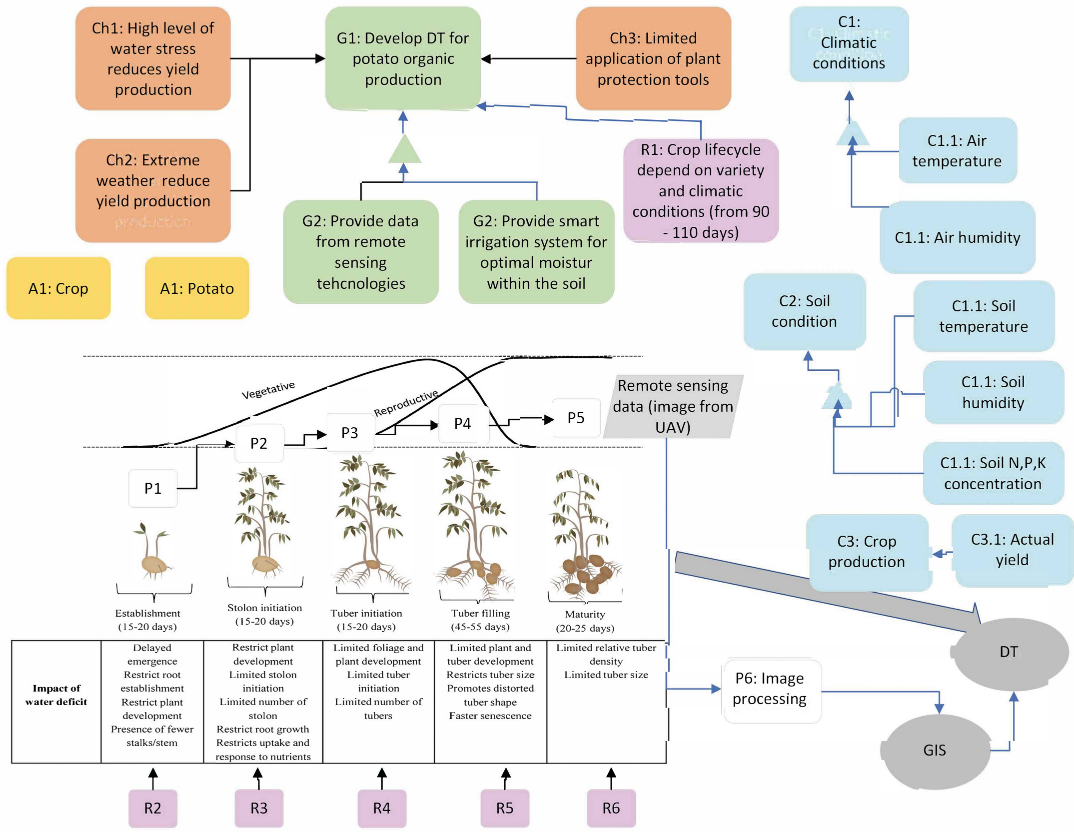

Figure 3: Conceptual model for ViPOSOM Design [3]

dimension. State representation and the time dimension are a crucial aspect that needs to be taken into consideration for meta-model development using ViPOSOM (see Fig. 5).

An architectural view represents a set of system elements and associated relations to support a particular concern. Having multiple views helps to separate the concerns and, as such, supports the modeling, understanding, communication, and analysis of the software architecture for different stakeholders. Architectural views conform to viewpoints representing the conventions for constructing and using a view. An architectural framework organizes and structures the proposed architectural viewpoints. Different architectural frameworks have been proposed in the literature [2]. Organizing the system as a set of viewpoints has also been addressed in enterprise application systems using so-called enterprise architecture frameworks [4], [9]. The notion of viewpoint now plays an important role in modeling and documenting architecture. So far, most architectural viewpoints seem to have been primarily used to support communication among stakeholders or, at best, to provide a blueprint for the detailed design. From a historical perspective, it can be observed that viewpoints defined later are more precise and consistent than the earlier approaches. Still, a close analysis shows that even existing viewpoints lack some precision. Moreover, since existing frameworks provide mechanisms for adding new viewpoints, the risk of introducing imprecise viewpoints is high.

An incomplete or imprecise viewpoint will hinder the understanding and application of the viewpoints needed to derive the corresponding architectural views and will likewise lower the quality of the architectural document [5]

Figure 4 illustrates a viewpoint-oriented process for meta-modeling. The basic idea is that an artifact exists in real-life situations, and various sensor data show particular aspects of the artifact. For particular DT development, necessary (or available) measurements are defined to represent the artifact from the viewpoint of particular stakeholders.

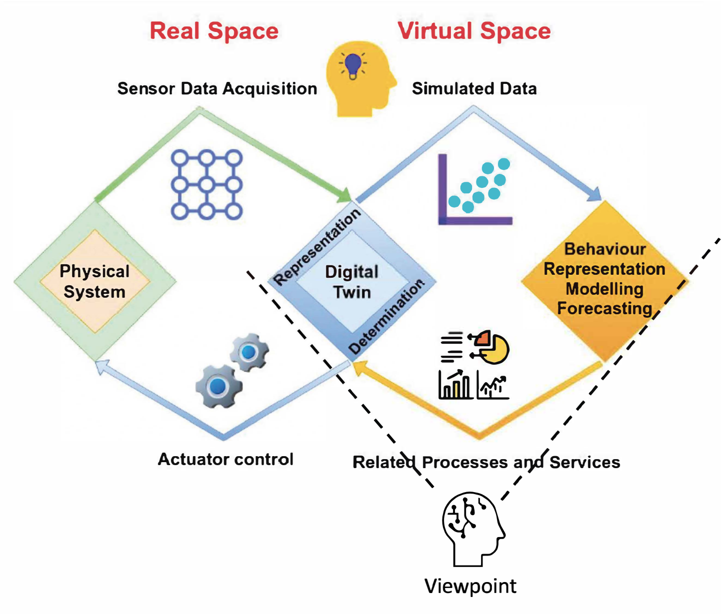

Figure 4: Main idea of ViPOSOM (Adapted from [10])

4. Application of ViPOSOM in Practice: Case Study of Modeling for Potato Organic Production Management

This section represents the practical application of ViPOSOM. The target of this representation is the development of a digital twin (DT) for potato organic production management. In this case, the DT represents the calculation of potential harvest and the influence of irrigation on the yield gap. Organic crop production management, from a broader technological perspective, includes a smart farming system. It is a cyber-physical control cycle integrating sensing and monitoring, smart analyses, planning, and smart control of farm operations for all relevant farming activities [11]. An important point here is the conceptual modeling approach to particular technological solutions. The solution lies in two directions:

1) sensing technologies and algorithms, and 2) a system for data extraction, processing, and loading. Figure 5 represents the application of the ViPOSOM methodology in practical application for DT development in potato production.

The ViPOSOM methodology includes the following steps:

1) set up a LivingLab according to the requirements for field experiments. This step is needed to identify the real-life object characteristics for technological sensing. This step is sometimes skipped in software engineering and substituted with analytical tasks or observation. However, it is a critical point for precise DT development in agriculture [11];

2) observe the real-life objects to identify their characteristics and development cycles that match with sensing technologies. This step requires transcript development in the structure, which includes the primary information needed;

3) identify viewpoints as well as subject-object relationships and their representation for each viewpoint;

4) set up the defined outcomes from Step 3 on a time scale according to the life cycle of a real-life object.

The time scale shown in Figure 5 shows potato five growing stages [12], [3]:1) establishment (15-20 days); 2) stolon initiation (15-20 days); 3) tuber initiation (15-20 days); 4) tuber filling (45-55 days); 5) maturity (20-25 days). The length of time for each stage (S1-S5) depends on the variety and environmental conditions, and this is the first challenge and requirement for the definition of DT for potato growth. The next challenge is the sensing technologies and algorithms that must be set up for each growing stage. In some cases, the same sensing technologies are used for every step: 1) potato plant sensing pictures (O1); 2) soil temperature and moisture (O2); 3) solar light (O3); 4) air temperature and moisture

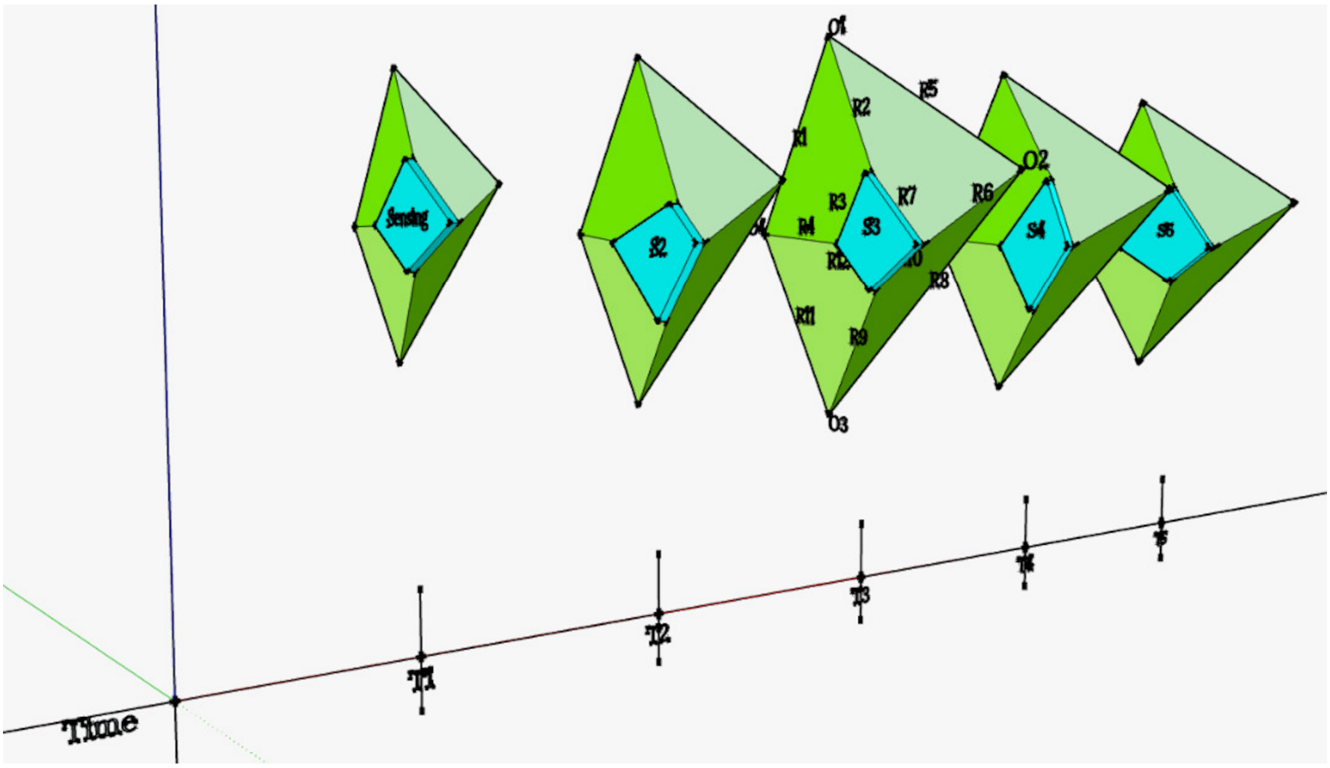

Figure 5: ViPOSOM concept for requirements definition

(O4). The next step is the definition of relationships among objects.
There are three types of relationships identified:
1) relationships among objects (R1; R5; R8; R11);
2) relationships from objects to sensing equipment, specifying what is measured and how (R2; R6; R9; R4);
3) relationships among sensing equipment due to the frequency of measurements and measurement range (R3; R7; R10; R12).
R1 represents potato growth according to air temperature and moisture. The challenge lies in the fact that the growing process is more intensive at the appropriate temperature. When the temperature is out of range, the growth intensity decreases. This correlation for the algorithm needs to be clarified through the LivingLab experiment. R5 represents potato water and nutrient consumption. The challenge here is to define an algorithm for identifying consumption patterns according to the growing stage, air temperature, and solar light.
R8 represents evaporation and nutrient intake influenced by solar light. The challenge lies in the fact that the algorithm needs to consider the growing phase, air temperature, and solar light.
R11 represents the solar influence on air conditions, which cannot be directly sensed with technological solutions, as well as the sun's influence on the earth's surface.
R2 represents a remote sensing process from the potato field using an unmanned area vehicle (UAV). The challenge lies in the frequency of data collection and its interpretation for simulation software.
R6 involves sensing from soil. The challenge lies in determining the sensing frequency because of data processing and accuracy. R9 focuses on sensing of solar light. The challenge lies in choosing appropriate sensing equipment and frequency based on the potato growing cycle.
R4 represents the sensing process from sensors in the potato field. The challenge lies the frequency of data collection and its interpretation for simulation software, as these measurements only indicate soil conditions. An appropriate algorithm must be developed to interpret the data for potato growth simulation.
R3 involves adjusting UAV data and sensor data with a timestamp. The challenge is adjusting the

frequency of measurements.
R7 focuses on adjusting sensor data and UAV images to align with frequency identification.
R10 involves adjusting sensor data and timestamps.
Figure 5 shows an example of the potato breeder's and agronomist's viewpoints. Adding more viewpoints would provide a more detailed reflection in the model. The challenge lies in managing the increased complexity and achieving the next level of harmonization for sensing frequency and data interpretation, while ensuring that the actual state of the digital twin's (DT) real-life objects is not lost.

5. Conclusion and Future Work

The research conducted by the authors has shed light on the increasing complexity of Digital Twin (DT) representations, which intensifies as the need to incorporate viewpoints from stakeholders becomes more pronounced. This complexity necessitates that modelers undertake the critical task of defining and clarifying these viewpoints and identifying specific requirements for the DT. To illustrate the model in practice, the research offers an example involving viewpoints from plant breeders and agronomists. The integration of further meta-models becomes imperative to encompass additional perspectives.

As additional viewpoints are brought into the analysis, the overall complexity of the DT representation continues to escalate. This growing complexity is a natural consequence of striving to comprehensively consider the diverse and nuanced needs and perspectives of the stakeholders involved.

Future work in this area will focus on harmonizing parameters and developing software algorithms. The evolving meta-models constructed will be used to tailor these algorithms. The research suggests that ViPOSOM could be instrumental in this process, helping to refine and fine-tune the software to better align with the complex interplay of stakeholder viewpoints, requirements, and needs in the realm of Digital Twin representation.

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