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Review

Cooperating and Competing Digital Twins for Industrie 4.0 in Urban Planning Contexts

Otthein Herzog [1,2,*], Matthias Jarke [3] and Siegfried Zhiqiang Wu [1]

1 College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China; wus@tongji.edu.cn
2 Department of Mathematics and Informatics, University of Bremen, 28359 Bremen, Germany
3 Databases and Information Systems, Rheinisch-Westfaelische Hochschule Aachen, 52056 Aachen, Germany; jarke@dbis.rwth-aachen.de
* Correspondence: otthein.herzog@uni-bremen.de

Abstract: Digital twins are emerging as a prime analysis, prediction, and control concepts for enabling the Industrie 4.0 vision of cyber-physical production systems (CPPSs). Today's growing complexity and volatility cannot be handled by monolithic digital twins but require a fundamentally decentralized paradigm of cooperating digital twins. Moreover, societal trends such as worldwide urbanization and growing emphasis on sustainability highlight competing goals that must be reflected not just in cooperating but also competing digital twins, often even interacting in "coopetition". This paper argues for multi-agent systems (MASs) to address this challenge, using the example of embedding industrial digital twins into an urban planning context. We provide a technical discussion of suitable MAS frameworks and interaction protocols; data architecture options for efficient data supply from heterogeneous sensor streams and sovereignty in data sharing; and strategic analysis for scoping a digital twin systems design among domain experts and decision makers. To illustrate the way still in front of research and practice, the paper reviews some success stories of MASs in Industrie/Logistics 4.0 settings and sketches a comprehensive vision for digital twin-based holistic urban planning.

Keywords: multi-agent systems; digital twin; data architecture; Industrie 4.0; Logistics 4.0; digital transformation strategy; urban planning and city operation

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1. The Evolving Concept of Digital Twins

Over the past 60 years, digitalization has augmented the classical scientific methods of theory and experiment first by simulation and, since the turn of the century, by data-driven methods and machine learning. In engineering, physical and digital simulation programs were initially separated from formal models and physical systems. Since the late 1980's, model-driven designs emerged in which software systems could be generated to drive physical systems, leading to early versions of cyber-physical systems. In parallel, several projects—adapting the 1990s idea of data warehouses for production settings—pursued the idea of a "product memory" [1–3], proposing the collection of data over the lifecycle of products as a basis for product maintenance, improvement, and recently also recycling and other sustainability-oriented "re-" technologies.

Nevertheless, all these approaches looked at either data collection and analytics or at model-driven development and control but rarely at both of them. Only around 2003, Michael Grieves and colleagues at NASA pointed out that these two partial developments needed to be combined in what they called "twinning" [4]. Twinning requires a continuous synchronization loop between observing the real-world (also called physical) twin through a physical-to-virtual link to a digital twin, which in turn controls the real-world twin through a virtual-to-physical link.

Figure 1 visualizes the twinning interplay in the co-evolution of real-world and related digital twins but additionally highlights that the physical-to-virtual link consists of two traditionally separately investigated parts: collected data from controlled sensing (metrology) need to be transformed into purpose-oriented digital shadows (DSs) as a basis for detailed analysis and decision making. We shall see later in this paper that bridging this chasm could be a major step forward for cooperating digital twins.

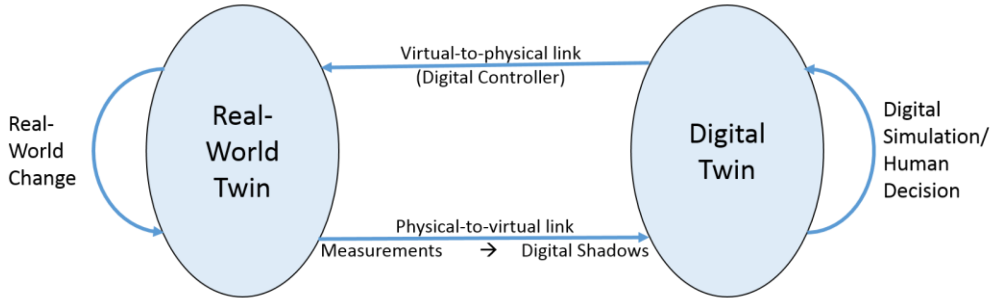


Figure 1. The twinning concept in cyber-physical systems according to [4].

Basic twinning systems, as shown in Figure 1, can be interpreted as atomic building blocks within a larger cyber-physical production system (CPPS), which is again monitored and controlled by a higher-level digital twin and can also interact with other CPPSs. Real-world applications do not just involve individual digital shadow links from sources to aggregated data for digital twins. They also demand controlled sharing of such DSs among interoperating digital twins within and across organizations [5]. This way, we are beginning to face the challenge of managing *digital twins in the large* and the relationships among their components.

The recent literature includes a host of definitions for digital twins; for overviews, see, e.g., [6,7]. A comparison of different existing digital twin architectures can be found in [8]. Higher-level aspects related to, e.g., sovereign data sharing or intelligent cooperation among digital shadows and twins are still subject to research and early development [9,10]. An exception is the industry-driven data exchange network Catena-X, which has recently begun to support sovereign data sharing among hundreds of companies related to automotive industries [11].

Rather than reflecting the full breadth of the debate on digital twin definitions, the following subsection focuses on two more broadly used digital twin definitions and characterizations to motivate the research in the present paper: the German Industrie 4.0 initiative and the mostly U.S.-driven Industry IoT Consortium [12].

1.1. Related Work in Large-Scale European and International Initiatives

In 2011, Germany announced its *Industrie 4.0* initiative [13–16], aimed at applying cyber-physical systems (CPS) for industrial innovation. Since then, many similar initiatives have been announced throughout the world, with numerous research and development projects and management discussions. A number of mostly medium to large international companies have demonstrated the potential of the approach. Digital twins can play a role throughout the whole lifecycle of products, processes, and socio-technical organizations, e.g., for

- Requirements engineering and model-driven development prior to existence of the physical twin.
- Monitoring and control in the testing and operational phase of the CPS.
- Requirements-level monitoring and end-user innovation in the usage phase.
- Long-term learning and planning for "re-" technologies (reuse/recycle/. . .) towards lifecycle end.

Therefore, Industrie 4.0 departed from the traditional abstraction hierarchy. Instead, it grouped all models and data related to digital shadows and twins of a particular real-world asset (e.g., a CPPS or business subsystem) in what they call an Asset Administration Shell (AAS). Perhaps stretching the digital twin concept, they call the AAS the digital twin of the asset at hand. Following the traditional wisdom of standardizing from the bottom up in the hierarchy of communication infrastructures [17], Industrie 4.0 focused first on the standardization of data exchange protocols.

In the context of a broad framework of Digital Twin Core conceptual models and services, the international *Industry IoT Consortium* agreed on the following definition:

"A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.

- *Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action.*
- *Digital twins use real-time and historical data to represent the past and present and simulate predicted futures.*
- *Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems."*

The Report [18] provides a detailed set of technological conceptual models for what they call the Digital Twin Core, focusing on interoperability aspects at the data and computational models, plus metadata, preprocessing, dataflow, and validation models. The report provides links to the dozens of international standards by ISO/IEC, IEEE, ANSI, etc., thus offering an impressive picture of the highly complex technological setting for digital twins from an object-oriented analysis and design perspective.

1.2. Problem Statement and Contributions

Given this complexity, it is perhaps hardly surprising that a thorough analysis of the more-than-thousand publications in the field [19] shows an alarming lack of uptake by small and medium enterprises (SMEs). The authors also point to a shortage of unbiased comparative studies on the economic impact of introducing digital twins. As highly specialized hidden champions, SMEs play a crucial role in engineering innovation and operational supply chain networks. Such networks result in networks of digital twins that are not just characterized by the technologies discussed in [18] but—at least equally important—by their roles and relationships in these networks, most prominently including cooperation and competition. Recent interviews with selected SMEs in the field of smart product-service manufacturing SMEs provide more in-depth, if anecdotal, evidence in this regard [20].

A striking practice example can be observed in the process industries [21]: Each single Yoghurt cup is touched by no less than twelve (!) companies, many of them supported by individual digital twins on disciplines as different as material sciences, engineering theories of gluing and cleaning, or machine tooling. To reduce the huge plastics waste and enable value-adding recycling or even upcycling, all these digital twins and their long-term digital shadows should be made semantically interoperable, a major research and business analysis challenge in the German AI Hub on Plastics Packaging [22].

In the digital transformation, *cooperative or competitive relationships* will be partially managed by human roles and in part by digital twins. Apart from socio-technical challenges of economic analysis, knowledge transfer, and personnel training in hybrid intelligence [23], we argue that there are conceptual, information management, and architectural challenges that need to be resolved (see also [24]).

Understanding and managing cooperating and competing digital twins requires higher-level abstractions for specification, analysis, and programming. Towards this goal, this paper proposes extended agent-based frameworks and methods. Agent-oriented approaches abstract from the question as to whether agents are real-world entities (humans, organizations, natural phenomena or forces) or digital twins. They have already proven helpful in several fields of computing and information systems, including AI, programming languages, conceptual modeling, requirements engineering, and business strategy.

Section 2 addresses research questions and technical contributions towards agent-based support for cooperating and competing digital twins from three perspectives:

- After a short overview of fundamental agent classification in Artificial Intelligence, we first discuss suitable implementation frameworks that enable effective workflows and other forms of interoperation in multi-agent societies of digital twins.
- Next, we address challenges and possible solutions in the fields of inter-organizational data integration and sovereign data exchange among digital twins. In particular, we discuss how the key bottleneck of linking the measurement side of the physical-to-virtual link to digital shadows can be relieved by suitable intermediate data models, and we adapt recent data space approaches to the setting at hand.
- Third, we extend the well-known requirements and strategy modeling language i* [25,26] and its analysis tools to the case of analyzing possible cooperation and competition scenarios in networks of real-world and digital twins.

Section 3 presents existing experiences and ongoing challenges from an application perspective in two important example domains: the quite advanced field of Industrie 4.0 logistics and the grand challenge of holistic urban planning under multiple intensively interacting perspectives including the UN SDG goals, with the question of how to make the enormous variety and scope of specific digital twins cooperate effectively, even in settings of conflicting goals and competing agents. The paper ends with a conclusion and outlook focused on this latter challenge and related domains.

2. Agent-Oriented Approaches for Cooperating and Competing Digital Twins

Obviously, connectivity and interoperability are the minimal necessary preconditions for supporting cooperating or competing digital twins. For example, in [7] (p.1), a connected digital twin is defined as *"a virtual representation of a physical object or process capable of collecting information from the real environment to represent, validate and simulate the physical twin's present and future behavior. It is a key enabler of data-driven decision making, complex systems monitoring, product validation and simulation and object lifecycle management"*.

Today, digital twins are integral parts not only of Industrie 4.0 concepts (named there as "Asset Administration Shells") in order to secure Industrie 4.0 requirements like ever shorter innovation cycles and mass production with lot size 1 [27]. They are also the technology of choice in all other areas in which the digitization of the analogue world is followed by the digitalization of object and process descriptions: the use and the analysis of data allows for creating autonomous models at a semantic level for the specific real-world aspects, e.g., for process control, simulation and optimization of processes, transportation, logistics, automotives, energy, health, smart cities, and also for mitigating climate change.

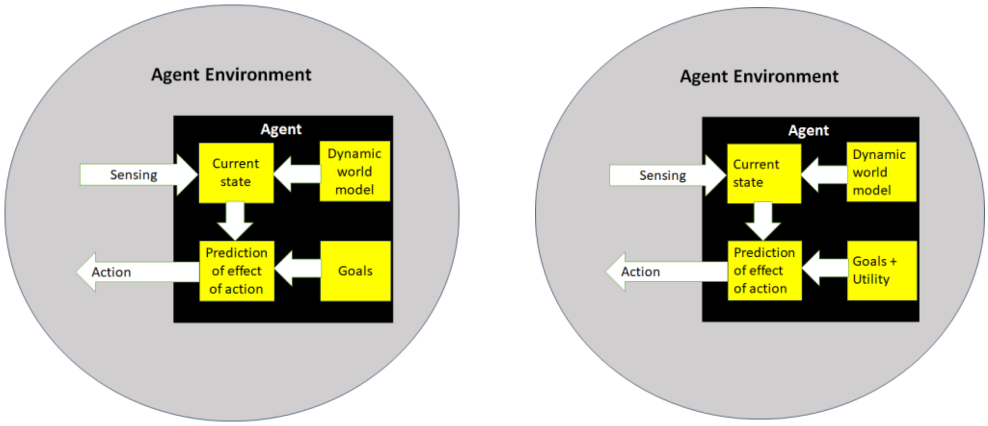
The generality of this approach indicates that a versatile technology must be used that is capable of implementing demanding requirements such as rationality, environmental data interpretation, learning, reactivity, pro-active planning according to objectives and goals, and communication, cooperation, and/or competition skills. Digital twins communicate with the environment, including with other digital twins. Therefore, there is a need for a communication infrastructure together with standardized interaction protocols in order to ensure a meaningful communication among digital twins and with the environment. As the concurrency and the complexities of real-world processes can be mapped quite naturally to concurrently acting (autonomous) digital twins, a system of autonomous digital twins might act in a completely decentralized way or in a combination of centralized and decentralized control, depending on the communication structure of the processes to be "twinned".

Digital twin systems can be made up of several digital twins that interact with each other in order to reach their own and/or system objectives. Consequently, digital twins can act in egoistic and/or cooperative ways, depending on the requirement to maximize their own benefits or to reach a common (sub-) goal.

The technologies that are necessary for the implementation of digital twins can be taken from some Artificial Intelligence fields that have been developed during the past 30 years, such as knowledge representation and knowledge processing, machine learning, and planning, software agents, and multi-agent systems, cf. [28,29]. Systems of agents can be established by several agents that interact with each other, trying to satisfy their own objectives and/or the objectives established for the system.

2.1. AI Perspective: Agent Frameworks and Interaction Protocols

Using AI technologies, goal-oriented or utility-oriented digital twins can be conceptualized as AI-based software agents, as shown in Figure 2.



(**a**) (**b**)

Figure 2. (**a**) Model-based, goal-oriented and (**b**) model-based, utility-oriented agent, after [29].

Utility-oriented software agents. Cooperation among software agents was deemed necessary for distributed problem solving, as it was obvious that no single agent in a distributed system would have sufficient expertise, resources, or information to solve a problem on its own. This leads to the basic assumption that these agents are benevolent, sharing common goals without the potential for conflicts of interest between agents.

Goal-oriented software agents. However, in many real-world scenarios, it turned out that distributed problems are not always solved by benevolent agents in cooperative settings: the agents could be self-interested actors without sharing common goals. Therefore, the agents in such a competitive setting must act strategically in order to reach their goals, i.e., they must be capable of dynamically coordinating their actions with other agents according to the utilities of their moves. A simplified approach would thus distinguish between cooperative and competitive agents, even if in cooperative settings, specific coordination mechanisms could also be based on competition, e.g., auction protocols.

Using cooperative or competitive multi-agent systems and other AI technologies such as learning and planning, digital twins can be employed for local autonomous process control. Systems of autonomous digital twins which use the Internet of Things and Services can also act together to implement functionalities such as:

- removing typical blind spots in manufacturing facilities across assets and facilities, e.g., machine health, tank levels, and temperature or humidity levels.
- Providing resilience of processes when the environment changes.
- Globally optimizing processes to reduce cost and maximize asset uptime to overcome increasing supply chain pressures, and to satisfy the need to improve sustainability.
- Implementing digitalized tools and applications for the control and visibility needed to meet these demands, which also aligns with global security and access controls.
- Enabling systems of digital twins for centralized global data availability and for monitoring remote facilities.

The communication between software agents was standardized already early on and supported through multi-agent frameworks. The Foundation for Intelligent Physical Agents (FIPA) [30] standardized middleware functions in 1996, and it transferred itself to the IEEE Computer Society as a standards committee in 2005. Among the platforms implementing FIPA specifications (for a comparison, see [31]), the JADE framework (Java Agent Development) [32] appears to be one of the active agent frameworks:

It *"provides a simple yet powerful task execution and composition model, peer-to-peer agent communication based on asynchronous message passing, a yellow pages service supporting publish subscribe discovery mechanism and many other advanced features that facilitates the development of distributed systems.*

A JADE-based system can be distributed across the Internet and can transparently deploy agents on Android and J2ME-CLDC MIDP 1.0 devices. The platform configuration as well as the agent number and locations can be changed at run-time, as and when required. Furthermore, suitable configurations can be specified to run JADE agents in networks characterized by partial connectivity…"

Interaction protocols for advanced communication among agents are an important feature of most frameworks, as they establish semantically limited but powerful interactive conversation methods beyond simple messages. The FIPA framework offers a considerable amount of interaction protocols that can initiate interactions, e.g., to establish auctions in order to optimize sparse resources, e.g., through an English, first-price sealed-bid, Dutch, Vickrey, or all-pay auction. Another interaction offered is an implementation of the contract net protocol [33,34], which is applicable to a fine resolution of controlling tasks in a distributed environment.

The FIPA contract net protocol specifies an anytime algorithm, since it only approximates an optimal solution. This characteristic is useful in dynamic and stochastic environments where the available running times are not known in advance [35]. It has been shown to be adequate for the scheduling of concurrent processes and to result in superior solutions compared with allocation algorithms [36].

2.2. Data Perspective: Efficient Data2Knowledge Mappings and Sovereign Data Exchange

As mentioned in the introduction, data management for interconnected digital twins is an important issue in many domains (cf., e.g., [37] for a detailed analysis in the construction sector). Digital twins face at least two key data challenges: firstly, a high effort for transiting from the metrology to the analytics (digital shadow) stages of data supply for digital twins; secondly, how data exchange and interoperation among multiple digital twins and digital shadows can be architected considering the tension of undisturbed high-performance transfer and preservation of the data and twin owners' sovereignty.

Concerning the first challenge, the metrology stage of the physical-to-virtual link faces an enormous heterogeneity of data sources (sensor data streams, legacy machinery, ERP systems, tracks of human–machine interaction), which already in itself poses a major challenge to meaningful and secure data sharing [38]. Equally, the digital shadow production offers an increasing method richness of data- and model-driven analytics and machine learning [6,39]. This complex *m:n* relationship between multiple data sources and multiple analytics methods requires at least a quadratic number of different individual mapping efforts between the metrology and analytics parts, which has to be repeated whenever sources or analytics methods are added, changed, or deleted.

To reduce this effort, an intense discussion about standardized formats for the interchange between both subtasks emerged. Industrie 4.0 has standardized the OPC/Unified Architecture [40], with successful application examples such as [41]. OPC is also investigating additional service-oriented language options such as XML/JSON. However, though language standardization obviously helps, it does not reduce the number of $m \times n$ necessary semantic mappings. Proposed highly sophisticated information supply networks lining up the workflow of processing and storing the digital shadow steps along the physical-to-virtual link [40,42,43] offer important technical infrastructure, but they do not solve the basic complexity issue either.

The formal goal here is to reduce the basic complexity from quadratic to quasi-linear, i.e., from $m \times n$ to $d \times (m + n)$. Here, d represents a small number of bridging data models with the property that each language allows (a) for representing sensor fusion results for a large class of widely used sensor application domains, which (b) can be directly used with a very class of analytics “at the press of a button”. Encouragingly, there does exist a first highly successful example of such a “data model in the middle”: the Object-Centric Event Log (OCEL) formalism. It offers a simple relational model of activities, objects, and events on which all kinds of process mining or robotic process automation tools can directly operate without any further effort [44]. Any sensor results that can be represented as networks of discrete events on defined objects (e.g., ERP data, discrete transport operations, etc.) can be mapped to this data model. Market-leading process mining start-ups such as Celonis demonstrate the value of such a purpose-oriented data model, which they also support by high-performance special-purpose DBMS. Research for further such data models, e.g., in production engineering, is actively underway.

Concerning the second challenge (data sharing), the introductory discussion around Figure 1 showed that the MAS interaction protocols of digital twins imply massive flows of heterogeneous data. Typical data management goals mentioned in the scientific and practitioner literature include producing added value by sharing data within and across company boundaries, enabling more variety (data heterogeneity) while ensuring veracity (data quality and provenance), and reducing the costs of managing large volumes (“big data”) with near real-time velocity.

To address these goals, several architecture patterns evolved from traditional DBMS, as depicted in Figure 3. Since the late 1990s, *data warehouses* radically separated operational transaction processing (OLTP) from online analytic processing (OLAP) to facilitate historical data analytics and reduce interference between short transactions and broad analytics [45]. In *Extract-Transform-Load (ETL)* processes, the *Transform* part ensured meaningful integration and data cleaning for OLAP but required manual schema integration for linking new data sources, even if OLAP analytics might only require these data later or never. Moreover, OLAP data were far away from representing the current OLTP state. Even this latter point could be partially addressed by *main memory databases*. Last but not least, dramatically failed IT mergers, e.g., in banking, demonstrated that data warehouses did not work well in today’s volatile corporate environment with frequent mergers, acquisitions, and re-organizations. This also makes them problematic for supporting large societies of interacting digital twins.

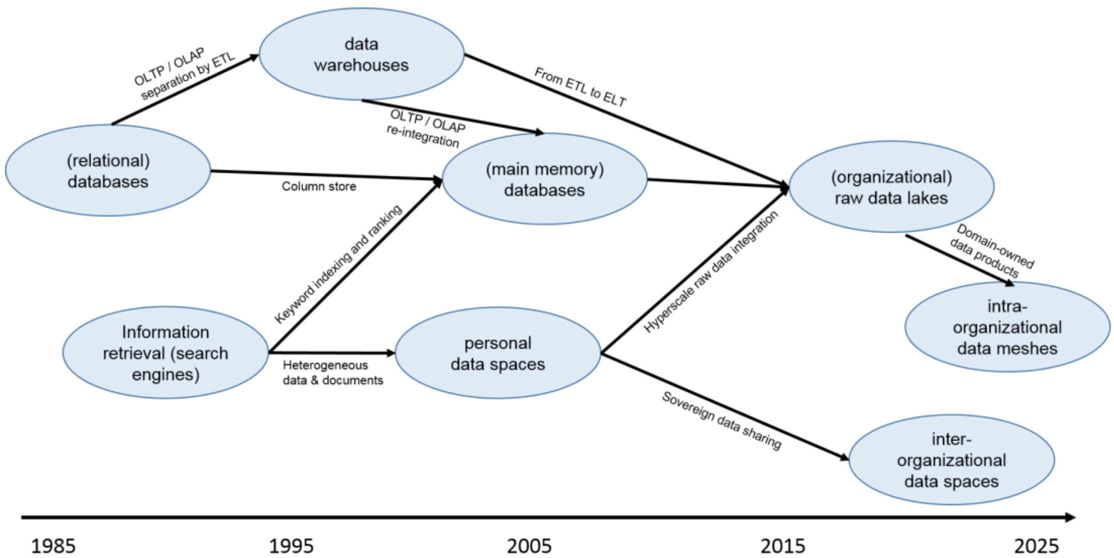


Figure 3. Evolution of data management and analytics paradigms over four decades.

By loading raw data and delaying the Transform action until its results are actually needed, *data lakes* [46] turn ETL into ELT, enabling “pay-as-you-go” instead of requiring full upfront Transform investment. Following Microsoft research on (*personal*) *data spaces* [47], they also adopt a “schema-on-read” approach, which helps users manage the growing wilderness of structured, semi-structured, and unstructured media data from different perspectives. Corporate strategists appreciate that loading and storing un-interpreted raw data with flexible schema-on-read facilitates corporate change: in a merger, you simply throw the raw data of the new partners into your data lake, and then have time to gradually understand and re-organize the semantic relationships among the data. Due to their flexibility, data lakes are popular as shared data stores for digital twins, especially in large organizations, including "hyper-scalers" such as Google or Amazon.

For many highly specialized SMEs, this hyper-scaler dominance caused concern about possible loss of "hidden champion" corporate knowledge. Such organizations want data sovereignty: to take advantage of the added value of sharing data but retain full freedom to decide and monitor who uses the data, and how.

Observing these concerns, [48] proposed an extension of the personal data space or data lake idea by a concept of sovereign data sharing, called *industrial data spaces.* This was quickly adopted by government and developed in large-scale projects on architectural standards, models, algorithms, and real-world applications [49]. On the political level, the ideas found their way into national and European data strategies, including, e.g., GAIA-X [50].

Technically, sovereign data sharing in data spaces is enabled by encapsulating data export and import facilities in so-called connectors [51], coordinated by auxiliary components in a data space infrastructure:

- Brokers help to match offers suitable for a data request
- Optionally supported by vocabulary services for supporting semantic matching, and by
- Federated data integration and machine learning from heterogeneous sources.
- Contract management and monitoring services (e.g., Clearing House).
- Identification services ensure that only members of a data space can operate in it.

In the original IDSA Architecture, such services are offered by a central organization. In contrast, GAIA-X requires decentralized federation services. For example, a data space application in industrial benchmarking [52] shows how both secret input data of the benchmark participants and the confidential algorithms of the benchmarking company can be protected despite the sharing.

The data space philosophy also caused rethinking of the central data lake IT strategy of large companies and public organizations (e.g., city governments). The new *data mesh* strategies [53] transfer the ownership of, and responsibility for, domain-specific data and digital twins to individual business domains, while de-emphasizing central corporate data lakes and IT departments. Data meshes thus aim to improve responsiveness to customers and promote business domain-driven digital twins. Simplistically, they can be seen as a top-down approach to reach the initially bottom-up concept of data spaces. This is but one striking example of the relevance of our next topic, strategy modeling in digital twin and human organizational agent networks.

2.3. Strategy Perspective: Analysis of Cooperation and Competition in Agent Networks

Data lake, data space, and data mesh approaches are not just technical concepts. They represent different philosophies of *socio-technical data and service ecosystems,* in which digital twins help human organizations pursue their goals, strategies, and (inter-)actions [54,55].

In the data space literature as well as in MAS languages, this is documented in multi-level information models [56]. Based on such models, MAS developers can be supported by visual agent modeling languages. However, due to their wide range of applications, such languages still require the generality of imperative programming languages. This puts application domain experts at a disadvantage, since they have to work through a lot of implementation complexity to contribute to large multi-agent digital twin models.

To empower a broader range of stakeholders to contribute to the design of multi-agent ecosystems, the social requirements modeling language i* [25] mimics the way domain experts and other humans naturally talk about such ecosystems—in terms of *intentions*, *dependencies*, and *actions or tasks*. Due to its concise graphical notation, which closely resembles the common-sense way of talking about social actors, i* has been shown in hundreds of cases to greatly reduce the effort required for discussing model details between developers and domain experts [57].

Specifically, i* combines two core aspects of goal- and actor-oriented requirements engineering. We illustrate its graphical notation in Figure 4 with a small real-world i* documentation of a strategy debate on urban water management in a low-income megacity quarter (cf. [57]):

- In the graphical i* notation, actors (agent roles) are represented by grey background shapes, in our example, *water user* and *local water supplier*. A *goal-task hierarchy* for each actor describes its goals and possible task combinations (actions) for their achievement. The goals thus serve as the *strategic rationale* for subgoals and tasks. Specific (must-have) goals such as *use water* are represented as ovals, whereas soft goals (also called non-functional requirements), such as *water quality* or *supply reliability*, look a bit like toppled *8*′s. A goal such as use water can be pursued by two alternatives: by the direct task/action *order water tanker* or by pursuing a subgoal *use tap water* with associated subtasks.
- Many goals or tasks cannot be achieved by the actor alone but need to be delegated to others, creating a network of *strategic dependencies*, represented as directed links between the various kinds of nodes. For example, achievement of the *water quality* soft goal by *water users* depends on fulfillment of the tasks *maintain water grid* and *supply water* by a *local water supplier.* Satisfiability of the latter task, however, depends on a sufficient *water resource*.

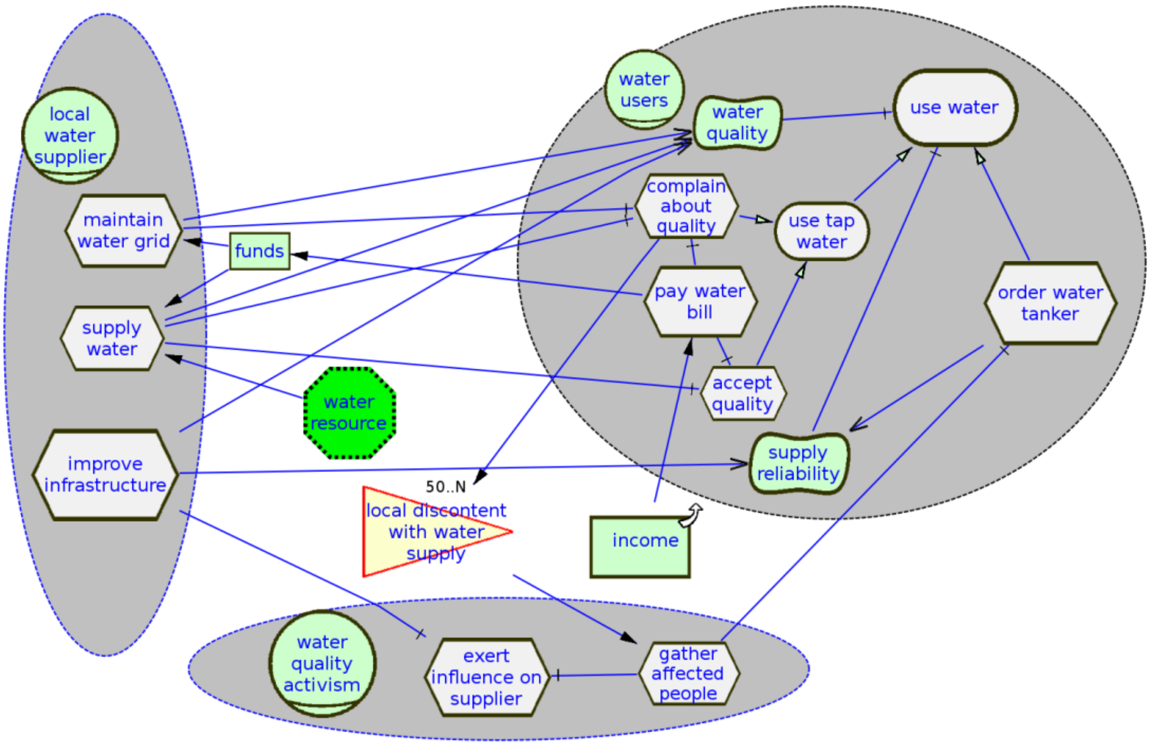


Figure 4. Initial *water user*-centered i* model of urban water management.

i* modelers can freely choose a suitable level of semantic abstraction for the specific strategy issue at hand, without concern for technical implementation details. Such a semantic abstraction could, for example, be a geodata model in which a specific city quarter could be chosen as the application site for the i* model (for details, cf. [57]).

Additionally, Figure 4 shows how one can simply indicate boundary conditions on three variants of context factors within the graphical notation: natural resources (dark-green hexagons), here a *water* resource on which both variants of *use water* depend; permanent socio-economic resources (rectangular boxes), here *income* of *water users* and available *funds* on which the *local water supplier* depends. Last not least, new actors (yellow triangles), here *water quality activism*, can emerge from accumulating events, e.g., a certain threshold of *complaints about quality*. Such potential actors can change the dependency net, such as *exert influence on supplier* to *improve infrastructure* for the *use tap water* option or *gather affected people* to jointly *order water tanker*. We note that predicting such an emergence could be predicted by a digital twin simulation, whereas other context factors might be derived from available statistical data resources or measurements.

The model in Figure 4 was the result of a (slightly neutralized for anonymity) actual strategy debate in which city planning stakeholders discussed the interplay between local water suppliers and the role of citizens as water users with different income levels, who are either able to pay for tap water or who depend on public distribution.

It prompted a deeper debate on the reasons behind the found issues, their further implications, and possible strategic remedies, whose results are documented in Figure 5.

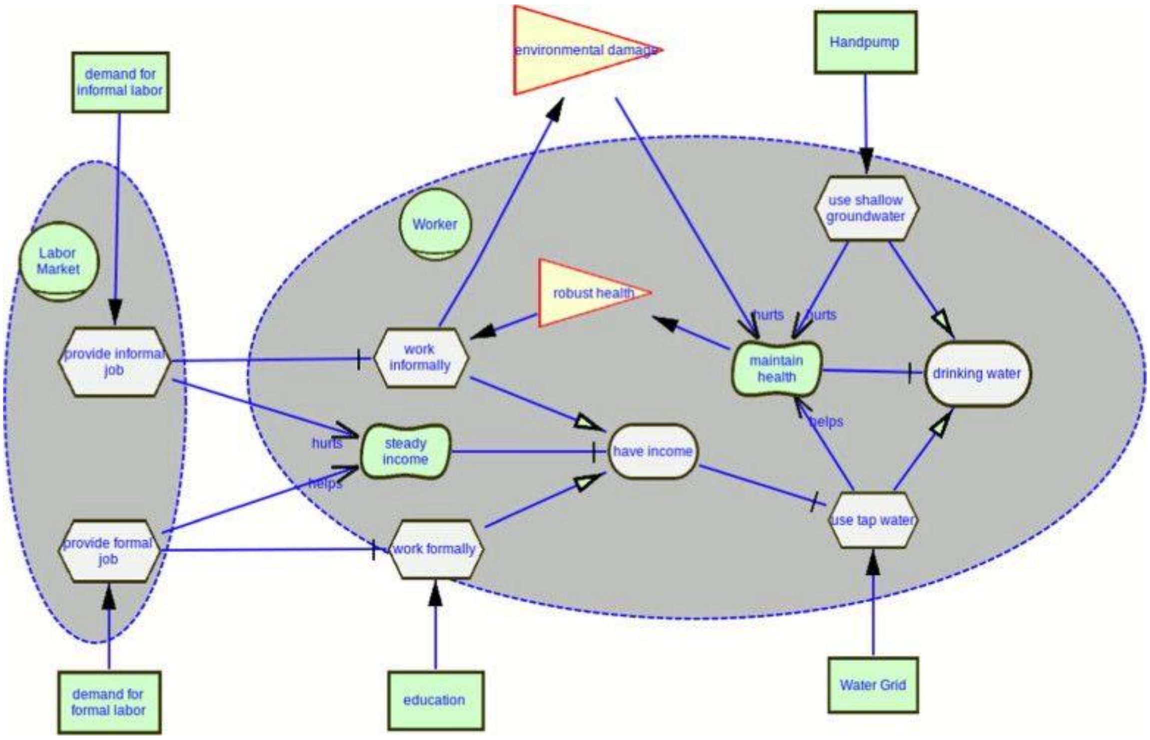


Figure 5. i* strategy model with broader water management debate including labor market, health, and environmental protection perspectives [57].

As low *income* was identified as a major issue in Figure 4, Figure 5 focuses on the *worker* role of inhabitants. A *labor market* role should help to increase water quality indirectly via attracting more *formal* (well-paid) instead of *informal jobs*, enabling more *use tap water* (a generalization of *use water tanker* from Figure 4) and reducing *environment damage* (sewage problems resulting from *use shallow groundwater*). However, workers must be empowered for such formal work by improved *education* and better maintenance of *robust health,* even when a high degree of informal labor would still persist. This way, the diagram exhibits the interplay of different disciplines in an easy-to-understand manner, thus setting the context for the interoperation of digital twins, which could support detailed planning simulation and consistent operational monitoring of this interplay.

The case study shows how i* strategy models create an even playing field among domain experts, politicians, project managers, and IT specialists. Based on such informed strategic agreements about goals, tasks, and dependencies among agents, i* models can also serve as a solid conceptual specification to which the interplay of cooperating or competing digital twins should be compliant. Similarly, data exchanges during the interoperation, via data space or data mesh approaches, must conform to the strategy model.

Fortunately, the last twenty years have seen extensive research concerning the linkage between i* strategy models and multi-agent simulations. In the early 2000s, the European-Canadian Tropos project network [26] investigated formal methods and supporting tools for how to map an i* model to operational MAS specifications, ranging from classical system dynamics simulations to contract nets, as discussed in Section 2.1, to declarative workflow languages such as ConGolog [45]. Specific research addressed the management of trust and distrust among agents [45] and, later, also multi-criteria decision support for choosing among competing ways to satisfy tasks while preserving legal regulations such as security, privacy, financial, or sustainability goals [58,59].

In essence, i* models can be seen as high-level specifications for data-intensive ecosystems [60], i.e., digital twins operating and interacting in an inter-organizational setting where both cooperation and competition, sometimes even simultaneously as so-called *coopetition*, play important roles. Such complex ecosystem design questions may require additional formal analysis tools, which have been explored in depth in [61]:

- A more precise calculation of *mutual inter-dependencies* among actors, indicating their relative power;
- *Complementarity* of the offerings among the actors, clarifying the added value of the cooperation;
- *Track record* of previous cooperation to evaluate *trustworthiness*;
- Exploring *reciprocality* options to reduce the risk of situational trust violation.

The power of this extended approach has been recently demonstrated by formally explaining steady and disruptive strategy changes observed in a ten-year longitudinal comparative strategic analysis [5] among two large-scale digital twin ecosystems with both steady and disruptive evolutions, but user support for this approach requires further investigation [62].

3. Applications

In some application domains with less complex interaction patterns, MAS implementations of cooperating and competing digital twins have already been successfully demonstrated and transferred to industrial practice. Many more complex domains, however, still face fundamental challenges due to the diversity of digital twins and their interaction patterns, but also in terms of complex interdisciplinary planning or power structures or sheer operational efficiency and security concerns, e.g., urban planning tasks exhibit highly intertwined dependencies between the different city domains, which makes it very hard to build a consistent and complete digital twin model of the constituent dynamic properties of a city. However, based on the success of digital twin models for Industrie 4.0, it is to be expected that these methods can also be successfully applied to digital twins for the development of intelligent cities.

In Section 3.1, we present examples of the former kind in the rather established field of Industrie 4.0, which also includes the corresponding concepts of Logistics 4.0 (cf. [63] and also the recent reviews by [64,65]). In Section 3.2, we use the concepts of interconnected digital twins for urban and regional planning and operation as a consequent extension of the digital transformation of industry and logistics to the city level as an example for one of the grand application challenges of the second kind.

3.1. Process-Centric Optimization with Digital Twins for Industrie 4.0 and Logistics 4.0

Communication processes among software agents representing digital twins are of utmost importance, especially if the digital twins are not only cooperating but competing with each other. With the formalization of a conflictual communication between agents through dynamic conflict management, in [66], it has been worked out how to ensure a priori, given the beliefs, goals, and intentions of a digital twin within a digital twin system, that this digital twin communicates "correctly" with "his co-digital twins" through a dynamic adaptation of protocols and negotiation protocols. This can be achieved through modeling user interactions and the adaptation of the digital twins to their environment and action plans in order to be able to recognize and resolve conditional conflicts between goals. This results in a deliberative behavior of digital twins that can dynamically change their roles with an "open adaptive communication" approach. In [66,67], it is shown that production planning and control can be integrated using these mechanisms with the consequences of much better opportunities for the optimization and possible reactions to process disturbances, as well as for satisfying the requirements of Industrie 4.0.

The study in [68] concentrates on a domain-independent framework of key performance indicators (KPIs) for the configuration, flexible adaptation, and efficient operationalization of quantitative goal systems for digital twins. This evaluation framework provides a quantitative multi-criteria model that can even be distributed among several digital twins. It allows for the evaluation of world conditions and the measurement of the quality of the local and global digital twin behavior in a system of systems of digital twins, also in the context of autonomous industrial and logistics processes of Industrie 4.0.

Refs. [35,69,70] applied the decentralized approach with a digital twin representation by multi-agent systems for the planning and control of logistics transportation processes that are closely coupled with production processes based on Industrie 4.0 concepts. In real-world logistics, groupage traffic and distribution and pick-up logistics with courier express and parcel services are characterized by many operational constraints, e.g., uncertainty of traffic conditions, time windows, the size of parcels, the unknown size of pick-up goods, and changing customer requirements. These properties require multicriteria optimizations and, in addition, almost instantaneous re-scheduling in these dynamic environments. This can be achieved by a MAS-based solution to the dynamic vehicle routing problem, with pick-up and deliveries with time windows and capacity constraints using a modified contract net protocol, leading to an anytime algorithm. This approach represented each truck by an agent implementing a digital twin. It could be validated with real-world transportation data provided by a large logistics provider serving the entire northwest of Germany. The study simulated the groupage traffic for a period of 10 days with approximately 1100 orders/day. The resulting distribution routes were validated with human dispatchers. They reduced the number of stops by almost 30% and the number of external transport requests by almost 76%. This clearly demonstrates the digital twin approach with a multi-agent system implementation to be feasible and efficient, satisfying the requirements for planning and control transportation processes in highly dynamic environments.

Refs. [36,70] base the scheduling of resources in open-pit mines such as trucks, shovels, crushers, and stockpiles on a scheduling model by associating a digital twin with each resource based on a multi-agent system approach. These digital twins encompass all data, information, and knowledge that is necessary for optimized open-pit mine operations, including maps, real-time locations, optimal routing, operational time constraints, process templates, and interaction protocols between cooperating and competing digital twins. This decentralized approach also includes local and global re-scheduling upon operational disturbances, as well as concurrent negotiations of competing digital twins based on an extended contract net protocol. It could be shown with real-world data from the open-pit mine Compañía Minera Doña Inés de Collahuasi in Chile that the material handling process could be organized more efficiently with such a decentralized approach than by a centralized "traditional" approach: The centralized mixed-integer linear programming (MILP) method was chosen to minimize the energy consumption of the shovels and trucks, taking into account the targets of the production plan. However, this centralized MILP approach applied to real shift data of 102 trucks, 12 shovels, 378,069.92 tons of transported materials, and 772.84 h of travel time had to be aborted after four hours of computation time without a scheduling result.

3.2. Digital Twins for Urban and Regional Planning and Operation

Urban and regional planning and operations provide many challenges and potentials for city digital twins, because this technology offers the opportunity to build a complex city/region model as a system of systems in a distributed and compositional way. This is especially important because of the many potentials of city digital twins [71], also in respect to smart cities and the many interrelationships among the different application areas for a city or region (see Figure 6).

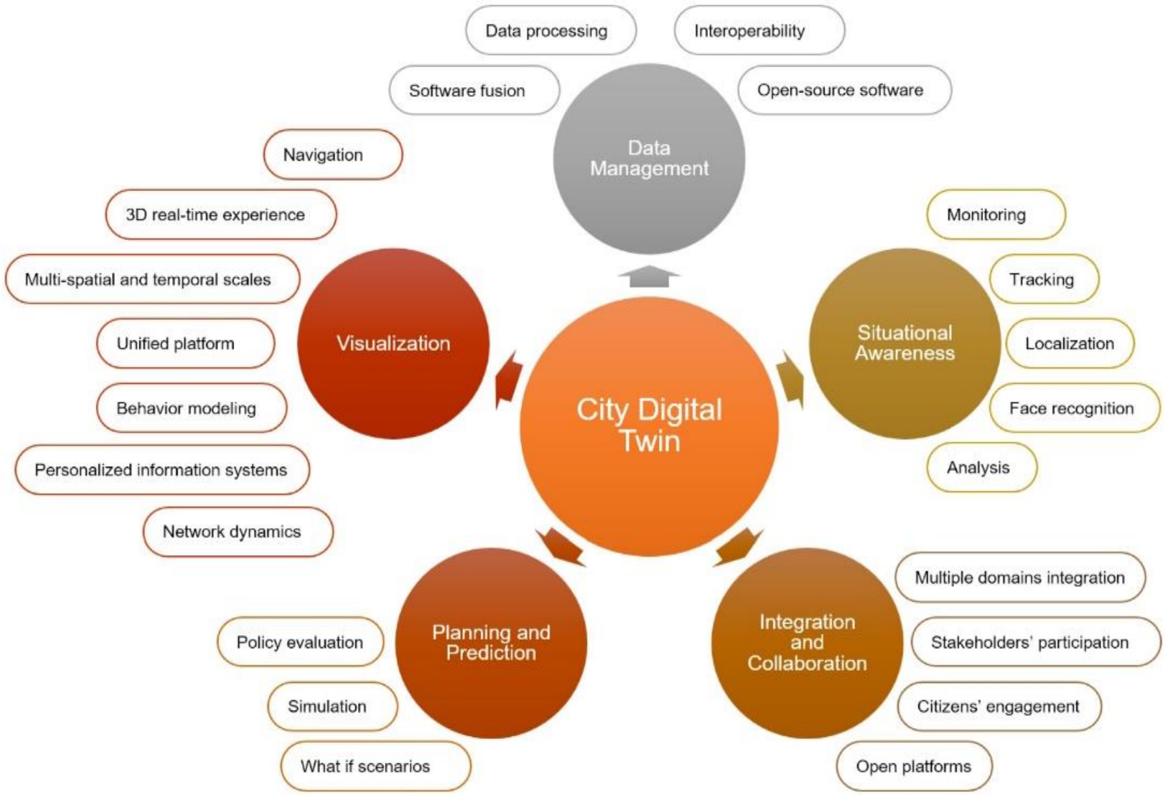


Figure 6. City digital twin potentials. From [71] (Figure 2).

On the planning side, city digital twins allow for an explicit representation of objects and their properties, processes, and communication and of the interrelationships between the different city domains. In addition, it is also feasible to develop what-if scenarios that support well-founded long-term decision making during the planning phases, e.g., for transportation planning and also for short-term decision support during city operation, e.g., for traffic control. In this way, city digital twins can be considered to be the technology to implement aspects of "smart" or "intelligent" cities.

Even if these observations are valid in general, and they certainly emphasize research areas that need more attention, there is already much progress in developing city digital twins, even if they are functionally complete for a specific application area but restricted in respect to cross-application area communication.

There are the so-called digital twin cities in Asia, North America, and Europe, among them Bangalore, Singapore, Shanghai, Shenzhen, New York, Zurich, Hamburg, Paris, London, and Barcelona. These cities have started their efforts with limited digital twin applications, e.g., with respect to transportation, city planning, and sustainability. A high-level architecture for a system of digital twins implementing a city digital twin is shown in Figure 7. Some examples are given in the next subsections.

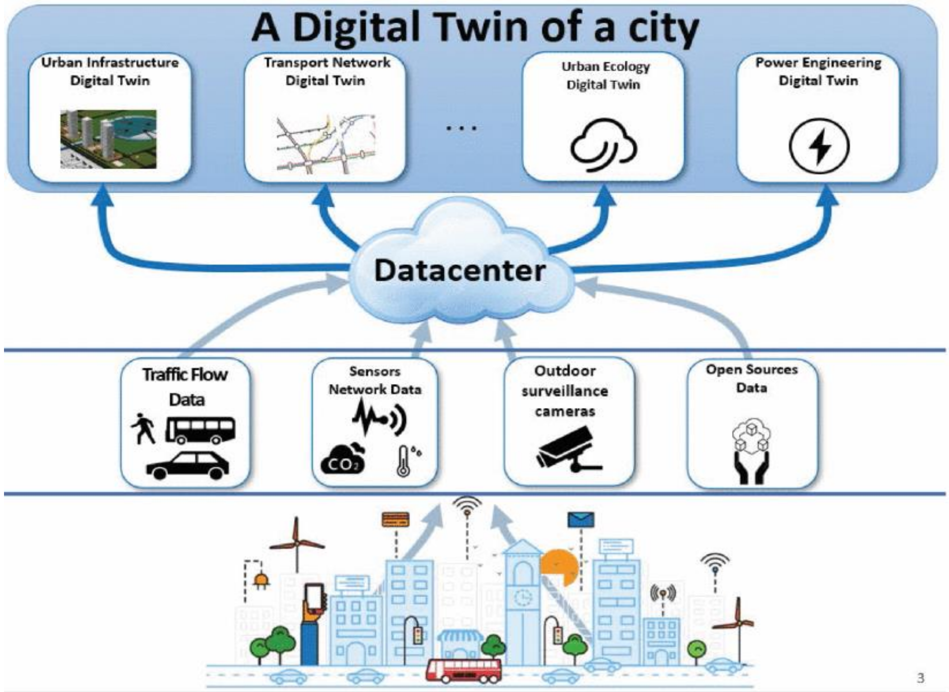


Figure 7. Architecture of a city digital twin, from [72] (p. 179).

3.2.1. Last Mile Transportation Simulation

In ref. [73], a digital twin system is described in detail for the last mile connectivity of several bus lines in the Indian city of Bangalore. The digital twin system is implemented as a generic multi-agent system model for different transportation agencies including autonomous vehicles, and it allows for planning and operation, where agents represent persons, buses, rickshaws, etc. It is based on a user needs study and several earlier transportation and traffic studies of the metropolitan area of Bangalore. The goal of this project was to provide the technological basis for travel information and route planning for megacities through an internet platform. A detail of a simulation with the corresponding city digital twins representing persons, buses, and rickshaws is shown in Figure 8.

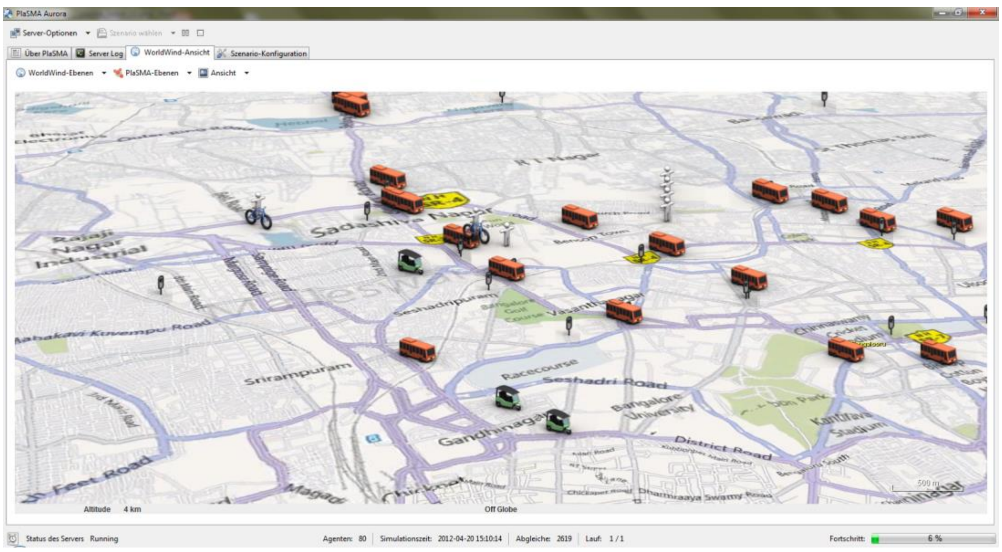
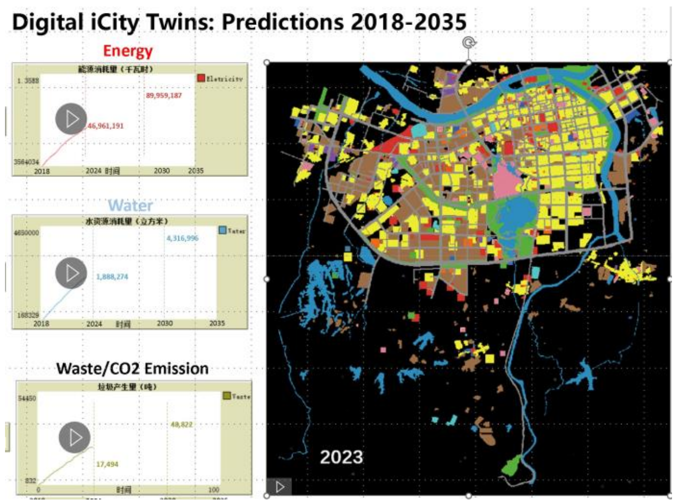


Figure 8. Simulation with city digital twins of buses, people, rickshaws, and bikes on top of a routing graph. From [74] (p. 328).

3.2.2. Digital Twins for Multiple City Domains

Refs. [75,76] have developed a set of "Digital iCity Twins" (digital intelligent city twins) for several city domains to provide planning decision support for urban and regional planning using deep-learning and multi-agent systems technologies. An important component is the incorporation of the outcomes of an analysis of the spatial development of 13,810 cities worldwide over 40 years each using deep-learning and clustering methods. The resulting seven city classes are used to classify a city at hand, so that the spatial development of this city can be predicted based on the learned classes. The generic digital twins implemented with multi-agent systems methods predict the development of urban domains over substantial time intervals, such as urban population prediction, land use, resource consumption (power, water) including waste with greenhouse gas emissions, city density, traffic, industrial development, public services infrastructures, multiple urban scenarios, construction time horizons, 3D city models, and regional development. Figure 9 shows partial results of an example simulation for the prediction of land use and the consequences for electricity and water demand, as well as waste amount associated to CO_2 emissions for the years 2023 (Figure 9a) and 2035 (Figure 9b).

(**a**)



(**b**)

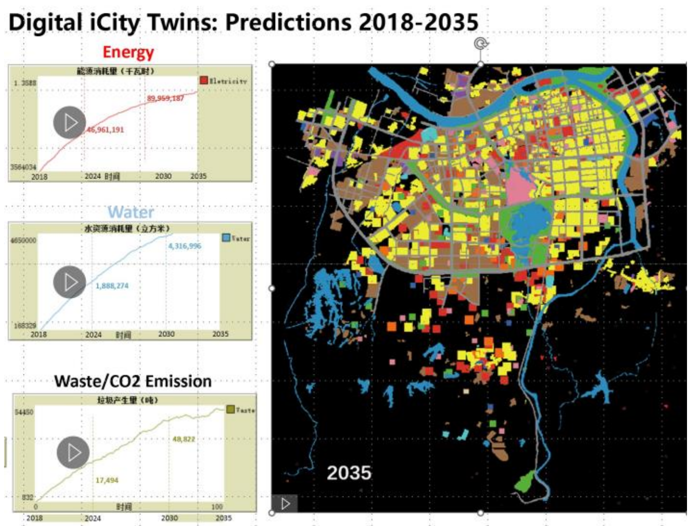


Figure 9. Digital twin city domain simulation predictions for energy and water use and for waste and CO_2 emissions, for 2023 (**a**) and 2035 (**b**), adapted from [75].

4. Conclusions

Digital twins that are implemented by multi-agent systems have been used very successfully as the models of choice for many application areas. The examples that are shown in this paper are from the Industrie 4.0 and the Logistics 4.0 domains, including production planning and control, optimization of transportation and distribution logistics, and strategy perspectives. Even specific application areas in urban and region planning and city operation are modeled and optimized by city digital twins. The digital twin success is based on the facts that

- They are an (AI) extension of object-oriented technologies, including knowledge representation and machine learning.
- There are powerful frameworks, such as JADE, available for their implementation.
- They are usually applied in restricted application domains.
- Their (almost identical) code allows for their use in the abovementioned domains in simulation and optimization during development, as well as for deployed operations in manufacturing, logistics, and in cities.

However, there are still open problems to be solved. In ref. [72], the following main challenges are explicitly noted for city digital twins: data management, situational awareness, integration and collaboration, planning and prediction, and visualization. These challenges are certainly valid in general, and they definitely emphasize research areas that need more attention in almost any modeling context.

Even if it could be shown in this paper that considerable progress has been achieved in applying digital twins to restricted application domains, the more demanding tasks that require more complex modeling and the simulation of complex interdependencies between, e.g., production and business processes or between different urban or regional application domains, e.g., to cover sustainability aspects and the reduction of greenhouse gas emissions, are at most in their conceptual stages.

It is to be expected that many more trans-disciplinary efforts must be spent to acquire and use formalized knowledge, e.g., those derived from big data, in order to cope with the distributiveness of large systems and to capitalize on the results of complex systems theory. Even beyond these obvious extensions for digital twins, it might be necessary to consider the systems to be modeled not as large machines but as mutually interrelated self-organizing systems.

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