Digital Twins of Socio-Technical Ecosystems to Drive Societal Change

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ABSTRACT

While the engineering of digital twins (DTs) of cyber-physical systems already faces a number of challenges, DTs of socio-technical systems are made even more complex by human and social factors, and a comprehensive representation of their internal relations is currently lacking. DTs for socio-technical systems could open up new ways of achieving common societal goals by i) providing an understanding of complex interactions and processes, and by ii) facilitating the design of and participation in collective actions. In this context, dynamic adaptation and motivational strategies would be required to swiftly address sub-optimal system behavior. To enable the model-driven engineering of DTs responding to such requirements, we propose a conceptual model of socio-technical systems and discuss it with use-case scenarios. The presented approach supports our vision of future DT-based model-driven interventions, empowering citizens and stakeholders in driving societal change and increasing community resilience.

CCS CONCEPTS

• **Software and its engineering** → **Model-driven software engineering**; **Domain specific languages**; • **Theory of computation** → *Data modeling*; • **Social and professional topics** → **Socio-technical systems**.

KEYWORDS

Digital Twin, Modeling, Socio-Technical System, Model-Driven Engineering, System Engineering

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1 INTRODUCTION

Digital Twins (DTs) of Cyber-Physical System (CPS) are already facing challenges, e.g., in the complexity of the technical systems, real-time requirements, and the long lifetime of the objects [31]. This complexity is increased for socio-technical systems, often also referred to as cyber-physical social systems [71], e.g., production lines [2], aerospace systems [9], hospitals [28], or cities [1, 22]. One has to additionally define system-human interaction and capture data from social systems, their culture, and goals.

A comprehensive consideration of the specifics of humans and their interaction with digital twins, as well as user-centric assistance services for digital twins [64], is currently not available. Current international research is either focusing on the twinning of cyber-physical systems [60, 67] or human-machine interaction without taking twinning into account. We address this research gap by employing a Model-Driven Engineering (MDE) approach to model representations of socio-technical systems to be used in digital twins. The model-driven engineering approach can help in defining mutually intelligible and interoperable models that can be shared and implemented across different domains and different hierarchical levels in socio-technical systems. The modeling effort made to design and develop digital twins can also provide a basis for socio-technical interventions that are not necessarily grounded in digital twin-related practices.

Different model types [62], e.g., SysML, User Requirements Notation (URN), UML, goal models, should be integrated to provide a multi-view and multi-layer comprehension of the interconnected socio-technical *eco*system. Different interconnected models that portray different aspects of the system would provide a nuanced and emerging understanding of the system's dynamics.

Our vision is to provide models and techniques to create digital twins of socio-technical ecosystems, driven by the following research question: *how can socio-technical ecosystems be modeled to engineer digital twins that guide positive change?*

These digital twins should be geared toward offering system monitoring and adaptation to maximize the collective achievement of goals, compatibly, in particular, with the UN SDGs [90]. Here we focus on the benefits that digital twins can provide to socio-technical ecosystems in terms of sustainability, inclusiveness, and community resilience. The two main digital twin components that enable our vision are i) motivational strategies (e.g., gamification), and ii) adaptation through monitoring and prediction.

We explore how MDE can support this vision, offering a structured approach to designing, developing, and managing digital twins effectively. Additionally, we present two concrete scenarios to illustrate the practical application of our conceptual model. The first scenario addresses depopulation concerns, and access to public (digital) services in remote valleys, while the second scenario delves into food waste management, showcasing strategies to engage both citizens and institutions in sustainable practices.

Through these scenarios and our conceptual model, we aim to provide actionable insights for leveraging digital twins to address complex socio-technical challenges while advancing sustainable development objectives. Moreover, these practical examples not only offer guidance on the engineering of digital twin systems but also serve as a catalyst for identifying research challenges in MDE and define our roadmap.

The remainder of this paper is structured as follows. In the next Section, we discuss previous work dealing with both socio-technical (eco)systems and digital twins. In Section 3, we present our vision for digital twins of socio-technical ecosystems to drive societal change. We provide concepts of socio-technical ecosystems to be used for MDE of DTs in Section 4 and explain its fundamental entities and relations. In Section 5, we discuss our model by providing case studies of scenarios as working examples. In particular, we focus on i) the problem of access to services and how digital twins can improve it in communities located in Trentino-South Tyrol, Italy; and ii) the problem of food waste and lack of valorization and upcycling in an Italian city. In Section 6, we discuss the next steps needed to concretize our vision regarding technology and motivational techniques, while Section 7 draws conclusive remarks.

2 BACKGROUND AND RELATED WORK

In this section we provide the foundational concepts necessary to introduce our vision. In particular, by discussing key concepts in socio-technical systems and digital twin engineering, we set the stage for exploring our vision's transformative potential in addressing contemporary challenges and advancing sustainable development objectives.

2.1 Socio-Technical Systems

From a socio-technical systems perspective, a system, e.g., an organization, comprises a set of interacting sub-systems [8]. These sub-systems are composed of different types of components [19] depicted in Figure 1: On the technical side, we have: (1) the used technology, i.e. software systems, (2) the physical infrastructure, and (3) processes. On the social side, we have: (4) people, individuals, groups, or teams, with capabilities, (5) cultural assumptions and norms, and (6) goals towards those people carrying out processes with strategies and metrics. These different components can be connected via various relationships, e.g., can be used or influenced by each other. This approach can be applied to conceptualize socio-technical systems, e.g., for the design process of information processing systems [37].

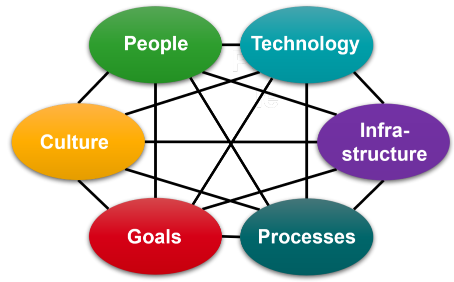

Figure 1: Relevant components for socio-technical systems and their connection (see [19]).

Several approaches, often adopted in computer science from psychology, aim to understand social aspects and socio-technical systems more systematically. Notably, looking into *activity theory*, Leont'ev [57] describes the relationship between processes and related concepts [49]: Activities are oriented towards a motive, actions are conscious processes directed at goals, and operations are routine processes and oriented towards conditions. This approach also describes the hierarchical composition of processes and goals; concepts that can be found in several goal and process modeling languages. Areas such as human-computer interaction and context modeling, follow these ideas: Kofod-Petersen and Cassens [55] use activity theory to describe context-aware systems. Their context taxonomy has a focus on the user and suggests five main context areas, namely the environmental, personal, social, task and spatio-temporal context. The context taxonomy [55] was adapted for describing *context-aware software systems*, e.g., for human behavior support [64, 65], reasoning on human behavior [95], for computer-supported cooperative work [20], or the design process of intelligent systems [7]. Recent works target the risks related to the interaction between technologies and humans in socio-technical systems. Notably, Sheikh Bahaei et al. [82] propose a modeling approach to describe automotive systems equipped with augmented reality, the user interactions, and the possible risks related to both technical and user-interaction failures.

Socio-Technical Ecosystems. Within this paper, we use the term *socio-technical ecosystems* to emphasize that also biological, physical, or chemical processes, technologies, or infrastructure are of interest for socio-technical systems. The term ecosystems was initially used in biology [17, 86] to depict interactions between different organisms and their environment as an integrated system. It was then adapted in information system research enabling the investigation of interdependencies and interactions between different actors [38]. More recent approaches [88] describe ecosystems with similar concepts as socio-technical systems, e.g., hardware, software, different people and actors (similar to Clegg [19]), however, Tsujimoto et al. focus more on the different types of actors, e.g., users, investors, entrepreneurs, innovators, policymakers.

Modeling Socio-Technical Ecosystems. When it comes to modeling these different components of a socio-technical ecosystem, heterogeneous modeling techniques can be used e.g., SysML, AutomationML, 3D or physical simulation modeling languages for complex technical systems and CPS, process modeling languages, the User Requirements Notation (URN), goal modeling languages, UML, architecture description and other software and system modeling languages to describe the software infrastructure, enterprise modeling languages to describe people and hierarchical structures, together with data-driven or AI models as well as domain-specific languages. MDE approaches can be applied to better understand socio-technical ecosystems. The diversity of information necessitates software systems capable of managing various information sources, such as digital twins.

2.2 Digital Twins

A digital twin of an original system can fulfill different purposes [23] such as analyzing systems [81], predicting behavior [14, 54], optimizing system behavior [11], assisting related users [64], simulating behavior [89], or exploring the solution space [4]. As a digital twin is an active software system, fulfilling its purposes requires data about the original system, models to describe it, and services acting on the data and models [41]. DTs include services to realize self-adaptive functionalities [12, 18], and they are well usable to realize functionalities of context-aware systems [64]. Those require methods for context acquisition via sensing and monitoring, context modeling, context reasoning in dedicated services, and context dissemination triggering actions [72].

MDE for digital twin engineering. Using MDE approaches for the engineering of DTs helps to overcome challenges in DT engineering such as the management of heterogeneous models from different areas, the bidirectional synchronization of DTs and the original system, and supporting collaborative development [13]. Moreover, the application of MDE approaches has many advantages such as increasing the development speed, better maintainability, reusability and interoperability [91]. Examples for the application of MDE for digital twin engineering are, e.g., supporting the connection from DTs to IoT systems [52], methods for the evolution of DTs [24], or integrating (model-based) DevOps principles with DT engineering [21, 46]. In addition, MDE could support the re-engineering and re-modeling of digital twins, e.g., when systems already exist and the physical reality has to be reflected in the DT.

Digital twins of cities. When dealing with socio-technical systems, humans can be considered as *things* interconnected with the rest of the system that provide means for sensing and actuating in the cyber-physical space [71]. Typical examples of these systems are smart cities, and, unsurprisingly, there exists a large body of work targeting digital twins for cities (also known as Urban Digital Twins or City Information Models) [48]. Digital twins of cities are focusing, e.g., on 3D models [93], visualizations of processes [77], particular civil structures [61], or the use of different kinds of technologies, e.g., cloud and Internet of Things (IoT) approaches [30]. They are often rather focused on technology aspects, e.g., to improve safety and security [47], or improve energy performance and efficiency [34]. Among the recurring open challenges in the existing literature data handling plays a pivotal role: since any human can be a data source storing the retrieved information becomes a relevant issue in terms of scalability; data integration is challenging given the heterogeneity of the sources (cyber, physical, and social); concerns like security, privacy, ethics must be taken into account [92]. Despite the availability of these research contributions, to the best of our knowledge, a solution is still missing that supports DTs for social systems considering humans as *actuators*, especially in the case of groups/communities.

3 THE VISION FOR DIGITAL TWINS FOR SOCIO-TECHNICAL ECOSYSTEMS

Socio-technical ecosystems include humans in the loop, which inherently convey uncertainty concerns to the resulting behavior. In the state of the art, digital twins are often used to survey runtime aspects [23] to both learn more precisely system's behaviors and possibly to counteract undesired divergences from design expectations. However, due to the presence of humans, we argue that the current concept of digital twins needs to be revised and extended to include humans in the loop. At a glance, this novel digital twin concept is context-aware and self-adaptive, in which humans make informed decisions about the needed evolution for the current socio-technical system. Moreover, humans are part of the actuation power of the digital twin, supported by motivational techniques.

In envisioning the future of digital twins for socio-technical ecosystems, we perceive a dynamic and collaborative process that unfolds across three interconnected phases: *co-design*, *co-production*, and *co-delivery* (see Figure 2). Within this framework, individuals assume diverse roles and form ensembles/groups [15, 44], each contributing unique perspectives, values, and competencies to achieve goals aligned with the overarching objectives of the process. This collaborative process can be supported and realized by a digital twin for the ecosystem. This requires (1) to provide services supporting co-design, co-production, and co-delivery, (2) data needed for these services, and (3) models describing the socio-technical ecosystem.

Throughout each of the collaboration phases, humans leverage technology to manage tasks that contribute to the overall goal. The collaborative and adaptive nature of the system we envision ensures that technology is integrated with the ecosystem optimally and unobtrusively, considering the needs of individuals with diverse interests and competencies. By harnessing technological tools and platforms, individuals can efficiently organize and execute tasks, ensuring progress toward the desired outcomes. Clearly, this vision could extend to socio-technical systems beyond CPS to all kinds of ecosystems where humans and technology are connected.

Calls for action in the form of missions, tasks, and challenges are integrated into the process, motivating participants to actively engage and contribute with their expertise. The calls for action serve as catalysts for collaboration and innovation, driving momentum toward achieving shared societal objectives.

An awareness component is also embedded into the process to foster domain-specific impact. Through feedback mechanisms, presentations, and visualization services, participants gain insights

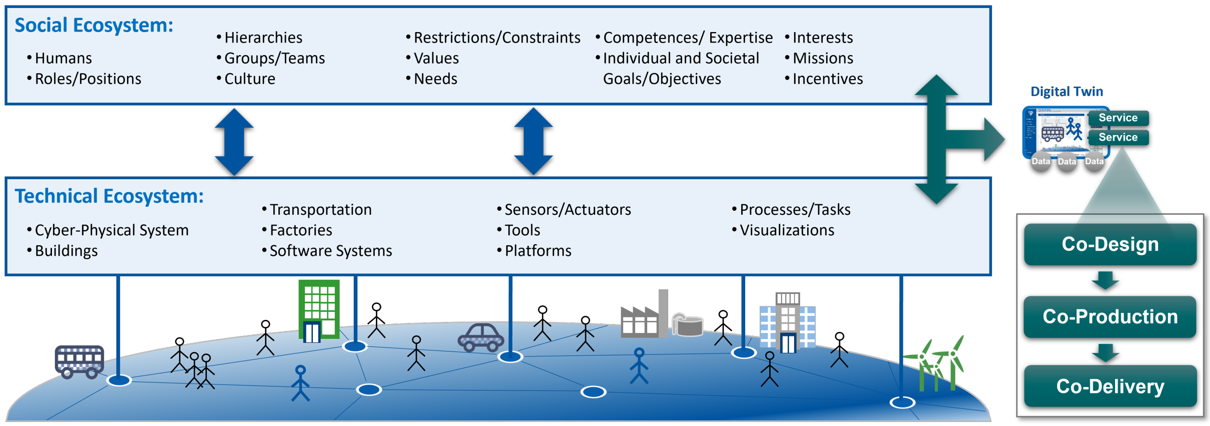

Figure 2: Socio-technical ecosystems and processes supported by digital twins.

about the tangible outcomes of their efforts. Incremental rewards based on points or monetary incentives are kept separate from the presentation of results to increase awareness about the broader impact of their contributions.

Central to the success of this vision are motivational techniques aimed at actively engaging people throughout the process. Harnessing the power of gamification to enhance engagement and incentivize participation, motivational components serve as catalysts for creativity and collaboration. They drive the co-design of novel solutions and ensure their successful co-development and co-delivery within socio-technical ecosystems. Through strategic exploitation of motivational techniques and predictive analysis, our vision is to empower stakeholders, drive behavioral change, and sustain communities in achieving societal goals and increased resilience. *By cultivating a culture of collaboration, innovation, and shared responsibility, we aim to pave the way for DTs serving as powerful tools for societal transformation and sustainable development.*

4 CONCEPTUAL MODEL

A digital twin for socio-technical ecosystems is a comprehensive framework including models and simulation services aimed at facilitating the design, analysis, adaptation, and evolution of complex socio-technical systems. It integrates various models representing the social, organizational, and technical aspects of the system, along with simulation services to analyze system behavior. The digital twin enables stakeholders to gain insights of system dynamics, evaluate different scenarios, and make informed decisions to optimize system performance and resilience in dynamic environments. Underlying the digital twin an internal representation of the socio-technical ecosystem is needed, which is reflected in a corresponding data model.

In Figure 3, we show an excerpt of the main concepts describing a socio-technical ecosystem which can be used to generate parts of a digital twin. The noted types of devices, types of services, types of software systems, types of roles, and types of activities are examples. When realizing a digital twin, they have to be tailored for the specific socio-technical ecosystem. The concepts are clustered into the different components of socio-technical systems as proposed by Clegg [19]. This approach is the base for many works on socio-technical system design [8, 10, 25, 45]. For us, it is of particular interest as Clegg's approach is also including the "physical" part of a system (called infrastructure). In socio-technical ecosystems where cyber-physical systems play an important role, we need a base model that does not merely represent the digital space.

We focus on a limited number of the existing relationships between the entities in Figure 3 for better readability; analyzing socio-technical ecosystems shows that any cluster has multiple connections to any other cluster (see Figure 1). The conceptual model also does not explicitly show "model" as concept: We could add models describing technical components, software, activities, goals, hierarchies and other aspects, however, this would increase the complexity of the explanations and is up to further research.

People. `Agents` are the humans involved in the system and can be organized into `Groups` based on hierarchical properties (`Role`) or competence and skill (`Capability`), or other properties. This enables, for example, certain agents to perform better as a whole in certain `Activities`. `Agents` lie at the micro-level while `Groups` lie at the meso- and macro-level [53]. `Groups` are compositional and can be associated with specific collective `Actions` or `Activities`.

Agents have capabilities [16] that can be compositional. A complex `Capability` composed of many atomic `Capabilities` may belong to a single `Agent` or a `Group`. Each `Agent` can perform several `Roles` that enable `Actions` relevant to the current `Activity`. An `Agent` can help another `Agent`, e.g., when performing activities. `Agents` are incentivized by `Rewards` to perform `Actions` and `Activities` and make `Decisions`. `Decisions` are taken with or without the `Recommendation Service`. `Roles` and `Groups` are associated with their hierarchical level, thus determining the decisional power. Each `Agent` has its `Interests`, which may or may not be aligned with the `Goals` of `Actions` and `Activities`. A recommendation service should ideally try to suggest `Activities` that align `Interests` with `Goals` if possible. According to self-determination theory [76], individuals are more (intrinsically) motivated to perform an activity if they are interested in it, if they have experienced high competence, autonomy, and relatedness. Intrinsic motivation can be stronger and last longer than extrinsic motivation, which is usually based solely on material rewards.

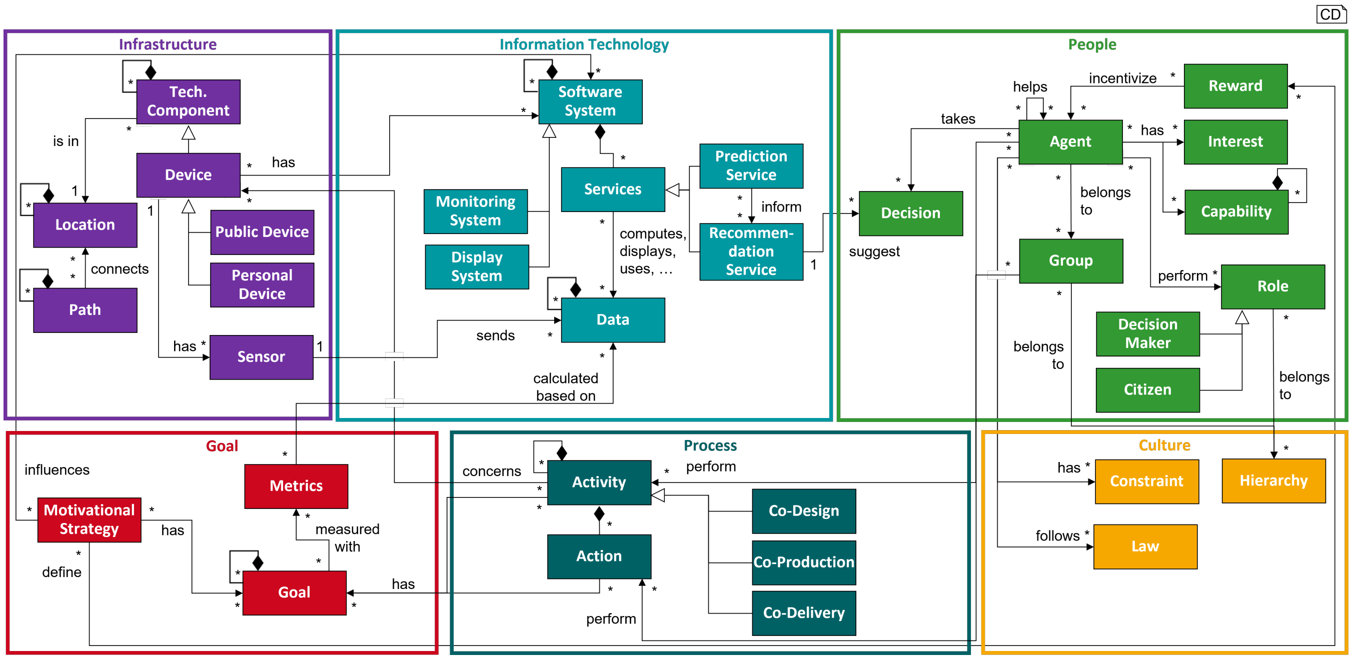

Figure 3: Conceptual model of a socio-technical ecosystem (excerpt) as UML class diagram.

Culture. Agents may have Constraints, e.g., psychological or cultural, concerning a specific Activity, which restricts certain or all the corresponding Actions. The Role belongs to a Hierarchy, which can be determined culturally and may be different for each case scenario, according to the Groups that are formed. Local Laws may also restrict certain activities.

Information Technology. The Software System orchestrates devices and data, it can be, e.g., a Monitoring and a Display System, and it is composed of different kinds of Services. Services may refer to, e.g., processing Data or displaying them. A socio-technical ecosystem can include several Software Systems that display different information on different Devices, e.g., about co-occurring initiatives. The Software System is responsible for collecting interactions from personal devices and informing, e.g., a Monitoring or Display System; the Monitoring System is responsible for extracting Metrics from the raw Data; the Display System ensures data take a human-digestible form and can be influenced by a Motivational Strategy, which may enrich the data presentation. A Prediction Service runs simulations aided by AI models, based on Metrics extracted from the raw Data collected by Sensors and Devices. The simulations inform the Recommendation Service which selects future Activities and proposes them to the Agents. The (Groups of) Agents then accept or reject the automated recommendations. Software Systems could include various additional Services relevant for DTs.

Infrastructure. Data may come from Sensors, Personal Devices (such as smartphones, and personal cars), and Public Devices (such as totems, vending machines, and buses). Devices are one group of Technical Components that can have several Software Systems running on them (also called CPS), whereas there might exist purely physical components as well. Locations can be atomic or compositions of locations (elsewhere understood as *wards* [4]), while Paths are connections between different Locations.

Processes. Actions are the atomic components that compose Activities. This level of granularity includes, e.g., initiating trips, and expressing a vote for a service on a Public Device. We also envision collaborative Actions enabled by the Information Technology and Infrastructure components, such as volunteering to offer help or to share Devices (such as vehicles). Actions may be performed as the result of publicly organized events and workshops or as grassroots initiatives. Activities can be composed of sub-activities and may include voting processes, ongoing sustainable campaigns, and workshops for citizen and stakeholder engagement. Each Activity and Action has a Goal or composition of goals. We envision three phases of societal intervention (Co-Design, Co-Production, and Co-Delivery) as higher-order activities that guide all other activities through the ecosystem transitions. As previously mentioned, this list is not exhaustive and other higher-order activities may be devised.

Goals. Goals are intended as desired end-states of Actions [57, 63]. Higher-level Goals are associated with a wider Activity that may be understood as a campaign, an intervention, or a public administration initiative. The achievement of Goals can be measured with Metrics, which are calculated based on the Data collected. Motivational Strategies can have several goals, influence Software Systems and processes, and define Rewards for contributing to this strategy.

Motivational Approach. A Motivational Strategy defines the features of a Software System and the Rewards that Agents could get. Motivational Strategies can be implemented through techniques such as gamification, i.e., the addition of game elements such as points, leaderboards, and badges to non-game contexts [27]. Specifically, Agents may be incentivized by specific Rewards (virtual or material) as well as specific (audiovisual) feedback provided through the Display System, i.e. a cognitive reward.

5 CASE STUDIES

We show the importance of the concepts in the conceptual model in two concrete case studies. The mobility scenario (Case Study 1) is inspired by SMART ERA[1], an ongoing 4-year Horizon project that aims to innovate rural areas. It is based on the real needs and requirements that emerged from the project meetings with stakeholders (service providers, mobility managers, public administrators, etc.). The food waste scenario (Case Study 2) is based on project meetings with representatives of an Italian municipality (such as a city councilor of Ferrara) and research institutes involved in the project (urban planning institutes, research centers, sustainability think tanks).

5.1 Case Study 1: Access to mobility services in rural areas

Trentino-South Tyrol is one of Italy's northernmost regions. It is almost completely mountainous and its economy heavily relies on mountain tourism. Municipalities located in this region, in Val di Sole and Val del Tesino in particular, are sparsely populated and constitute peripheral, isolated communities. Orographic constraints contribute to the overall isolation of the communities and pose real challenges in accessing services such as health, education, and mobility in and out of the territory. In addition, these areas are currently undergoing negative demographic trends. We show the entities involved in this scenario and explain how a socio-technical digital twin may help in reaching societal goals for mobility services.

Goals. A high-level Goal associated with this scenario, a possible end state is, e.g., *access to services increased by N%.*

Culture. Addressing societal issues by means of innovative approaches including information technology may face the following Constraints in rural communities: *resistance to technology*; *resistance to change*; *lack of mobility*; and *lack of connectivity.*

People. Technology and user-centered design can help achieve societal goals by fostering collaboration and facilitating access to services. At the same time, digital barriers (i.e., absence of connectivity, low digital competence), especially in rural areas characterized by isolation and population aging, hamper effective interventions. In these areas, adoption and use of technologies is low, despite a need for connectivity that even exceeds that of less remote areas [78]. Because of this tendency, many users may not be acquainted with technology-based services such as, e.g., carpooling. This is why we envision two types of Agents: *Active Agents* and *Passive Agents.* In a rural development scenario, such as this one, *Active Citizens* would typically bring competencies such as *digital literacy* and *technology-related skills.* The ability of a Group (composed of one or more Agents) to perform an Action (within a certain Activity) depends on its Capabilities, and Role, as well as on cultural Constraints and Laws. Groups and Roles are not intended here to be immutable. Emergent system behavior can bring about the necessity to adapt them according to the system performance and the ongoing changes.

Information Technology. Information technology in this scenario includes *mobility tracking apps*, *carpooling apps*, *GPS systems*, *campaign platforms*, and software systems employed to carry out *collective brainstorming, voting*, and *decision-making*. Gamification techniques may influence the design of the applications involved. For example, mobility tracking apps may rely on rewards such as points, leaderboards, and badges (PBL) [26, 74], and involve*competitive and cooperative challenges* and *missions targeted at specific user profiles* and adjusted according to the system performance in reaching the Goals.

Infrastructure. The most relevant Infrastructure entities in this scenario are *vehicles* (inherited from Personal and Public Devices), *smartphones* (inherited from Personal Devices), and Public Devices such as *totems* and *ticket vending machines.* New devices may however be designed, developed and delivered through the whole digital twin-guided process making a strong connection to the system design of complex systems necessary.

Processes. At the level of Activities, we find: *defining correct engagement strategy*, *identifying territory strengths and weaknesses*, *involving citizens in data collection activities*, conducting workshops with decision makers, organizing public events, designing awareness campaigns. At the lowest (atomic) level of Processes, we find Actions, such as: *offering carpooling availability*, *starting business to business (B2B) events*, *expressing a vote for service*, and *launching awareness campaigns.*

This scenario involves a Co-Design phase to *identify weaknesses in the territory* such as natural barriers hampering access to services, along with *collectively-guided solutions* and *activities to overcome the barriers*, and possible technology and motivational strategies. The Co-Production phase would involve *developing/identifying the software artifacts* and *identifying devices and areas* to implement the system changes. The Co-Delivery phase would involve *starting and monitoring the deployment of the design solutions* on the territory, *collecting data*, *assessing post-intervention changes*, and *feeding potential weaknesses to new design processes*

Possible solution and benefits provided by digital twins. In this scenario, a developed digital twin would help identify key weaknesses concerning the community and the territory via simulations, define a general Goal and predict possible effective interventions. A possible Goal is *increase access to transportation by N%.* It is crucial that people are involved in collecting data to understand the real socio-technical system state, run possible scenarios (e.g., via AI-driven predictions) to design the interventions and implement the solutions accordingly.

Co-Design phase: Identifying Constraints during the Co-Design phase, based on the data gathered by Infrastructure Sensors, is instrumental to guiding the prioritization of steps to improve access to services. Data may include *maps, satisfaction questionnaires, typical routes and* Path *connections, isolated Locations, and demographic information.* This phase involves identifying key Agents and agent Groups, Devices, Activities, and Motivational Strategies to identify mobility solutions collaboratively. For example, natural and technological barriers could require specific Devices, Software Systems, and Activities. In addition, identification would be needed of Motivational

[1]https://smartera-project.eu/

Strategies that incentivize Device or Software System adoption and use (e.g., carpooling apps), and of (active) Agents able to design and communicate new mobility initiatives and contribute resources. The analysis of weaknesses and design of possible solutions is aided by the Monitoring System and the Prediction Service, which output recommendations for Decision-Makers, such as the public administration, local entities, and public companies. These entities can then initiate activities for collecting data and design interventions accordingly with ad-hoc processes. Motivational strategies such as gamification would be fundamental in this phase to reward participants for their participation. For example, gamification elements like PBL may incentivize sharing ideas, issues, questions, and requests. Gamification may foster creativity by incentivizing collaborative and competitive activities to brainstorm ideas, needs, and possibilities.

Co-Production phase: This phase ensures the correct devices and artifacts are chosen to tackle the corresponding issues. In this scenario, carpooling apps may be identified or developed; Activities could be devised to disseminate the new initiatives among isolated communities; decision-making stakeholders should establish development partnerships with academics and practitioners, B2B events and workshops, the output being specific devices and artifacts. Gamification strategies should also motivate end-users and citizens to participate in potential pilot tests using PBL and monetary rewards. After implementing the solutions, such as new technology-based mobility tools and services, adoption and use of such solutions must be encouraged and maintained [78].

Co-Delivery phase: This phase is necessary to ensure the output of the Co-Production phase is seamlessly introduced into the system and to assess its impact. Motivational strategies help maintain high engagement, i.e., by showing the data extracted via the digital twin in a meaningful way to disseminate the impact of interventions effectively. For example, apps on personal devices and totems may display clearly and interactively the impact of the phases on community development. New mobility opportunities could be communicated via an interactive map. In contrast, the predicted impact of mobility on community development could also be shown in the digital twin in terms of new work opportunities, social connections, and new possibilities for public and cultural events.

5.2 Case Study 2: Food waste reduction in cities

According to data reported in Eurostat 2023[2], yearly food waste in the EU amounts to 58 million tonnes, about 131kg/inhabitant, while it is estimated that roughly 10% of food available to EU consumers is wasted. This tendency should be tackled from several perspectives: social, economic, educational, and technological. We take as an example an Italian city, Ferrara, which is estimated to currently waste about 80kg of food per inhabitant per year. We discuss a scenario where the municipality implements and starts a food campaign to avoid waste and foster upcycling, and describe how the digital twin and motivational strategies devised in our vision may help drive such a change.

Goals. Goals in such a scenario include, e.g., *food waste reduced by N kg per inhabitant per year.* At a lower level, the digital twin may help identify end states such as *new food waste awareness application* or *new educational paths for students and employees to educate about food waste data and prevention practices.*

Culture. Cultural factors in buying, cooking, and consuming food may be among the causes of waste and should be taken into account within the represented ecosystem.

People. Actors are consumers, producers, educators, and policy-makers. All of them can perform different roles in Activities and Actions. Within the Role of the consumer, for example, consumption data and food purchase habits may be shared.

Information Technology. Here the Monitoring System would be employed mainly to track food chains, detect patterns in waste, make sense of the Data collected in collaborative Activities. The Display System would take care of showing Metrics (e.g., *current food waste per inhabitant, current potentially wasted food availability on the territory*) on ad-hoc apps and in public contexts such as public monitors and totems.

Infrastructure. The physical infrastructure includes personal Devices to *visualize the campaign results, calls to action*; public Devices that *show Metrics* to raise awareness in the public about the intervention and show key information about the designed solutions' impact; key food supply chain locations and paths, along with sensors to track the food chain and distribution network.

Processes. Co-Design processes include workshops, educational and awareness-raising activities, the design and identification of food waste monitoring tools, and (e-)participation platforms. Co-Production involves developing *food waste monitoring apps*, building *facilities to distribute surplus food*, and *developing platforms for B2B communication* between food distributors and suppliers. The Co-Delivery phase is where Metrics regarding food waste are kept within the projected ranges and where adaptations are suggested according to the system performance.

Possible solution and benefits provided by our envisioned approach. A digital twin can help communities and societies that are implementing food waste reduction campaigns identify key Agents, Activities, *technologies*, and *practices* to collaboratively pursue the objective of wasting less and upcycling more.

Co-Design phase: This phase consists of identifying the main ecosystem weaknesses, i.e., what (Groups of) Agents (public or private) are wasting and what practices are leading to waste (for example restaurants and supermarkets in the city). Key Agents may also be identified that can drive the change actively (e.g., local food and consumer associations). The Co-Design process aided by the digital twin may identify entry points where corrections could be made in the ecosystem, which would not be evident without a multi-view approach. Relevant Data may include consumption-related data such as questionnaires and data about food purchase and consumption, data from food waste reports; geographical data such as the distribution of supermarkets on the territory, and data about the logistics of the local food supply chain. In this context, new facilities could be needed to carry out intervention initiatives or to realize ad-hoc events and enable new business. For instance, Agents may come up with the idea of food distribution hubs. In this sense, the exploitation of, for instance, unused or abandoned locations could be a viable option.

An accurate representation of seemingly unrelated entities and their properties, either inserted manually or detected by the monitoring system, enabled by a digital twin, can provide resources

[2]https://food.ec.europa.eu/safety/food-waste_en

by intelligently re-proposing existing ones. Some of this data may come from `Sensors` and `Public Devices`, and is extracted by the `Monitoring System`. A digital twin can be used to help identify weaknesses in the presence of `Data` and availability of `Sensors` and suggest improvement. `Agents` could then start spontaneous data-collection initiatives or infrastructural changes based on the digital twin recommendation. Importantly, this phase would output `Goals`, such as *reduce food waste by N kgs/inhabitant/year*.

`Motivational Strategies` may be diverse. In the `Co-Design` phase, they may include rewarding citizens with points/discounts for sharing data about food preferences and purchase habits, e.g. via a participation app. Motivational strategies may also help brainstorm ideas in workshops involving developers, representative citizens, and associations. Identifying all of the key interconnected `Agents` in a data-driven way is crucial for the digital twin to produce effective and actionable recommendations on how to design the next steps, especially by fostering collaboration between `Agents` that often remain separate. Having a clear picture of `Groups`, `Roles`, `Capabilities`, `Interests`, and cultural factors such as `Constraints` is fundamental in this phase, especially considering the circular nature of sustainable economies that can counter food waste tendencies.

Co-Production phase: In this phase, it is crucial to actively involve participants to ensure the technologies and services identified are effective, by conducting pilot tests, running predictions, and imbuing software with gamification elements. A digital twin helps *identify room for collaboration between, e.g., restaurants and entities capable of upcycling bio-waste* (e.g., by *producing soil nutrients*); and, at the social level, between `Agents` in the same neighborhood. Motivation strategies include *rewarding citizens and companies for participating in pilot tests*, and *gamifying teamwork* with, e.g., leaderboards.

Co-Delivery phase: In this phase `Metrics` associated with food waste `Data` are monitored by Information Technology `Services`. Adaptations could be suggested by the `Recommendation Service`, e.g., when poor interactions with campaign apps and artifacts are detected. In this phase, identified `Motivational Strategies` include *incentivizing companies, restaurants, and canteens to donate their surpluses in exchange for partnerships, services, and advertising*; *rewarding citizens for maintaining their sustainable behaviors through gamification mechanisms*, such as *employing apps with gamification elements to monitor waste and reward virtuous users.* Again, only an integrated, multi-perspective view provided by a complex digital twin may enable data-driven suggestions or selection of optimal solutions.

6 RESEARCH ROADMAP

To realize a digital twin of socio-technical ecosystems requires finding solutions for several challenges. We present a research roadmap (see Figure 4) for the areas: Holistic modeling approaches and their connection to data, simulation techniques for prediction, motivational techniques to drive societal change, and evolving DTs.

6.1 Multi-layered and multi-view modeling framework

The envisioned digital twin must have the capability to effectively manage the multi-level and multi-dimensional complexity inherent in socio-technical ecosystems. To achieve this, holistic modeling approaches are indispensable, complemented by predictive and adaptive processes. Such an approach enables us to comprehend the intricate interactions among various models, ensuring that they accurately represent the real system behavior. Furthermore, it facilitates the identification and prediction of anomalies and inconsistencies, allowing for timely revisions of the models to maintain their alignment with the evolving real-world dynamics.

Effectively representing the proposed digital twin requires models capable of describing intricate structures and multi-level interactions. Current modeling approaches, drawing from fields such as Artificial Intelligence [80], Mathematical and Physical Models [3], Optimization Techniques [35], and Complex Systems [36, 84], offer diverse methodologies. However, for analysis, simulation, and prediction of socio-technical systems' behavior and evolution, these models must be integrated and interconnected. The integration is crucial, particularly for model-driven and data-driven decision support systems. In this respect, ***challenges*** include: the definition of overarching integrated models from heterogeneous modeling approaches; and the validation of the models and their analysis and prediction capabilities. Thus, the first important step in the ***research roadmap*** for creating digital twins for socio-technical ecosystems is realizing comprehensive modeling paradigms. We aim to redefine the modeling landscape by advocating for an *ensemble* approach [43], which involves curating collections of interconnected models, each revealing various aspects of the socio-technical ecosystem. These models are organized within a multi-view and multi-layer architecture to capture the intricate interdependencies and complexities inherent in such ecosystems.

A key aspect of this future research direction involves establishing systematic prediction processes to extract insights from the ensemble's models, thereby enhancing the understanding of the socio-technical ecosystem. This entails analyzing interconnections between models within each ensemble for eliciting patterns and emergent properties to evolve the ecosystem's behavior. Moreover, we emphasize the importance of adaptability in managing complex socio-technical ecosystems [15]. To realize this, our research roadmap proposes a framework for identifying adaptation needs based on insights gained from the ensembles. This will involve continuous monitoring of the ecosystem's performance, identification of areas where existing models may be inadequate or outdated, and the formulation of specific solutions to revise and refine the models.

6.2 Capturing Data of Social Aspects and Model-to-Data Connections

The DT for socio-technical ecosystems needs to make meaningful connections between the information captured in multi-view and multi-layered models and the data software systems can receive from the ecosystem. When it comes to capturing this data we face the ***challenge*** of how to capture aspects such as competencies, interests, goals, or the culture of people and how to get data from legacy systems. Another challenge is related to the link between models and data [13]: data coming from heterogeneous sensors or software systems needs to be mapped to individual model elements within different modeling approaches.

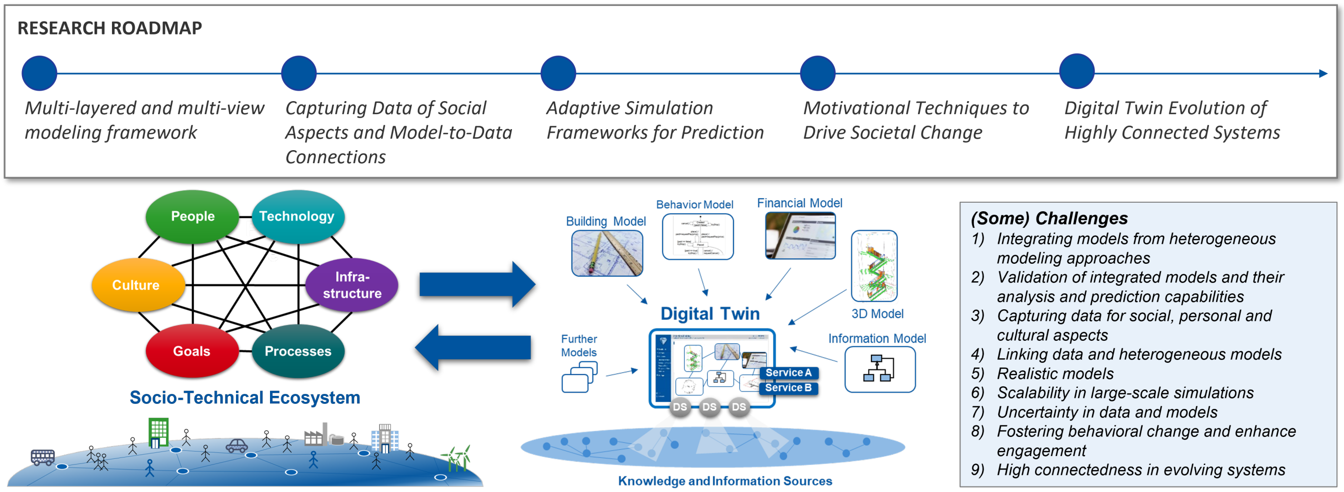

Figure 4: Research Roadmap to realize DTs for socio-technical ecosystems.

Two important steps in the ***research roadmap*** are (1) to develop methods for better data capture for digital twins of socio-technical ecosystems and (2) to establish methods for model-to-data linkages. New data capture methods include, e.g., the incorporation of "virtual sensors" which treat user feedback via software systems the same as sensor information [83] to capture information about situations where sensors are not available. This alone might not be enough to get all relevant data, so the DT engineering process for socio-technical systems needs to systematically analyze data needs in all socio-technical dimensions, analyze existing data sources and their accessibility, and we have to develop motivational approaches for users and institutions to provide the needed data. For linking the models to data, we have to establish such linkages for different types of data and different types of modeling languages. The envisioned multi-view and multi-layer architecture for models could support this need, if it is designed in a way that not only model-to-model but also model-to-data connections can be defined. Research in this area needs to be done for DT engineering of all kinds of systems but when it comes to socio-technical ecosystems, we need the support of experts from, e.g., psychology, social science, economics, or other areas to establish correct links. In addition, we need to develop balancing methods between a large amount of sensor data coming in and prior knowledge [79] we have already captured within a DT.

6.3 Adaptive Simulation Frameworks for Prediction

Despite the strides made in simulation techniques for socio-technical ecosystems [73, 85, 94], several challenges persist [39, 50, 58]. These ***challenges*** encompass the need for more realistic and data-driven models, grappling with scalability concerns inherent in large-scale simulations, and the crucial task of integrating uncertainty into simulations. Addressing these challenges requires a paradigm shift towards a holistic approach, where models in the digital twin are not only combined but also interconnected within an overall model of the entire system.

Models interconnectedness is crucial for effective analysis, simulation, and prediction of the behaviors and evolution. In particular, it is vital for model-driven and data-driven decision support systems, and especially essential for digital twins [5, 32]. Mirroring real-world environments, digital twins demand a comprehensive representation that encapsulates the intricate interplay of various factors and entities within the system. To address this challenge, we propose in the ***research roadmap*** to leverage the ensemble model (as described in Section 6.1) as a powerful tool.

Each model within the ensemble acts as a building block, contributing unique insights and perspectives to the collective representation of the system. By interconnecting these models in a cohesive framework, we unlock the potential to capture the complex dynamics and emergent behaviors inherent in the digital twin. Furthermore, we acknowledge the symbiotic relationship between interconnected models: updates or adaptations in one model reverberate throughout the ensemble, fostering a dynamic exchange of information and refinement that enhances the fidelity of the system representation. This synergy not only amplifies the realism of predictions but also fortifies the foundation for informed decision-making processes.

Harnessing the versatility of the ensemble model, we aspire to create adaptive simulation frameworks capable of dynamically adjusting to evolving system dynamics. Through these concerted efforts, we aim to set new benchmarks in simulation techniques, empowering stakeholders with the tools and insights needed to navigate the complexities of socio-technical ecosystems with unprecedented precision and efficacy.

6.4 Motivational Techniques to Drive Societal Change

Motivational techniques play a pivotal role in driving community participation across the three collaborative phases of innovation guided by the digital twin. Gamification can be leveraged as a means to enhance engagement and foster behavioral changes [6]. It has been employed for co-design in previous literature in the field of, e.g., education [29] and neighborhood services [68]. More in general, gamification has been applied to e-participation [40] and citizens' engagement in decision-making processes [69]. Common gamification elements include points, leaderboards, badges, achievements, missions (with time constraints), and prizes [40]. Although the employment of gamification is widespread and its effectiveness is backed by extensive work, ***challenges*** persist as to how engage different types of `Agents`, who may have different stances towards technology, device and software use, and different competencies. Indeed, engaging different types of users in different ways based on their profile is object of a large body of work [51, 70, 75, 87].

Addressing this challenge entails a ***research roadmap*** that investigates personalization in gamification techniques that not only takes into account different "player" profiles, but also different types of technology users, different competencies, cultural backgrounds, and different media (i.e., digital vs. analog).

In the `Co-Design` phase, where stakeholders collaboratively conceptualize and design sustainable innovation processes, motivational techniques ensure active participation and idea generation [66]. For example, goal-setting [56, 59], progress tracking, and feedback mechanisms [33, 42], further enhance engagement and ensure that diverse stakeholders actively participate in the `Co-Design` process. The integration of gamification methods and tools not only incentivizes involvement but also serves as a mechanism for comprehensive data collection and analysis.

During the `Co-Production` phase, where the designed solutions are refined and developed, maintaining momentum among participants is crucial. Leaderboards, badges, and virtual rewards sustain active participation, fostering a sense of achievement and collaboration. For example, leaderboards have been shown to be motivational in team work and well explained by goal-setting theory [56]. Additionally, feedback loops and regular communication channels ensure that participants remain motivated and invested in the `Co-Production` process. Building upon the insights from the analysis of the actual situation, available resources and competencies, and the real needs in the `Co-Design` phase, the `Co-Production` phase becomes more oriented to call-to-action initiatives. Leveraging predictive analysis, which attempts to forecast the potential impact of various call-to-action strategies, preferred initiatives are identified and prioritized based on their projected effectiveness.

In the `Co-Delivery` phase, where the implemented solutions are deployed and evaluated, motivational techniques sustain community participation and facilitate behavioral change. Feedback mechanisms, reward systems, and social incentives reinforce desired behavior changes, empowering communities to take ownership of the pursued targets.

By leveraging gamification to enhance engagement, foster collaboration, and incentivize participation, our vision not only facilitates the co-design of innovative solutions but also ensures their successful co-production and co-delivery.

6.5 Digital Twin Evolution of Highly Connected Systems

Socio-technical ecosystems are continuously changing in various aspects: New processes occur, new regulations, other societal goals, new technologies, and cultures are changing and actors change their interests, gain additional competencies or lose them, and change roles and groups. The main ***challenge*** for socio-technical ecosystems is that due to their high connectedness, changes in one place might also affect other areas in a ripple effect.

As an additional step in the ***research roadmap***, we have to establish evolution methods that are capable of handling these changes in the digital twin of a socio-technical ecosystem on different levels and in a highly automated way. Changes in a model affect its linked models, related visualizations and views, as well as the services they are used in. Ecosystem additions, e.g., from new infrastructure assets, will come with their additional models from system design. Those have to be integrated into the existing digital twin to enable more comprehensive system and software analyses. Besides changing and new models, also incoming data might change fostering the need for automated data migration strategies. Moreover, services can change or new ones might occur which have to be reflected in the DT.

7 CONCLUSION

We do not envision digital twins for socio-technical ecosystems as a "window" on the ecosystem that helps a few decision-makers in performing some actions according to its representations, measurements, and predictions. We rather envision it as an *integrated component of an ecosystem*, where all agents can exert their agency towards a common goal by performing their actions. The digital twin is not detached from the ecosystem but is rather an adaptive component that enhances it. This implies that the digital twin can evolve in time, following the ecosystem itself, and its architecture (i.e., interactive representations, ad-hoc sensors, etc.) can be revised in the future by means of interactions with itself and its output representations and projections. Thanks to this vision we can capture emergent phenomena that would not be captured without resorting to a digital twin. Digital twins may very well be instrumental in realizing that a certain representation is not sufficient or is outdated to predict accurately future scenarios and to design effective societal interventions accordingly. Only by virtue of the interaction between models and their dynamic refinement through time is it possible to give timely predictions and suggestions, and design effective system changes.

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