Digital Twin Modelling for Eco-Cyber-Physical Systems: In the Case of A Smart Agriculture Living Lab

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Abstract

Digital Twin (DT) models are becoming popular in various industries as simulation environments or as digital representations within the virtual environment. Most of them are cyber-physical, socio-cyber-physical or socio-technical systems. Eco-Cyber-Physical Systems (ECPS) are coming into the arena of cyber-space with the advancement of technological solutions for environmental modelling by the application of remote sensing technologies and intelligent solutions for interfering technologies. Modelling DT is a complex task because it requires using information from real word phenomena that is incorporated into digital representations. Adding verification and validation processes to this procedure makes it more complex. This paper suggests using Enterprise Modelling (EM) as the baseline for DT design as a representation and functional analysis of (ECPS). Living Lab (LL) methodology is applied as a continuous improvement test bed for DT of ECPS. This also provides resilience to technological solutions applied in the DT design, development and verification and validation processes of ECPS. This paper presents a practical application of a proposed solution in the case of organic potato production. The proposal is based on an analysis of the related literature and real life field experiments conducted in Latvia.

Keywords

Enterprise Modelling, Eco-Cyber-Physical Systems, Digital Twin, Smart Agriculture, Internet of Thing

1. Introduction

Enterprise Modelling (EM) is currently spreading among a variety of industries and not only covers manufacturing, logistics, healthcare [1], cybersecurity [2],but also agriculture. Complex solutions for data acquisition and process automation in smart agriculture are possible using the Internet of Things (IoT) and Artificial Intelligence (AI). A big challenge remains in the requirements process because of the continuous changing environmental conditions and the behaviour of real-life objects and their surrounding environments. EM as a methodological driving force for complex analysis and digital transformation is being applied in various business,

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industrial and social aspects and has become more popular especially for the analysis of complex systems with an emphasis on security and resilience aspects. But, so far, it has not often been applied in the agricultural sector. But, the rapid changes in the climate and the environment requires smart solutions and the deployment of intelligent automated systems in agriculture and environmental management, and that is leading to a new kind of methodological solution for requirements development [3]. The focus of this paper is on the expansion of EM methodologies for the application of the development of DT in agriculture through a case study in a living lab.

Digital Twin (DT) is the next step in the evaluation process of a simulation model and virtual and augmented representation. It is designed and evaluated through the integration of various technologies such as the Internet of Things, artificial intelligence, machine learning, and data science, which enable living digital simulation models to be created that reflect the changes of the physical counterparts [4]. Due to the multiple existing concepts and solutions based on DT across industries, a diverse and only incomplete understanding of this field exists [5]. Digital Twin, in general terms, is a real-world representation within the digital world. Many definitions exist for this term and its contexts. Examining DT in any context, one might identify a common understanding of Digital Twin as producing digital counterparts of physical objects [5]. For context of this paper, we use Kritzinge's definition of DT , which defines DT as the digital representation of an existing or planned physical object with the data flows between an existing physical object and a digital object being fully integrated in both directions ([5]. In such a combination, the digital object might also act as a controlling factor for the physical object. There might also be other objects, physical or digital, which induce changes of state in the digital object. A change in state of the physical object directly leads to a change in state of the digital object and vice versa [5]. For a more complex and deeper view, we would define it as not only representation but also as an active influence or action from cyberspace back to the real environment. This simultaneously realised link is the representation and main characteristic that distinguishes DT from the complex simulation model.

Eco-Cyber-Physical System (ECPS) is a complex phenomenon that has arisen in the last decade with the accelerated development of the Internet of Things (IoT) and remote sensing (RS) technologies which are incorporated in practically all industries and processes. Previously in the modelling field, scientists and practitioners dealt with such terms as sociotechnical [6], cyber-physical [7], and socio-cyber-physical systems [8] modelling. All these terms are also used within the modelling field nowadays. But,the explanation varies according to the context and complexity of the real-life phenomena and available technologies for process management. A socio-technical system refers both to the interrelatedness of social and technical aspects of an organisation or the society as a whole, whereas technology, not including material things, does include organisational structures and processes [8].

The case of a smart agriculture living lab (LL) is presented in order to prove the concept in a real-life situation. A living lab by definition, is a physical or virtual space used to solve societal challenges, especially for urban areas, by bringing together various stakeholders for collaboration and collective ideation [9]. Through a review of the pertinent literature the characteristics of living labs have been taken into account in the development of a smart agriculture living lab: context (e.g. context research, familiar context, real-world context), users (involving users as co-creators), activity (e.g. co-creation, technical testing, evaluation), challenges (discovery), and innovative outcomes (e.g. large-scale solutions) [9]. LLs are an open innovation ecosystem for society, communities, or stakeholder members used to: (a) identify problems in their lives and; (b) propose solutions [10]. The LL integrates the research and innovation processes within a public–private–people partnership and is a tool and platform that can be used effectively in allowing suitable representatives to participate in the decision-making process in various contexts in order to find solutions to practical problems in real life and to directly participate in solving those problems [10]. In order to improve innovative solutions, the co-creation paradigm comes in to the arena [11] which is not typical for the EM situation. This is interesting concept and approach, where the EM model is updated on the basis of real-life solution evaluations, is incorporated can be accessed by the stakeholders as well as the modelling facilitators and project leaders. This paper provides validating evidence for using DT in potato (Solanum tuberosum) production, where digital twin (DT) modelling is designed to provide technological solutions in the growing stage and to make harvest predictions according to climatic conditions and the specific properties of a potato variety. As a benefit, DT in crop production may help in decision-making for precise timing and application of plant protection products to improve plant health and crop yield. DT, used in agriculture, is a simultaneous digital representation of real-life objects with real-time data and the factors that influence plant growth. The development of DT for agriculture is a complex process and requires the live knowledge-sharing process with adaptation to a particular environment (farm conditions). The potato crop was chosen because of the fact that it is a crop more sensitive to water stress, and building a DT model can contribute to more precise decisions regarding irrigation based on sensor data and climatic conditions.

This research paper is organized as follows: after the **introduction** section, the **second section** refers to eco-cyber-physical systems modelling and its context-specific requirements. It outlines characteristics of real-world phenomena in the context of modelling tasks, and specifies architecture requirements for DT development, highlights various viewpoints and incorporates the stakeholders' involvement in terms of knowledge-sharing and case design planning and evolution which is an important part for such complex solutions. **The third section** includes a DT modelling roadmap for ECPS. It outlines the main processes for planning and deploying DT projects in order to reach the goal for simultaneous updating of a modern technological solution. **The fourth section** describes the application of the 4EM methodology for ECPS and DT development and expands the notation necessary in a particular context. **The fifth section** describes the smart agriculture Living Lab (LL) dedicated to testing and evaluating the proposed approach. This step is being conducted in a field trial conducted in 4 places in Latvia ie. the districts of Vestiena, Priekuļi, Līči and Stende. The section outlines the results and main findings for future work. **The sixth section** includes the conclusion and suggestions for future work.

2. Eco-Cyber-Physical Systems Modelling

The term Eco-systems in computer science has been well-known for a quite long time [12], [13] and has been applied in various contexts, but often, it is a term describing an organizational system within its environment [14]. The term Eco-Cyber-Physical-System (ECPS) is new and, in the literature, is defined as " a combination of the living and non-living components of the ecosystem in conjunction with the cyber-physical sensors and intelligent agents in the environment, interacting as a system" [15]. The goal of the ECPS is to use the power of artificial intelligence combined with the Internet of Things (IoT) in order to provide smart solutions for rural, agricultural and natural ecosystems. The collected data from satellite and Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicle (UGVs), smart enterprises and smart villages can be used for modelling the living and farming behaviours of rural communities (Majidi et al., 2021). The proposed definition perfectly describes the main function of ECPS in the surroundings outlined above, but does not incorporate digital twin as a representation and component from cyberspace that can interact and influence real-life objects or phenomena. The authors define the Eco-Cyber-Physical system in this context as "an interaction of the living and non-living components of the ecosystem virtually incorporated within the digital environment considering self-regulation, adaptation, and interoperability principles".

ECPS positioning (Figure 1) happens through the incorporation of six types of systems integration: 1) physical systems which are remote sensing and actuating systems for DT support with on-line data flow, including equipment and vehicles for application within the agricultural domain; 2) cyber systems are information systems (local or cloud based) which provide information storing, processing and visualisation as well as cybersecurity; 3) cyber-physical systems highlight the links between digital and physical entities in systems such as agricultural systems, and rural areas wherein physical objects and processes are replaced, or complemented, by digital ones [8]; 4) ecosystem is a biological community of interacting organisms in their physical environment [16]; 5) the eco-physical systems approach is designed in order to integrate the energy dimension into the physical design when selecting materialized views, one of the redundant optimization structures [17]; 6) is an interesting domain identified by the authors and these are artificial intelligence based systems working in cyberspace with the aim to simulate, predict or recognize an ecosystem's phenomena (image recognition systems).

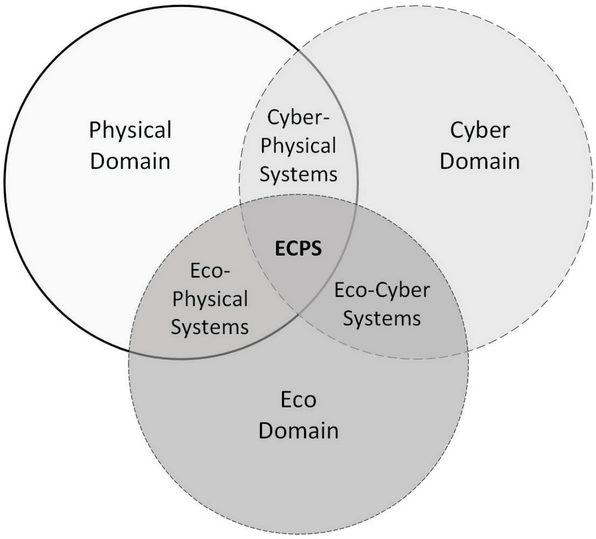


Figure 1: Positioning of Eco-Cyber-Physical Systems (ECPS) adapted from [8] and [18]

ECPS consists of:

1. A biological phenomenon which is a general object for digital representation and simulation. In our case, it is a potato plant;

2. The environment is characterised by various parameters. In our case, it is soil characteristics (permanent and changing within a relatively short time, weather conditions, environmental characteristics like air temperature and humidity, soil temperature and humidity);

3. Physical equipment takes parameters from the environment and biological phenomena and effects or influences phenomena or their environment;

4. Cyberspace where DT is reflecting and simulating real-life objects.

A Digital Twin model can significantly enhance the required control capabilities of ECPS by enabling the decoupling of physical and information aspects of farm management [19]. Table 1 includes components of ECPS for digital twin modelling that can be used to monitor the actual state of objects, prescribe desired states, predict future states, and to remotely correct the state of real-life objects [19]. Components can vary in response to the application field. Table 1 analyses the components of the agriculture living lab.

The next chapter explains the DT modelling process for ECPS in more detail.

3. DT Modelling Road Map for ECPS

For DT modelling in ECPS in smart agriculture the following issues have to be taken in consideration:

1. DT as phenomena or object – what we need to reflect on, analyse or predict;

2. Quantity, granularity and equality or influence – do we analyse each object or do we collect them and do they interfere with each other;

3. DT environmental or influence factors – what is influencing real real-life object;

4. DT life cycle – what will be the life length of one DT instance;

5. DT development stages – what are the states of DT, how long are they and what outcomes do they produce;

6. DT data security – it is important to follow the security triad (confidentiality, integrity, availability).

In order to develop DT models for ECPS in smart agriculture, it is very important to incorporate the Living Lab (LL) approach for a better understanding of real-life phenomena and reach more precise results and beneficial outcomes for stakeholders. Figure 2 represents a process road map for DT development for ECPS in smart agriculture.

In figure 2 the full process starts with the DT real-life object definition, which in practice means that we have to define very precisely what the object will be. In the case of smart agriculture it could be a crop or an animal or some disease. It depends on the type of DT, and according to that, we choose and define the object. The next step is the definition of the environment, which means influential factors. In the smart agriculture case, the factors influencing crops are soil type, fertility and humidity as well as air temperature and humidity. With DT development for ECPS the complexity lies in various factors influencing DT real-life objects. When we develop DT and its surroundings, we assume that the probability of other influential factors is very low. The third step is the author's proposed building of the 4EM model with extended notation, which includes the mentioned aspects in Table 1. After the

Table 1
Components of Eco-Cyber-Physical Systems from the Enterprise Modelling Perspective (from the Case of Smart Agriculture Living Lab)

Component type by the application domain	**Aspect for Modelling**	**Parameters to include in the 4EM as notation**	**Technological solution for interaction with DT**
Eco (living)	Life cycle length	Full development length in days	Data repository (database for collecting and processing data)
	Behaviour	Growing stages	Imaging technologies (cameras, UAV, UGV)
	Health/disease	Healthy, damaged, infected	Imaging technologies, Thermal cameras
	Output (harvest or animals ready to be slaughtered)	Amount of biomass or livestock	Digital measuring
Eco (non-living)	Environmental characteristics for living creatures, plants and organisms	Sensing frequency of measurements	Environmental sensors
	Tools for creature protection against diseases or other living organisms	Application conditions	Automatic spreading via sprinkles, UAV or tractors
Physical	On-site sensing Measurements	Sensing frequency	Data from environmental sensors
	Equipment for surrounding environment preparation	Process prerequisites, frequency of application Impact on environment	Precise time planning, work done, time spent, resources spent
Cyber	Data repository	Data repository structure	Distributed computing
	Brokers functions and data	Brokers for IoT data interoperability	Third party involvement
	Visualisation screens	Visualisation from stakeholder's view	Visualisation according to the stakeholder's need
	Security	Data security	Functions and procedures for data protection
	Data transfer on real-time mode	Data transmission period/synchronization	Algorithm in the case of no communication channel available
	Granularity or complexity	DT level of details and surroundings	Precise definition of DT
	DT type	According to type	Type definition within 4EM

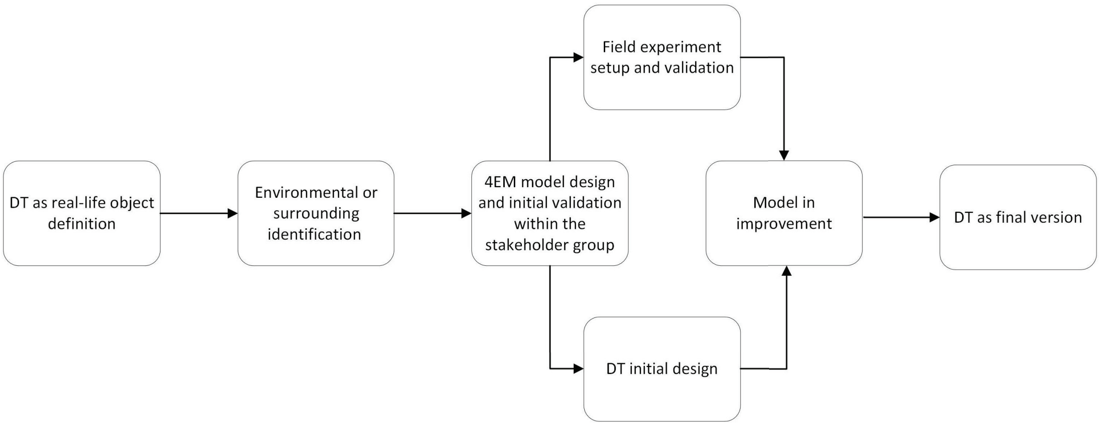


Figure 2: Process road map for DT development for ECPS in smart agriculture

model development comes the design and set up of the field experiment and initial design of DT, which includes building information and communication infrastructure and development of the information system according to requirements defined in 4EM model. The next steps are the evaluation of initial results, DT update and development of the final version. The Improvement of DT could be in various steps, but we need to take into account that agriculture is a field which is characterised by seasonality, and it means that no more than 2 cycles are possible within one project. The next section reflects the expansion of 4EM for EPS for smart agriculture.

4. Expansion of 4EM for ECPS

The 4EM Enterprise Modelling method [20] consists of six sub-models for modelling goals, concepts, business rules, business processes, actors and resources, and information system technical components and requirements models [21]. They are designed to be sufficiently general to be able to capture and represent most modelling problems related to the organizational designs [22]. Expansion of the 4EM methodology for ECPS for smart agriculture is required in order to cover all aspects mentioned in Table 1 (Section 2) and for the development of a DT component and deployment of a smart agriculture Living Lab. Expansion is required because DT models go beyond static product designs, like CAD models, or representation of logistics processes, design of robotics or other engineering systems. The DT model comprises dynamic behaviour and is the perfect solution for the elaboration of ECPS for smart agriculture. This dynamic nature of DT may include the representation of current behaviour of real-life objects, but also the simulation or prediction of future behaviour and the recollection of historical behaviour [19]. The challenging task is to reflect dynamic behaviour with static structure in order to plan, monitor, control and optimize farm processes [19]. The main idea of expansion for the 4EM method came through collaboration with farmers within the STARGATE project, where discussion about requirements elicitation and constructive discussion arises. The main goal was to develop the next stage for the simulation model – DT and modern technologies in smart agriculture offer a large range of possibilities for application. The author's idea was to expand the existing 4EM methodology with necessary aspects for the design of DT for ECSP in smart agriculture. Before designing a smart agriculture living lab (described in the next section), the authors studied the literature about the requirements for a framework or methodology for DT for ECSP in smart agriculture [19], [4], [23], [24]. For the expansion of the 4EM method Verdous's basic principles for framework development where applied to create a practical application for a smart agriculture living lab as described in 5 section [19]:

1. Representation of a cyber-physical control cycle of smart farming or a particular DT;
2. Sensing and monitoring, smart analyses and planning and smart control of farm operations for all relevant farm processes or a particular DT elaboration;
3. Includes imaginary, monitoring, predictive, prescriptive, autonomous and recollection DT types;
4. Supports the implementation of essential characteristics of DT, ie.timeliness, fidelity, integration, intelligence, and complexity;
5. Addresses the specific challenges of implementing DT in farm management, ie.farm object complexity, farm network dynamics and farm process dynamics.

Table 2 represents additional extensions for the 4EM method [22] in order to apply it to the development of DT for ECSP in smart agriculture.

Table 2
Extension for 4EM sub-models and DT aspects for ECSP in smart agriculture

4EM sub-models	Aspects form ECPS perspective	Principles applied
Goal model	Granularity or complexity, DT type	Addressed specific challenges
Business rules model	Life cycle length, Health/disease, Data transfer on real-time mode	Rules for real-life imaginary, sensing and control, intervention frequency
Concepts model	Output, Environmental characteristics for living creatures, plants and organisms	Specification of characteristics
Business process model	Behaviour	DT types, sensing, monitoring and prevention techniques
Actors and recourses model	Crop type, characteristic or animal type and characteristic	DT real-life object characteristic
Technical components and requirements model	Tools for creature protection against diseases or other living organisms, On-site sensing Measurements, Equipment for surrounding environment preparation, Data repository	Supports the implementation of essential characteristics of DT

This next section describes the implementation of DT for ECPS within a smart agriculture living lab. It also represents a practical implementation of requirements in the technical solution and describes the evaluation process and improvement of DT for practical deployment on farms.

5. Case of A Smart Agriculture Living Lab

A Living Lab is the perfect tool for the design of Eco-Cyber-Physical systems as it contributes to a better understanding of the ecosystem and its representation within and collaboration with cyberspace and the impact of the physical equipment. Living Lab (LL) is designed as the space for so that Living Labs are spaces for innovative and participative research, for development and activities that use multidisciplinary approaches, and promote the co-creation paradigm and focus on many different arenas of human life [11]. LL is characterised by an innovation and co-creation process [11]. A common practice for LL applications is the involvement of users at all stages of developing new solutions for socio-economic or technological challenges. Living labs are suitable for developing, co-creating, validating, and testing technologies [9]. This practice perfectly fits and resonates with the 4EM paradigm and suits DT development through the continuity of the co-creation process and the active solution improvement within real-life settings by evaluating co-creation cycles. The overall method consists of four steps: 1) Living Lab set up and identification of main challenges; 2) Expansion of the 4EM method for analysis and representation; 3) building DT in order to help decision making; 4) field trials for practical evaluation.

The first step – The Living Lab process was organised in various places in Latvia. There were organised meetings with stakeholders in order to gather knowledge and establish the requirements for DT design In total four sessions were organised. In practice there are two parts: 1) Living Lab set up and planning; 2) Development of 4EM and expansion for DT design. Face-to-face sessions in the practitioner's community were held to gather knowledge related to the 4EM model and to set up field experiments. Both steps were conducted simultaneously during the specially organised sessions with stakeholders. A Living Lab in this step serves as a platform for requirements elicitation from stakeholders regarding main challenges facing climate-smart agriculture and ascertaining how climate and environmental sensor data can give a benefit or make a contribution to meet the challenges. The first session was held in Priekuļi, Latvia with representatives of the Institute of Agricultural Resources and Economics. This session was organised in two parts where the first part was dedicated to explaining the research field and any problems. The second part was dedicated directly to requirements elicitation. During the first part, moderators explained the possibilities of IoT and remote sensing methods and their application for building DT which could help in the decision-making process for climate-smart agriculture. The second session was organised in Stende at a branch of the Institute of Agricultural Resources and Economics. This session was organised in a similar way to the session which was organized in Priekuļi. Additional to the meeting on the institute premises, a field trip to potato fields was organized. This was done to understand the potato production process and its main challenges and to identify the necessary data flow for potato production and yield gap calculation. The third session was organised on the farming operation "Vietalas" near Valmiera. This session took place on the field and included the same topic about challenges in potato production. Additionally,a demonstration of remote sensing technologies for crop health evaluation was conducted . A practical demonstration was carried out by the authors. It helped to engender fresh and innovative thoughts about technological possibilities concerning smart agriculture. The fourth session was organised on a farm named "Dzeņi" near Varakļāni, Latvia. This session was similar to the session organised in "Vietalas" but with an additional demonstration from farmers about the new functionality of modern tractors and how they are applied in potato organic production. After the sessions all results where summarised in two main outcomes: 1) aspects for 4EM extension; 2) identification of main components for DT design.

The second step - 4EM method development and expansion was elaborated based on principles for model development [21]. Crop development stages were incorporated as an extension from traditional model, where business processes and information flow is identified. The outline from the developed model is shown in the 3. The first task from face-to-face sessions elaborated in step one of the LL was to choose a crop for DT development. There were two options: 1) wheat; 2) potatoes.

The authors made the decision to choose potatoes for DT development because of three main issues:

1) the significance of the DT development in terms of yield gap reduction as it provides more precise predictions. Potato (Solanum tuberosum) is a crop which is sensitive to water stress, as this has a negative influence on-field production either as a lack of water or too much water. There are many phenological characteristics which can be reflected as particular parameters within the digital environment and these can be captured by various types of sensors and remote sensing equipment;

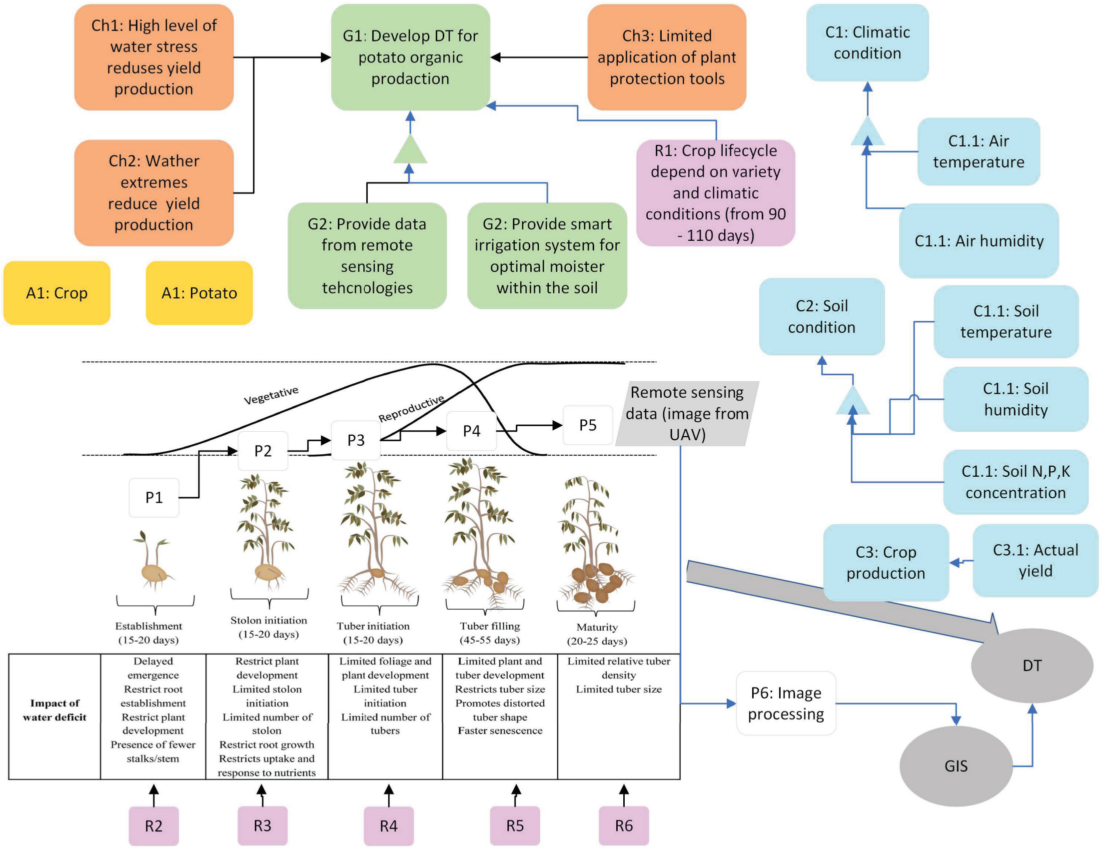
2) availability of a large set of historical data needed for DT. Latvia has a long history in potato production and research done by the Institute of Agricultural Resources and Economics (https://www.arei.lv/en) gives extensive background on potato production processes and a solid data set related to all DT types.

3) economical benefit for potato processing because there are two large production companies who require good quality potatoes as production material. These companies are Aloja Starkelsen SIA (https://alojas.lv) and ORKLA branch "Ādažu čipsi" (https://cipsi.lv/en/about-us/). Representatives of these companies and those from the Union of Potato Producers and Processors expressed interest in this issue.

Figure 3 represents an outline of the 4EM model and its extension. The model represents all six sub-models:

- Goal model (marked with green colour and labelled with G) – shows the main goals that need to be reached by the elaboration of smart agriculture LL;
- Actors model (marked with yellow colour and labelled with A) – shows the potato as the main actor participating in the DT;
- The challenges model (marked with orange and labelled with Ch) – shows challenges that need to be addressed or taken into account for DT development;
- The business process model (marked with white and labelled with P) – shows potato development stages and the duration of each stage. Traditionally this model includes processes and knowledge flow. In the extended version of 4EM, the authors are able to demonstrate crop development stages as a process and show impact factors as an extension for the rules model which reduce the actual potato harvest;
- The business rules model (marked with pink and labelled with R) – incorporates specific rules for crop development and also the reduction factors within the development stages in the water-limited situation;

- Concepts model (marked with cyan and labelled with C) – reflects concepts explained from the other models and shows characteristics of the crop environment;
- Technical component and requirement model (marked with grey and labelled with T) – reflects digital twin (DT) and Geographical Information System (GIS) as the main components with the data flow to them.



	Establishment (15-20 days)	Stolon initiation (15-20 days)	Tuber initiation (15-20 days)	Tuber filling (45-55 days)	Maturity (20-25 days)
Impact of water deficit	Delayed emergence Restrict root establishment Restrict plant development Presence of fewer stalks/stem	Restrict plant development Limited stolon initiation Limited number of stolon Restrict root growth Restricts uptake and response to nutrients	Limited foliage and plant development Limited tuber initiation Limited number of tubers	Limited plant and tuber development Restricts tuber size Promotes distorted tuber shape Faster senescence	Limited relative tuber density Limited tuber size

Figure 3: Expansion of 4EM model for DT development for a smart agriculture living lab

The third step – building DT for its application in the living lab. Design includes four conceptual parts: farmer as stakeholder who identified requirements and gets benefit from DT; conceptual modelling component where 4EM modelling results are incorporated in the further processes; a data acquisition system and applied technologies for data gathering; components that are included in DT. The designed concept is incorporated in the smart agriculture living lab.

The fourth step – Field trials as living labs were elaborated in four different places: Vestiena, Priekuļi, Stende an Līči. Figure 4 shows the map with location of the living labs. Within the living lab,a field trial was elaborated. In all places, there was a plan for the potato field set up. according to best practices for field trials in potato production. Figure 6 reflects all DT components from a real life potato crop as the central object. To explain, a Living Lab is set up as a reflection of a real-life object from one aspect and also as a test bed or simulation environment from a different aspect. It means that various scenarios can be simulated in the virtual environment to show potential outcomes. For example, we use soil moisture sensor data for precise decisions on irrigation to see the outcome or economic benefit of the application of a particular amount of water. The irrigation functionality was only installed in the Veseta living lab and is now being tested (during summer of 2022). The potato crop DT model is constantly updated with new data sets which the authors see as valuable for the simulation model behind the DT and also for new findings about technologies applied for remote sensing data incorporation in DT.

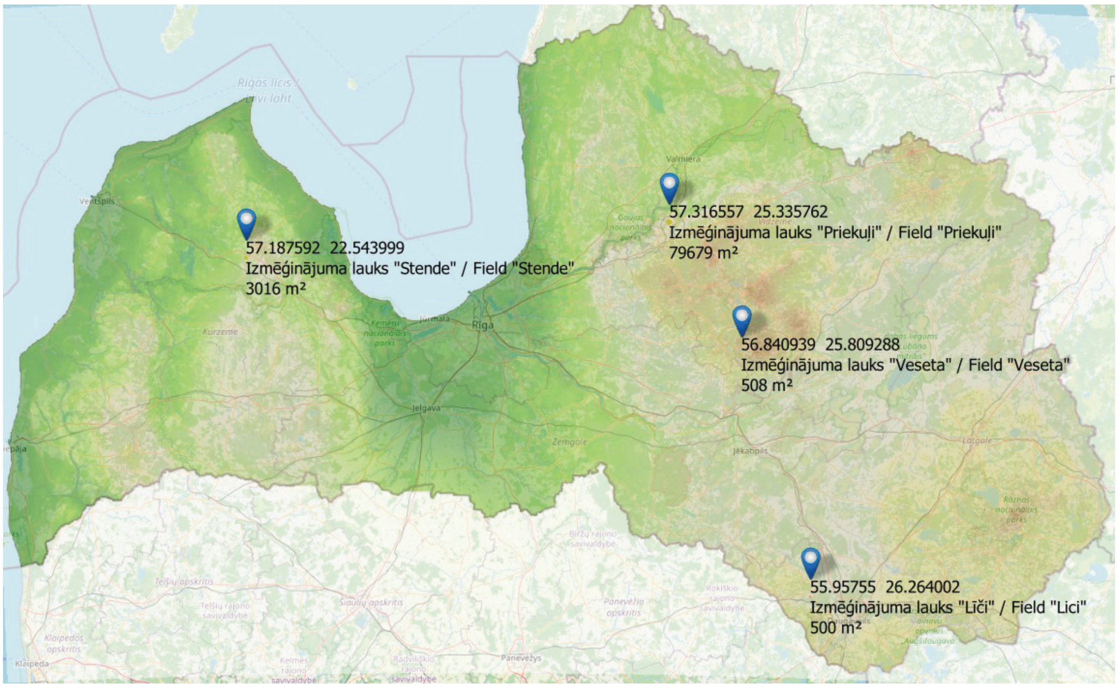


Figure 4: Map with locations of the Living Labs

6. Conclusions and Future Work

EM methodologies till now have been applied mostly in the manufacturing, logistics, healthcare, organizational problem domains. In the literature research conducted by the authors of this paper no cases for the application of EM methods for the agriculture domain were found. This creates an interesting and challenging task because of the dynamical changes in the domain as itself. The challenge relates to a large variety of dependent variables and also to the traditional approaches used by agricultural experts to conduct research. The 4EM methodology has a lot of advantages. . The paper's authors have almost 20 years experience that show that 4EM has proven its real value when applied to very challenging and also relatively easier issues in domain analysis and requirements definition for information systems. New challenges are arising in DT development and incorporation not only in manufacturing, construction building and medicine, but also in agriculture. The agriculture domain requires an ecosystem approach for analysis of problem domains. The Eco-cyber-physical systems (ECPS) approach to modelling, system thinking and the building of DT is a valuable and necessary tool in order to get appropriate results for decision making and intervention in production.

The application of LL within the DT process gives value not only by developing a more iterative process, but it is also significant for ECPS development as far as new findings that give technological solutions, and that initiate new conclusions which may change sensing and intervention practices. Smart LL for potato organic production is an example of such a result. An IoT solution provided more detailed and precise data about environmental conditions of crops and visual sensing gave results about crop development stages. Based on these data new frequencies for the measurement of soil moisture and humidity was set up in order to get more precise data about the necessity for and quantity of irrigation. In this Living Lab the 4EM model served as a big picture for the technical team generating a better understanding of domain and DT development directions. It contributed to decision making about practical aspects, such as: what kind of sensing equipment is needed; how many sensors are needed on the field and how to distribute them. The authors recognize that they were fortunate that they benefitted from close collaboration from other research institutions in terms of knowledge sharing and innovative strategies. But,there remains the challenge of more fully representing all the dynamics involved in this type of modelling for ECPS to evolve to its potential.

Future work lies in ensuring there is continuous improvement of DT in field trials and the next step should happen as a field trial on a real farm. Future technological development should come in ambient IoT development focussing on 4EM with incorporated extensions.

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