applied sciences

MDPI

Article

Implementation of Cognitive Digital Twins in Connected and Agile Supply Networks—An Operational Model

Kostas Kalaboukas [1,2,*], Joze Rožanec [3,4,5], Aljaž Košmerlj [3], Dimitris Kiritsis [6] and George Arampatzis [1]

[1] School of Production Engineering and Management, Technical University of Crete, University Campus, Akrotiri, 73100 Chania, Greece; garampatzis@pem.tuc.gr
[2] Gruppo Maggioli—Athens Branch, Andrea Papandredou 19, Maroussi, 15124 Attica, Greece
[3] Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia; jose.rozanec@qlector.com (J.R.); aljaz.kosmerlj@ijs.si (A.K.)
[4] Qlector d.o.o., Rovšnikova 7, 1000 Ljubljana, Slovenia
[5] Jožef Stefan International Postgraduate School, Jamova 39, 1000 Ljubljana, Slovenia
[6] EPFL—École Polytechnique Fédérale de Lausanne, Route Cantonale, 1015 Lausanne, Switzerland; dimitris.kiritsis@epfl.ch
* Correspondence: kkalampoukas@isc.tuc.gr or Kostas.kalaboukas@maggioli.gr; Tel.: +30-210-008-3985

Abstract: Supply chain agility and resilience are key factors for the success of manufacturing companies in their attempt to respond to dynamic changes. The circular economy, the need for optimized material flows, ad-hoc responses and personalization are some of the trends that require supply chains to become "cognitive", i.e., able to predict trends and flexible enough in dynamic environments, ensuring optimized operational performance. Digital twins (DTs) is a promising technology, and a lot of work is done on the factory level. In this paper, the concept of cognitive digital twins (CDTs) and how they can be deployed in connected and agile supply chains is elaborated. The need for CDTs in the supply chain as well as the main CDT enablers and how they can be deployed under an operational model in agile networks is described. More emphasis is given on the *modelling*, *cognition* and *governance* aspects as well as on how a supply chain can be configured as a network of connected CDTs. Finally, a deployment methodology of the developed model into an example of a circular supply chain is proposed.

Keywords: agile supply chains; cognitive digital twin; cognitive supply chains; cognitive manufacturing

Citation: Kalaboukas, K.; Rožanec, J.; Košmerlj, A.; Kiritsis, D.; Arampatzis, G. Implementation of Cognitive Digital Twins in Connected and Agile Supply Networks—An Operational Model. *Appl. Sci.* **2021**, *11*, 4103. https://doi.org/10.3390/app11094103

Academic Editors: Richard (Chunhui) Yang and António Vieira

Received: 26 February 2021
Accepted: 27 April 2021
Published: 30 April 2021

1. Introduction

Manufacturing is becoming global, distributed and cognitive [1], making it necessary to operate in complex networks of suppliers and logistics chains. In parallel, it is transforming into "local" by supporting collaborations with local manufacturers to address flexibility, resilience, personalization, and environmental reduction [2].

In the broader context, supply chains are moving from the traditional hierarchical structures to "value webs", characterized by complex, connected and interdependent relationships, where knowledge flows, learning, and collaboration are almost as important as more familiar product flows, controls and coordination [3]. This is recognized as key strategic goal by the Industry 4.0 paradigm, being expressed as "*the transformation of existing manufacturing supply chain networks into more digitally connected and agile ones*" [4].

The importance of connectivity and agility in supply chains is justified by various factors.

First, the need for shortened product lifecycles together with the growing product complexity, creates a pressure on realizing an effective and efficient product development [5]. The need for customization imposes supply chains to be more connected and aligned by sharing knowledge. The trend is to transform existing mass production models into smart products (by collecting information streams on their use and applying Artificial Intelligence

(AI) services) [6], which are modular and with high degree of customization. To reach the goal of customization, decrease the time-to-market and improve the flexibility of the development process, the concept of agile product development is increasingly applied within manufacturing companies [7].

Also, improved visibility and supply chain optimization is becoming more important by the manufacturing companies. According to various studies, manufacturers are willing to invest in new applications on improved value chain visibility, closely followed by risk control and improving responsiveness. All these factors rank higher than cost control (65.4% of business leaders rank value chain visibility as "very important" and 54.8% rank it higher than simply cost control), and this is a major change in perspective for manufacturers [8]. Real-time supply chain optimization is shown to be a key factor able to reduce inventory costs typically by 20–50% [9], while in other studies cross-organization data interoperability in manufacturing industry is recognized as the top trend [10].

Last, the need for resilience is critical and given the COVID-19 experience supply chains need to find the way to respond to different situations by disrupting the whole model and ensure flexibility to changes. The need to ensure manufacturing and materials flow requires new approaches with real-time information sharing, collaboration and simulation/optimization models to assess alternative network setups either ad-hoc or even at the strategic level.

In response to the above, the transition to agile and connected supply chains, is highly dependent on the digital transformation of each participatory actor. Whereas various ICT solutions allow monitoring and information flows using digital models, they are still compartmental and do not offer the full supply chain "visibility" and interoperability envisaged by the paradigm. This can be achieved by a more holistic and "digitally smart" approach through the application of a virtual, but realistic, digital equivalent to physical entities or the DT [11], which is slowly taking a central position in digital transformation [12].

The usage of DTs and their benefits in the industry have not been fully realized yet. In fact, until very recently, experts still identified DTs as one of the top 10 strategic trends organizations need to explore [13]. In the context of connected agile supply networks, the usage of DTs is very important, since it allows a manufacturing company to virtualize its assets holistically and fully simulate, monitor and control their performance at factory level. Moreover, DTs can potentially improve production planning and predictive maintenance [14], monitor virtual production lines by connecting all involved stakeholders [15] and optimize packaging, materials and logistics [16].

However, the DT as an independent digital model is not sufficient to realize the dynamics and the needs of supply chains as described above. The need for synchronization, knowledge sharing, responsiveness and optimization at the supply chain requires interconnected DTs with cognition capabilities (cognitive Digital Twins—CDTs) able to share information, reason on top of this, understand complexity and perform actions, which impact other actors in the network.

The scope of this paper is the conceptualisation and development process of such a CDT model, focusing, beyond that, on its application to empower connected agile supply networks. Section 2 outlines the approach, justification of CDTs in agile supply chains followed by the description of main CDT enablers and the operational framework. The cognition process together with the deployment methodology and reference application scenarios are explained and discussed in more detail in Section 3, while Section 4 presents an example of configuration and operation in a circular supply chain. Finally, Section 5 summarises the study's conclusions and future work.

2. Methodological and Operational Framework for CDTs

An investigation of the present usage and adoption of DTs by manufacturing companies shows that current approaches to the implementation of DTs in manufacturing lack a solid methodological framework. At the same time, there is no systematic approach in scientific literature that applies the concepts of CDTs in agile supply chain networks.

Though some early adopters have demonstrated applications of DTs for manufacturing, current implementation limitations are:

- Inadequate understanding of the connotations of CDT-driven manufacturing.
- Focus mostly on operation and maintenance of production lines and not on the value chain.
- Lack of application frameworks and reference models for CDTs [17].

The methodological approach, followed in this paper, for the definition of such framework is based on the following three steps:

(1) Understanding the concept and functionality of a CDT.
(2) Positioning the CDT into the manufacturing context and more particular in reference Industry 4.0 architectures using some reference scenarios.
(3) Define the basic enablers for a CDT and explaining how they apply in the reference scenarios.

2.1. Understanding CDTs

A DT in manufacturing industry is defined as a digital replica of the physical system (e.g., the entire supply chain) or integral parts of it (e.g., a factory, a production line) that: (i) is an accurate enough virtual model of the real system, (ii) can simulate both the physical state and behaviour of the system, (iii) can be uniquely associated with any single specific instance of the system and its entities and (iv) it is for that purpose connected to it, updating itself in response to known changes to the system's state condition or context [18]. A Digital Twin has a bilateral integration with the physical object by both getting information from the object and controlling the physical object. It also combines an advanced data-acquisition system, information technology and network technologies to create a virtual, digital replica of a production system with various capabilities in manufacturing industry. Consequently, it must:

- Create and manage a virtual model of the system.
- Virtualize the behaviour of the physical entity.
- Have different capabilities allowing to simulate, predict and optimize.
- Connect virtual (model) entities with physical ones, updating itself in response to known changes to the entity's state condition or context.

An advanced functionality of the DT is "Cognition" (i.e., CDT): a DT able to "reason" and "act" taking into consideration the data, the states of the object and its behaviour [19]. This means that a CDT is able to understand, early detect and predict the impact of different types of behaviour observed [20]:

- The Predictable Desired (PD), which is the desired (normal) behaviour of the system.
- The Predictable Undesired (PU), which are problems that are expected but we cannot understand why they happen.
- The Unpredictable Desired (UP), which is the "surprise" and benefits/good behaviour of the system that we did not expect to happen.
- The Unpredictable Undesired (UU), which is a serious fact and relates to behaviour that we did not expect to happen, and we do not know why they happen.

A key differentiation between DTs and CDTs is that while some cognitive functions are present in DTs, such as simulations, those focus on solving a specific task but lack a holistic view of the existing models and aspects addressed by the DT. The CDT provides such a view to relate their outcomes among different CDTs, learn how UP and UU events affect the physical counterpart, taking cognition abilities to a higher abstraction level. CDTs address how to enhance cognition over time by providing means to improve a specific model through knowledge gathered from past UP and UU events or relating different types of knowledge that are introduced to the CDT or emerge from different models or components present in a DT [21,22].

2.2. CDTs Positioning in the Supply Chain

DTs have an important role in the manufacturing and supply chain context. In agile supply chain networks, connectivity among all factory assets and supply chain entities is of utmost importance. The RAMI industry 4.0 architecture [23] emphasizes how to connect different hierarchies of the factory from an individual asset up to connected processes, the enterprise level and the supply chain (connected enterprises). Such "assets" are orchestrated along the different product lifecycle phases (from development up to the product use and maintenance). Similarly, the Industrial Internet of Things Connectivity Framework is based on a hybrid interconnection in all product lifecycle phases and through on a vertical (field device up to Service system) and horizontal level (supply chain) [24]. The common denominator of both approaches is the need for modelling all production assets in a way that:

- There is an up-to-date representation of the operational behaviour, which is fed by streamed data from sensing devices or other supporting measurement systems.
- All possible interactions with other production assets are known thus creating a virtual representation of the factory/supply chain as a dynamic system.
- Combining the behaviour and the networking of such asset we can monitor, simulate and optimize its performance.

Already large enterprises have adopted the concept of DTs in different models and applications [20,25]. Furthermore, different DT scenarios are introduced in the literature [19,26,27].

The importance of CDTs in the supply chain is that through their cognition capabilities we have a holistic view of the whole context, relating entities and processes at various levels of abstraction, and providing means to learn from them and their interactions. This is essential, since we go beyond the typical boundaries of a physical object and through this interaction concept, we are able to have a holistic approach of event detection, simulation, impact assessment and optimization (actuation) in complex supply chain networks.

In the next subsections we will elaborate on the CDT characteristics and operation in supply chains. We will define the main CDT enablers (characteristics) and a reference operational model. At the end, we will provide some indicative application scenarios and will elaborate more on a circular supply chain case, where stakeholders are interacting in an attempt to optimize waste flows.

2.3. Enablers for CDTs in Agile Supply Chains

As introduced in the previous section a production entity (workstation, production line, Factory) or a supply chain is considered as a network of inter-connected DTs, each one having different capabilities. To realize this concept, each manufacturing context (factory, supply chain) can be modelled accordingly with different levels of cognition, communication and monitoring needs. Such configurability can be achieved by allowing the end user to configure and monitor the physical assets as CDTs and associate them with different capabilities/enablers presented in Figure 1.

Most of the above enablers have already been introduced in the literature [12,18,19] and from different perspectives. Some of them are by default functions of a DT (profile, lifecycle, visualizations); others have already been introduced as well (communication, trustworthiness and computational). We propose the above approach which is in line with the focus on agile supply networks. We are also complementing the previous work, by emphasizing on the communication (among CDTs) and CDT governance aspects, an issue that has not been elaborated much and with regards the applicability in the supply chain.

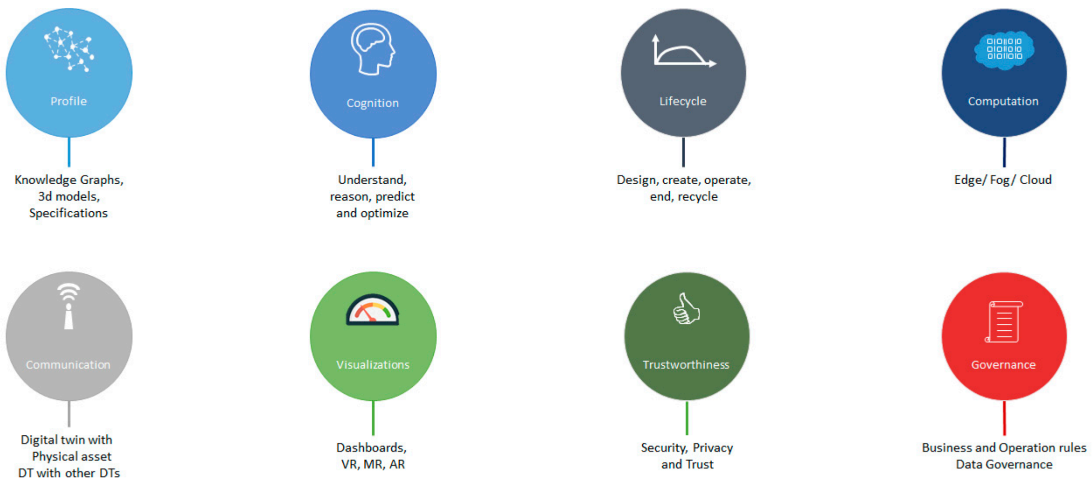

Figure 1. Basic CDT enablers.

2.3.1. Profile

The CDT profile is all about its status, behavioural model, specifications and associated models. It is the basic model of the CDT, which can be realized using a Knowledge Graph-centric framework [22] addressing: (i) the underlying processes where the DT is part of; (ii) ontologies supporting the semantics and syntax; (iii) APIs with analytics and optimization services that support the whole cognition process (see Section 3).

2.3.2. Cognition

Cognition is the ability to understand context, reason on top of existing information, predict and optimize behaviour. This ability comprehends all analytics and cognition services, and each DT can have different cognition capabilities (from simple simulations up to complex predictive models, anomaly detectors, and optimization). The basic blocks of cognition are the following:

- Reasoning services, which are responsible for understanding a context and generating new knowledge-based on existing domain knowledge, past data, data streams from the physical entity, and insights obtained from simulation and prediction services, or optimization models and services.
- Simulation and Prediction Services that propagate a DT's behaviour in the future to understand which future scenarios are most likely to happen and provide insight into whether an undesired outcome is about to take place. Prediction services can be used to learn from past anomalies and predict if new observed values are considered anomalous.
- Optimization models and services, which allow finding valid and, in many cases, near-optimal solutions, given a set of constraints.

To realize the cognition process, a CDT must embed the necessary analytics models and provide APIs so that external analytics services can consume the insights. According to IDC report [28] cognitive enabled supply chains can be a key to respond to key priorities such as: eliminate waste, improve supply chain traceability and predictability, improve service performance. In Section 3, we will analyse in more detail the cognition process.

2.3.3. Lifecycle

This refers to the ability to monitor and control the DT behaviour through its entire lifecycle. As the DT illustrates the behaviour of a physical entity, the DT lifecycle can be considered from the Product Lifecycle view [20,29], consisting of the following steps:

- Creation, where the profile of a DT is defined. Different configurations are assessed and—using data streams—"asset's" behaviour model is identified. This is achieved through experimentations/simulations and removing unpredicted and undesirable behaviours.

- Production, where interfaces and created between the DT and physical asset and are ready to communicate each other.
- Operation, where information between physical asset and DT is exchanged. There any change in the physical asset (e.g., parts replacement) updates the DT model and further information coming from the DT can predict anomalies or changes in the physical asset's behaviour. In principle, the operation is a continuous alignment of the physical and virtual operation.
- Disposal or recycling. At the final stage, the full operation of a DT is considered as source of learning to avoid future mistakes in next modelled production systems.

During the CDT lifecycle, the cognition models play a very important role since they model, calibrate and improve the CDT's behaviour. From the early phases of the CDT design (Create and Production) we need to experiment different scenarios and conclude on a particular desired behavioural model to be made. The desired behaviour also needs to be calibrated with first operational data, which validates and refines the initial assumptions. In the operational level we are dealing with information about the actual operation and possible deviations that reflect either failures or even areas of improvement. Finally, at the disposal level, we have a complete set of knowledge about the CDT's operation (associations, rules, behavioural aspects), which can be replicated in the design and operation of other CDTs thus minimizing the design time and cost. Recyclability of the CDTs in this case is about reusing the knowledge/lessons learnt about the CDT in a particular context and applying it in a similar case.

Depending on the application, different DT lifecycles from the creation, duration and end of life perspective may appear. At first, we have the static CDTs, for example, in a production line inside a factory, a machine that has a long lifetime and is part of a fixed process (which behaviour can of course be upgraded but as an entity remains a long). In such a case, the production line is a network of such fixed CDTs.

We might also have the case of an ad-hoc and more dynamic CDT. This is a case where in existing production of supply chain networks we have for specific occasions the need to incorporate a physical asset in an operation. Let us take the example of collaborative logistics where a truck has a problem on the route and must find an alternative solution. if we consider the logistics operation as a distributed network of collaborative CDTs (Logistics Objects), the truck can identify a collaborator (i.e., another truck, which is in a close geographical range) that goes to the same direction, fulfils all the needs of delivery (conditions, capacity) and the governance/collaboration rules. In such case, the CDTs of those trucks can identify through "social networks" such CDTs and "tweet" each other to negotiate a collaboration [30].

Another example is the case of customized products. For a particular feature requested by a customer, the manufacturer might need to assess different external asset providers (e.g., 3D printing), which can deliver the part to be integrated in the product. In such case, a DT of the candidate producer can be built in line with the CDT enablers so to assess the performance. The lifetime of this CDT can be:

- Very short (creating and operating only in the planning phase: just examining whether to collaborate with a producer).
- Time-limited in the case of a collaboration but in specific timeframe (e.g., only for a particular and seasonal batch of products).
- Longer and lasting, in a case of more permanent collaboration with the producer.

2.3.4. Computation

Power computation is recognized by the Industrial Internet as a core element that enables the equipment's ability for failure prediction, energy analysis optimization, predictive maintenance and other applications [24]. In a CDT context, this is translated into its ability to perform computations (considering the load of functions and calculations need to perform) either or cloud and/or edge, depending on the CDT deployment and operation.

2.3.5. Communication

Is the ability of a CDT to communicate with its physical asset and with other CDTs as part of the network it belongs (e.g., Workstation A with Workstation B, which belong to the same production line). Communication services are supported through a messaging layer which is responsible for the interoperation and information exchange. Through the communication services we can model and operate networks of CDT, for instance:

- A production line: Network of interconnected machine CDTs.
- A factory: Network of interconnected operational entities that illustrate the main manufacturing operations in the entire value chain.
- A supply chain network: A supply chain network will be a network of interconnected CDTs each one representing the entities participating in the whole network (factories, suppliers, customers, warehouses, etc.).

2.3.6. Visualizations

Refers to the ability to monitor the performance and lifecycle of a DT (using dashboards, VR, MR and XR technologies). Visualization services are collecting the processed by the CDT information. Through an API such information can be visualized either in dashboards or XR tools.

2.3.7. Trustworthiness

This is a combination of all technologies, models and applicable regulations (e.g., GDPR) to ensure that data are generated, transmitted, and received among CDTs under a holistic trustworthy framework [31]. This includes data security, traceability, transparency, confidentiality and integrity.

The above aspects are very critical and apart from the (cyber-)security technological aspects to be deployed we need to enforce the right rules and policies for data sharing, use and authorization. Let us consider a scenario of materials flow monitoring in the supply chain: information such as product quality, delivery times and potential events (machine breakdown, delays or predictive maintenance activities) have to be shared in a transparent way in order to allow for re-scheduling from other stakeholders in the chain. In such scenario where a factory CDT has to inform about an event, we need to ensure the following:

- The right information is generated with respect to factory CDT's sharing policies. This means that the factory CDT will send only the necessary information in the supply network without disclosing anything that is marked as "confidential".
- Such information is sent and can be used only by the authorized CDTs. This is done by enforcing access control policies in the network and applying the rules of collaboration and governance aspects (which are detailed in the next section).
- Such data is actively monitored to ensure its integrity and detect potential data poisoning, that could disrupt machine learning models training, and their outcomes.
- Any action from the CDTs on the information shared can be traced, thus providing transparency of use in the whole supply chain and ensuring trust among the collaborators.
- The information is accurate and values the rest stakeholders by updating their production schedules and other internal operations.

2.3.8. Governance

According to the Canadian Institute of Governance [32] there are three main questions to start understanding and structuring a governance framework:

- who has a voice in decision making?
- how are decisions made?

- Who is accountable?

To propagate in the CDT concept, such questions are very important since CDTs are linked with autonomous behaviour capabilities (cognition). Therefore, are aspects on how information is processed, and decisions are taken from business, operational and ethics point of view are quite important to agreed and incorporated in the design and implementation of CDTs in different supply chain contexts. For example, in smart cities an interesting work on governance is made on modelling Cambridge city as a DT [33]. In connected supply chains, we have CDTs of Assets that belong to different owners (as entities) and we need to ensure accountability together with the right decision-making procedures, norms, and rules, so to allow a synchronized decision making, depending on the case occurred.

In the real (physical) world, information is shared, processed and decisions are taken considering some business/operational rules or policies and in compliance with the applicable regulatory framework. In the same manner, in the virtual world, the DT needs to be aware of those rules or even that reflect the priorities, policies and other terms of collaboration under which, this DT operates. Such rules can be:

- Data sovereignty and governance: Introduced by the Industrial Data Space [34], this refers to the rules of data management (ownership, terms of conditions and use).
- Prioritization of criteria in a context of decision-making (optimization): Imagine a 3d-printing-as-a-service company, which gets an order from a "big customer". In the decision on the delivery date (by combining other orders and reschedule its production plan), if there is a strict service level agreement (SLA) of 24h delivery for the customer, this changes the priorities and gives a higher level of important to this particular order.
- Legislation/Regulation: Let us assume the case of materials logistics using drones or other autonomous vehicles (according to McKinsey [35], semi- autonomous delivery is expected to be a trend from the near terms in the beginning of the 2020–2030 decade). In such a case, there are specific regulations (with regards where to fly, etc.), which must be modelled and enforced in the operation of the CDTs. Such rules are very important and special attention has to be given to avoid liability issues.
- Reputation and past-experience knowledge: considering again the case of a contractor manufacturer (3D printing), the past-experience creates knowledge and some predicted rules of collaboration behaviour. If the manufacturer's supplier has not proved trustworthy in the terms (e.g., delivery dates) then the 3D printing company faces some risks in delivering the product according to the SLA. Reputation mechanisms and records from previous transactions can form those rules to be considered in the decision-making process.

Liability and Compliance with Legislation/Regulation and Ethics

DTs are a virtual entity and a question raised is whether liability falls on it should also be accompanied with the necessary of information sharing and processing using AI [36]. DTs are bound with the operation of the physical world and in some cases, there are various issues of liability. Let's take the example of materials autonomous delivery which is giving a lot of attention [37]. In the case of B2B delivery using autonomous vehicles we have the famous social dilemma on where an autonomous vehicle should move to avoid the death of the driver or a passenger [38]. Apart from this, depending on the context of the supply chain we cave specific regulations that have to be met (e.g., Supply Chain Regulation of Pharmaceutical Samples [39]).

During the supply chain modelling phase, the role of each CDT must be defined along with the information to be processed and decision-making autonomy. Then, liability will be defined in accordance with the terms of collaboration and the applicable regulatory framework.

The Need for a Code of Fair Operation

It depends on the complexity and nature of operations the CDT is to perform and on the degree of autonomous behaviour of the actor. In a context of agile supply chains, an example can be in the materials logistics. In such case, a truck receives (through its CDT) a request for an ad-hoc delivery. The CDT can then proceed on the decision about the actions to be done or propose a plan to the person monitoring the CDT behaviour (driver or operational support whoever is the decision-maker) and the latter confirms the action [30]. In a fully autonomous behaviour, a CDT might decide to abandon a particular request with consequences on the future collaboration with the customer. Companies need to think of a code of fair operation in line with its organization values and principles and model them as rules to be enforced in all phases of CDT operation.

CDT Governance Approach

Our approach on CDT governance will be based on a similar deployment approach used to model DTs in the city of Cambridge [33]. The main aspects to consider are:

- Define the context of operation (in which factory/supply chain hierarchical structure does the CDT belong?)
- Identify relevant stakeholders, CDTs and needs (physical asset, other involved assets/CDTs): Include appropriate external stakeholders where needed (e.g., customers who give input on the design aspects of a product manufactured by a particular production line CDT).
- Define interactions among stakeholders/CDTs: Clearly identify inputs/outputs, information sources and needs.
- Define roles per stakeholder/CDT: Who does what? Which are the decision-making power and authorizations? Is a particular CDT able to autonomously make decisions and initiate actions?
- Agree on liability and legislation issues: Agree on the ownership and liability of any malfunction of the CDT. Define any applicable legislation rule that affects the operation of the CDT.
- Define rules of collaboration, such as: Who owns data? Which are the norms/rules of collaboration/information exchange/processing and decision making? Which are the applicable information authorizations (access control policies, etc.)?
- Define required AI models: Agree on valuable insights that can be provided by forecasting future outcomes based on past data, or anomalies learnt based on past data. Explanations should be served along with those insights, to understand models' rationale behind a forecast or detected anomaly.
- Procedures/workflows: Given an information input and knowledge acquired (cognition) what is the process to be followed? How can cognition improve this process?

3. The Cognition Process: A Reference Operational Framework Model for CDTs

3.1. The Model

The above enablers are functioning together in an integrated concept, where for each of the CDTs we can monitoring the flow of information from collection to understanding and behavioural alerting as indicated in Figure 2:

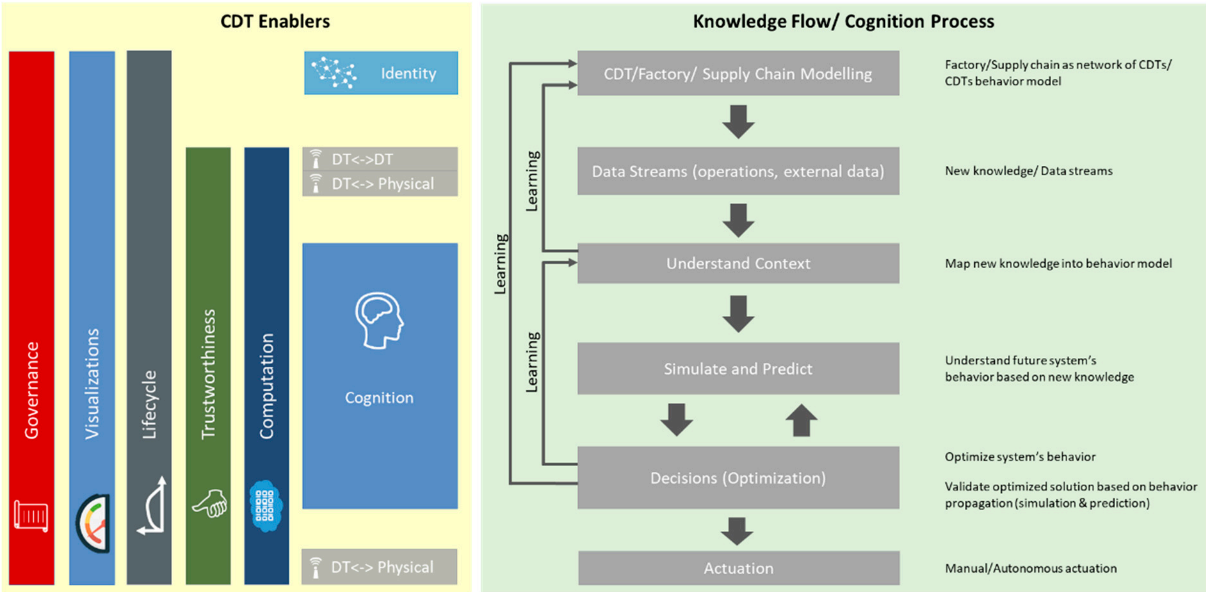

Figure 2. CDT Operational Model.

The main steps are:

Step #1: Configuration phase/Modelling: Here, we model a factory or any hierarchical structure of a factory/supply chain as a network of interconnected CDTs along with interactions and information to be exchanged.

Applicable Enablers:

- Profiling: Define the knowledge about the CDT, assign relationships with other CDTs (parent-child) to create the structure of the network
- Visualization: Monitor the configuration phase and the different parameters/CDT characteristics.
- Lifecycle: Define status of the CDT, make ad-hoc or static CDTs, etc.
- Governance: Define governance and decision-making policies; rules of collaboration among CDTs.

Step #2: Collect data streams about the behaviour of the CDT: Each CDT will collect information about its behaviour from sensors, systems, other CDTs or external sources (standards, databases, etc.).

Applicable Enablers:

- Communication: Communication capabilities of the CDT that defines the sources of the data streams (either from the physical assets and/or from other CDTs that represent different information sources).
- Computation: refers to basic calculations and transformations that happen either at the cloud and/or edge.
- Trustworthiness: refers to the applicable security/privacy/trust services and policies that apply in the process of collecting info from other physical asset/CDTs.
- Visualization: Data streams visualization.
- Lifecycle: Monitor status of the CDT (modelled in step #1).
- Governance: Apply governance policies.

Step #3: Understand Context: Once data is collected it is mapped against the CDT's behavioural model. Through cognition services, the CDT understands potential trends, anomalies or creates new knowledge (in the form of new rules, associations, etc.) that is not yet known.

Applicable Enablers:

- Cognition: Analytics based on existing behaviour models or data-driven knowledge extraction that updates the existing model.

- Computation: Refers to whether cognition services will run at the cloud and/or edge.
- Trustworthiness: Refers to the applicable security/privacy/trust services and policies that apply when processing info from other physical asset/CDTs.
- Visualization: Knowledge visualizations.
- Lifecycle: Monitor status of the CDT (modelled in step #1).
- Governance: Apply governance policies.

Step #4: Simulate and Prediction (S&P): Once an incident, trend or anomaly is identified (in the Understand and knowledge generation phase), S&P should allow simulation of the behaviour of the CDT in the future and predict potential failures in the future. Simulation is performed based on root-cause analysis and using the existing behaviour model (propagating the behaviour of the system in the future using the new data).

Applicable Enablers:

- Cognition: Simulation and prediction services propagating the system's behaviour with the new knowledge in the near future and identify potential anomalies.
- Computation: Refers to whether cognition services will run at the cloud and/or edge.
- Trustworthiness: refers to the applicable security/privacy/trust services and policies that apply when processing info from other physical asset/CDTs.
- Visualization: Simulation and prediction visualizations.
- Lifecycle: Monitor status of the CDT (modelled in step #1).
- Governance: Apply governance policies.

Step #5: Decisions (optimization): After simulating and predicting the CDT's behaviour, robust optimization services will offer suggestions for improvements. Optimization services will propose a new state of the CDT's behaviour, which has to be validated using the simulation and prediction services. This feedback loop will consider the new CDT's behaviour inputs, simulate and predict its behaviour in the system and assess the performance (is the problem solved? Is the trend fixed? Other?). If the solution is not validated, then optimization services have to run again and the feedback process continues.

Applicable Enablers:

- Cognition: Robust optimization services to identify new behaviour parameters. Simulation and prediction services propagating the new (proposed) system's behaviour in the near future and identify potential anomalies.
- Computation: Refers to whether cognition services will run at the cloud and/or edge.
- Trustworthiness: Refers to the applicable security/privacy/trust services and policies that apply when processing info from other physical asset/CDTs.
- Visualization: Behaviour visualization.
- Lifecycle: Monitor status of the CDT (modelled in step #1).
- Governance: Apply governance policies.

Step #6: Actuation: Once the optimized solution is validated, the actuation services will create the necessary messages to the physical asset in order to alert the behaviour accordingly.

Applicable Enablers:

- Communication: CDT with physical asset communication.
- Computation: Refers to whether services will run at the cloud and/or edge.
- Trustworthiness: Refers to the applicable security/privacy/trust services and policies that apply when actuation is performed from CDT to the physical asset.
- Visualization: Monitoring the status of the actuation (confirmed or not, other).
- Lifecycle: Monitor status of the CDT (modelled in step #1).
- Governance: Apply governance policies.

3.2. Deploying the CDT Operational Model in Connected Agile Supply Networks

3.2.1. Overall

The usage of CDTs in connected factories and supply chains is very important. Through CDTs, a manufacturing company can virtualize its assets and have a better monitoring of their performance both at factory and inter-factory level. They can also improve Production Planning and Predictive Maintenance [14], monitor virtual production lines by connecting all involved stakeholders [15] and optimize Packaging, Materials and Logistics [16]. Similar to the concept that a factory is a network of interconnected CDTs, a vision for agile and connected supply chains is illustrated in Figure 3 and includes the following:

- A dynamic, living system of "cognitive digital twins" representing all assets, operations and actors involved: factory, logistics service provider (LSP), trucks, warehouses, etc. Each entity participating in the supply chain can be modelled as a CDT. Deploying the enablers described above, each CDT can share only the necessary information with other CDTs and agree on governance aspects and rules applicable in all communications and decision-making process.
- Interconnected CDTs at intra- and inter-factory (supply chain) level. This implies the definition of the information/events to be shared under a common security/privacy and data integrity framework.
- Different levels of cognition. Depending on the level of autonomy (defined in the governance framework for each of the CDTs) different cognition capabilities will apply. Those will vary from basic understanding to autonomous decision making and actuation.

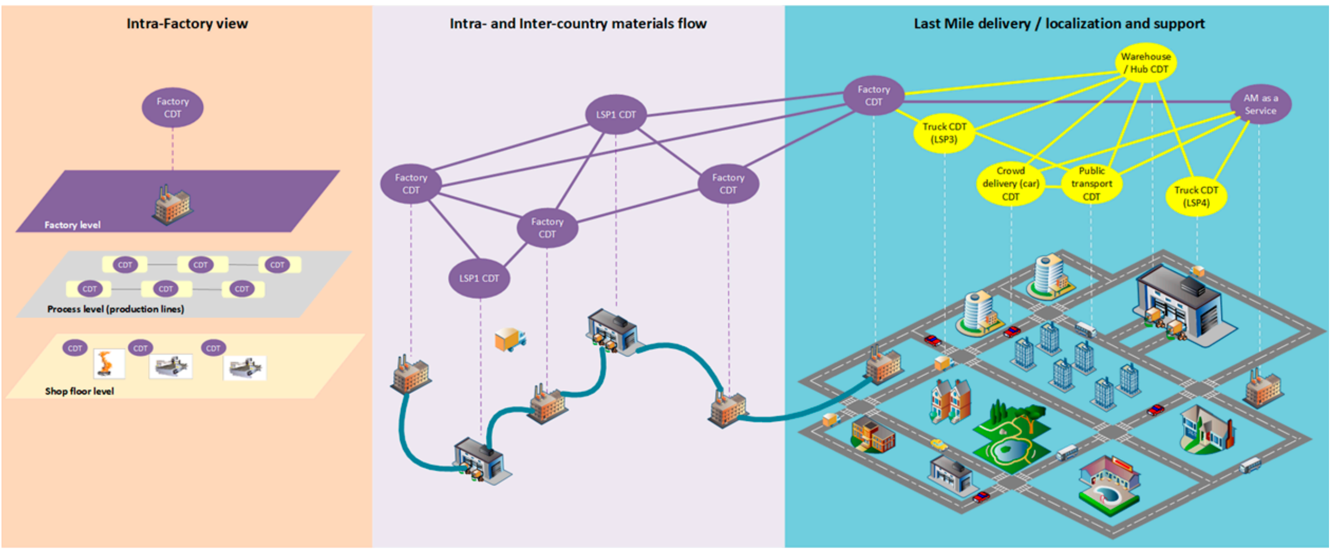

Figure 3. Agile supply chains as network of inter-connected CDTs.

3.2.2. Deployment Methodology

The deployment methodology is illustrated in Figure 4 and follows the principles of the CDT lifecycle described in Section 2.3.3.

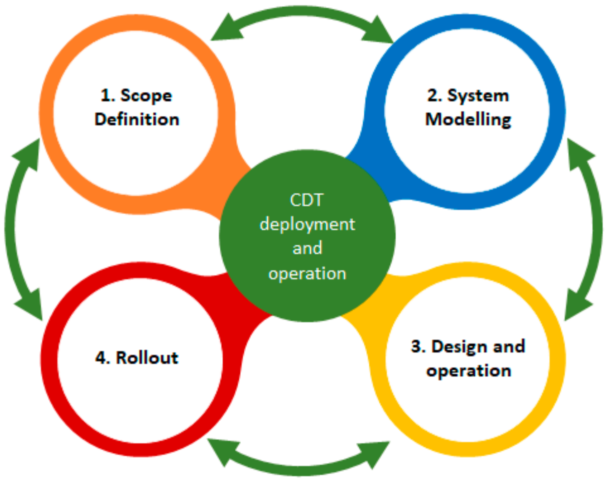

Figure 4. CDT deployment methodology.

Scope Definition

This is the first phase where we define the case for monitoring and improvement of the agile supply chain. We need to analyse the challenges, problems and areas of improvement we expect to address with the CDT model. The basic questions to answer are:

- What is the overall operational flow of my supply chain?
- Why is it critical to monitor the supply chain? We need to justify our focus with KPIs and other quantitative/qualitative metrics.
- Define the core stakeholders: Who are the ones that contribute most to the challenge/problem defined above? here we need to define our system boundaries (either we focus on a specific supplier tier or even select the most important in multiple tiers).
- Define and select the process where to focus: Depending on the challenge, we need to identify the critical process(es), which will be the focus for modelling and operation.

System Modelling

Once we identify the problem and the case, we need to understand how the collaborative supply chain processes work, where the needs for CDTs are and understand the different capabilities/needs in relation to the CDT enablers described in Section 2.3. After that, we will be able to configure the cognition operational model process (presented in Figure 2).

More particularly, the things to address are:

- Operational/process modelling: Create the process workflows and map the stakeholders, roles, inputs and outputs.
- Define the needs for CDTs: Depending on the challenge, the workflows we need to understand which asset/process or even entity in the supply chain has to be modelled as CDT. We might come with a 1-to-1 relationship between CDT and entity or a group of inter-connected CDTs.
- Elaborate on the CDT enablers: For each of the CDT identified, we need to understand how the enablers apply. This is a time-consuming issue since all actors have to agree on the information to be monitored, governance issues, cognition levels of autonomy per CDT and other parameters.
- Understand and model information needs: The focus is on the information to be exchanged/collected which will be further used in the analytics/cognition models.
- Deploy and train the necessary cognition/analytics models: Different strategies are required to train different types of models. To ensure the quality of the service exposing them, special attention must be put on monitoring concept drift, and models' performance over time.
- Deploy the necessary optimization algorithms for decision making.

In this phase we might result in some improvements on the scope and prioritization of the processes/actors.

Design and Operation

After the modelling phase, we move to the design and operation which is the actual implementation of the CDTs operation. Here, we create all inter-connectivity services (data collectors, data exchange services, integration with existing stakeholder's backend systems) and necessary cognition/optimization services and visualizations. Initial deployment is done at the different stakeholders and a first operational trial is done for testing.

The trial phase can be on selected CDTs and a specific scenario. The main goal phase is to refine and fix the models and enablers (configured in the modelling phase) and the overall CDT performance.

Rollout

In the rollout we extend the operation to the rest CDTs and scenarios in the operational model (defined int eh scope definition). It is a continuous and scalable process where we can extend the scope of the implementation thus redefining and re-implementing the deployment model.

3.3. Application Areas—Reference Scenarios

The realization of the above operational framework can be applied in different supply chain contexts and scenarios. Indicatively we can name the following:

3.3.1. Optimizing Material Flows in Circular Supply Chains

Circular economy is becoming more important and many initiatives have launched on city, manufacturing and other areas. In such a context, all actors need to collaborate to monitor the waste material flows in a reverse logistics model. We can model all actors involved in the supply chain (waste producers, logistics operators and recycling or processing factories) as a network of interconnected CDTs where they exchange information about the current or predicted waste offer, to simulate and optimize logistics network and factory planning. This scenario is detailed in Section 4.

3.3.2. Virtual Supply Chain Production Lines

This responds to the need of supply chain alignment. The main idea is to create a virtual production line at the supply chain where all actors (supplier, manufacturer, warehouses) are modelled as CDTs and planning is performed at the supply chain level similar to intra-factory. Events such as machine breakdowns, maintenance activities and other potential delays are shared among the supply chain and through the CDTs we can simulate the impact in different individual production plans and re-optimize them.

3.3.3. Optimize Material Flows in the Supply Chain

This scenario is more on the logistics aspects where we can optimize the flows from the factory (product deliveries) and the incoming materials thus improving demand forecasting and synchronized planning [40].

We can model all involved actors (LSP, origin supplier, factory and other external LSPs) as CDTs where they can propagate information about their delivery status (delivery from the factory, load factor during transportation, delivery destinations, SLA terms, etc.). through a peer-to-peer network all CDTs can assess potential alternatives (merging deliveries, exception management as a response to an event) and negotiate with other CDTs optimal solutions to minimize deliveries times and cost. To do this, the CDTs need to consider other stakeholders' plans (delivery plans, MRPs for the factories, etc.) so a more holistic view and approach is needed that extend beyond each CDT status.

3.3.4. Localization: Ad-Hoc or Constant Collaborations with Local Manufacturers

One of the key factors for resilience in supply chain networks, is the ability to make the best use of local manufacturers. The deployment of flexible shop floors (3D printing, micro-scale manufacturers, etc.) enables more agile and local manufacturing sites. Furthermore, smart specialization platforms (S3P) [41] are local catalogues assisting companies to find local partners. To cope with the needs of personalization, customization and production flexibility, responsiveness (time to market, time to fixing, time to replacing parts, etc.) and cost effectiveness (inventory, production and other costs) are the key factors for sustainability and resilience within the whole supply network. In such a model, we can have the local manufacturers as CDTs where we assess various strategies for SLA management (production or spare parts in response to customer claims).

In the long term, we can model different production networks, distribution and local support centers as CDTs and perform various scenarios for optimal response taking into consideration aspects such as: capacity, delivery times, historical customer claims data, etc. Each actor as a CDT will have its own behaviour and in such simulation scenarios we can assess the behaviour of the network.

In the short term, we can have also ad-hoc decision making for a particular part that is not in the production pipeline (for e.g., a part requested by a specific customer). Through the utilization of CDTs we can assess various alternatives depending on the real-time information about availability, capacity, delivery times and other parameters.

4. Deploying the Model into Circular Supply Chain—The Case of Circular Supply Chain

In the case of a circular connected supply chain we have different actors interacting together to collect, forward and process organic waste from different sources (the farm, motorhomes-RVs) ending to the recycling processing factory. Our focus will be on the configuration aspects (modelling, communication, governance) and cognition aspects. The rest enablers (visualizations, computation, trustworthiness, and lifecycle) depend on the case context, IT/infrastructure maturity, level of trust and other factors, which need to be analysed per case.

We will start with the overall description of the case (Section 4.1); then we will present potential scenarios of dynamic behaviour of the supply chain (Section 4.2); finally, we describe how the operational model works for those scenarios (Section 4.3) in line with the steps described in Figure 2.

4.1. The Case of Circular Supply Chain in Rural Areas

The case is about a circular connected supply chain in rural areas where we connect all potential organic waste providers with a dynamic logistics system and the factory, which process it and returns it back to the rural community (Figure 5). In such a model we can connect different rural areas through an ecosystem aiming at reducing CO_2 emissions and minimum waste in the environment.

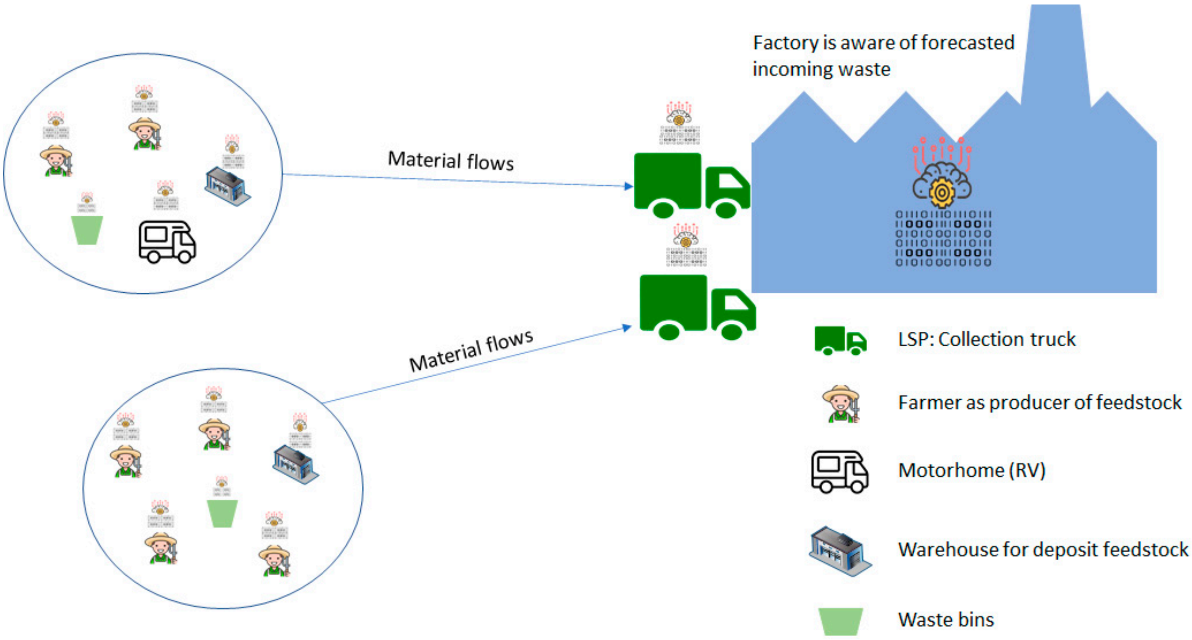

Figure 5. Connected rural ecosystem in a circular supply chain model.

4.2. Operational Scenarios

From operation point of view we can have different scenarios of how this connected model can work:

4.2.1. Scenario #1: Informing about Feedstock Availability and Collection/Deposit Points

The request for waste collection can happen through the following ways:

Collection from farmers

Farmers monitor information about their feedstock. Organic waste for example is modelled as CDT with the following parameters: (a) Type of waste; (b) Quality characteristics; (c) Quantity. Some of those parameters can be monitored with sensors and others manually. A request for collection by the farmer will be sent to the system. Such request will be forwarded to the factory and the LSPs (responsible collection partners) with whom the farmer or factory has a contract.

Collection from motorhomes (RVs)

If the waste tank of a RV is almost full (this can be understood either from an embedded sensor or the driver inserts this information thought a mobile app) the RV CDT propagates the information about its location, feedstock type/quality characteristic and quantity and requests a suggestion for deposit or collection.

Local LSPs or bio-processing factories are informed about the availability of waste to be collected.

Deposit feedstock waste in the bin

Following the above collection cases, the feedstock provider (farmer or RV) might be suggested to deposit the waste in a bin that is close to its location.

4.2.2. Scenario #2: Optimized Logistics Operations

LSPs/Feedstock collection actors need to organize their resources and operations in a more flexible and predicted manner. This means the following:

- Predictions of feedstock availability based on experience and historical data: In such case, the LSP can organize better the collection points. Those can be for example, deposit bins or mobile processing units where possible and/or daily positioning the network of trucks in specific locations to respond quicker to a particular need.

- Optimal planning (or re-planning to satisfy the different requests): (re-) Planning can have the following forms: a) routing (finding the optimal route) or b) find the truck that (based on its location and existing route) can fulfil the particular order. Further to this, optimization will deal with the problem "Where to find the nearest actor to deposit my waste of someone to collect it".

4.2.3. Scenario #3: Waste Incoming Handling from the Factory

The factory is aware in real-time of requests from feedstock providers about quantities to be received and can make a better planning of the incoming materials handling process and further create an optimal schedule of the process.

Improving scheduling of the incoming materials will improve cost-effective storage and better quality of the by-products to be processed (depending on their characteristics: for e.g., some by-products need to be processed immediately while others can wait some days).

4.3. Configuration/Modelling Phase (Step 1 in the Operational Model)

4.3.1. Stakeholders, Roles and Applicable CDTs

Following the above context and scenarios, we have the following stakeholders and their roles in the supply chain:

4.3.2. CDTs Liability, Collaboration and Governance

For each of the CDT there are different possible configurations with regards governance, cognition and the rest enablers. This depends on the level of control of CDT by its owner. The table below illustrates the main CDTs interactions in terms of information to be exchanged, liability, cognition and autonomy levels.

4.4. The Cognition Process (Steps 2, 3, 4, 5 and 6 in the Operational Model)

4.4.1. Collect Data Streams about the Behaviour of the CDT (Step #2 of the Operational Model)

Every actor in the supply chain is modelled along with its assets as a CDT (see Table 1) and the whole value chain is modelled as a network of all stakeholders' CDTs with all interrelations among them (see Table 2). Each stakeholder has different levels of interaction with others and with the necessary information to be exchanged (e.g., a farmer can send information about waste availability and the receiver is both the LSP and the factory).

Table 1. Stakeholders in the case of circular rural value chain.

Stakeholder	Description	Role in Connected Supply Chain
Factory	Waste processing factory	• Is informed about real-time material flows • Improved handling of incoming materials • Optimized logistics and production planning
Farmer	Producer of incoming materials (woods, organic waste, etc.)	Using an app, informs about the availability of materials to be collected
Waste bin	Bin where other people can deposit waste	Using a sensing device communicate with the LSP the need for waste to be collected
Warehouse	Deposit place where farmers can throw their waste with their own trucks	Informs the LSP about the availability of waste or forwards it to the factory
Motorhomes	Moving actors which need to deposit their organic waste into the bins	Using an application, they can identify the nearest waste bin to deposit their waste
LSP	Collection and forwarding waste into the factory	Gets notifications from farmers, bins, warehouses, and motorhomes, about the availability of material to be collected

Table 2. CDTs and inter-relations in the circular value chain.

CDT	Information Receiver						Liability (Stakeholder)	Autonomy for Decision Making
	Processing Factory	Farmer	Waste Bin	Warehouse	Motorhome	LSP Truck		
Processing factory	-						Factory	Per case
Farmer's waste	Waste to collect			Waste to collect/deposit		Waste to collect	Farmer	Per case
Waste bin	Waste to collect				Availability and location to deposit the waste	Waste to collect	Owner of waste bin	Automatic
Warehouse	Waste to collect					Waste to collect	Warehouse owner	Per case
Motorhome			Location and waste availability				Motorhome manufacturer/driver	Per case
LSP truck	Waste to forward						LSP provider/driver	Per case

A CDT is also always aware of its status ("where am I", "how much waste quantity I have", "waste quality characteristics", etc.). Such information is a result of data streams coming from sensors or existing systems (real-time information or manually inserted using a mobile application) communicated from the "physical waste" to its CDT representation.

The CDT broadcasts the public information to the rest CDTs in the network in a secure way. For example, a motorhome publishes its specific information about its status (location, waste type, etc.) and searches the nearest and more relevant (for the waste type) bin for deposit.

The CDT constantly communicates with its fellow CDTs and tries in a collaborative way to effectively collect the waste in the most optimal way.

4.4.2. Understand Context (Step #3 in the Operational Model)

Data broadcasted by the CDT (see Section 4.4.1) reflect the current state of the physical counterpart in all modelled aspects. Virtual mapping procedures can be used to map data to a knowledge graph, considering semantic meaning of data, and known relationships. Reasoning can be then used to create new deductive knowledge based on the one encoded in the knowledge graph. Anomaly and concept drift detection models can be applied on incoming streams to detect irregular context and decide whether forecasts can be trusted, or existing models should be updated.

To ensure trustworthiness, it is important to inform how new deductive knowledge was acquired. If probabilistic soft logic is used for link prediction, probabilities should be informed along with the relationships. For anomaly and concept drift detection models it is desired to inform reasons why certain data is considered anomalous, or how strong the concept drift is, which may provide additional insights when applying heuristics to automate decisions, or to guide users' decision-making.

Visualizations play an important role. By conveying acquired information in a simple and understandable way, they allow to monitor the status of the CDT, their evolution and provide ground for decision-making regarding simulation and prediction models based on mirrored data.

4.4.3. Simulate and Prediction (Step #4 in the Operational Model)

Simulation and prediction models mostly provide insights into normal operating conditions. Data-based models can be used to learn from past anomalous situations and recognize new ones while also explaining the reasons to do so. Once an anomalous situation is identified, simulations can be run to predict expected outcomes. Such insights can provide high value to end-users assisting them in decision-making.

Visualizations are of utmost importance since they can convey much information regarding future scenarios simply and understandably and providing different insights based on the end-user role. They should provide information regarding typical operational scenarios, how anomalous situations differ, and eventually highlight the top reasons driving those forecasts. Through these visualizations, the user can understand the magnitude of the changes or anomalies observed, expected outcomes, and weight reasons considered by the models to decide if they should be trusted or additional considerations are required.

4.4.4. Decisions (Optimization) (Step #5 of the Operational Model)

In each of the scenarios we have different decisions, which correspond to suggestions by the CDTs:

- Farmers to get a proposal about which is the optimal way to deposit the waste: either finding the nearest available bin/mobile processing unit or send a request to an LSP because a truck is nearby and is available to pick the waste.
- The nearest truck CDT gets a request about a waste to be collected. Given its existing route/collection plan, the CDT gets the request and processing it and decisions can be:
    - The CDT collects the plan with a new optimized delivery plan or
    - The CDT communicates with other truck CDTs and "negotiate" the collection from others.
- The RV gets a recommendation of the optimal way to deposit the waste: a nearby bin CDT or a truck CDT.
- The factory CDT gets optimal recommendations for production scheduling, material handling based on the real-time information and forecasts about the incoming materials.
- In a more strategic view, the LSP can organize better the collection points. Those can be for example: deposit bins or mobile processing units where possible) and/or position the network of trucks in specific locations to respond quicker to a particular need. Based on the supply chain behaviour of how waste is collected, how often and from which location, the LSP can assess different scenarios and find an optimal network that can satisfy ad-hoc requests and with the minimum respond time and cost.

4.4.5. Actuation (Step #6 in the Operational Model)

Actuation depends on the level of autonomy defined in the governance model (in the configuration step). We can have the following:

- Manual actuation from the user (driver, farmer, etc., which means no CDT actuation).
- Semi-manual actuation: the CDT gets the approval by the end user about what to do and the CDT performs the action.
- Automatic actuation: this can be for decisions that the CDT is able to perform and act.

5. Conclusions

In this paper we have presented a holistic approach to configuration and operation of the CDTs in agile and resilient supply chains. Our proposed model is built on the fundamentals of inter-connectivity, information sharing and cognition capabilities of the Digital Twins. Through the cognition process we can understand failures and trends, simulate different scenarios, predict impact, and assess different optimization solutions in the whole supply chain context.

Deployment and operation of the model requires collaboration at the design phase. All actors in the supply chain need to work together and agree on a very detailed configuration scheme addressing not only the cognition process, but also all enablers that supports the information exchange, processing and actuation. This is an exercise that takes time and requires trust and transparency among stakeholders. IT alignment is a challenge, but the most important one is change management: the ability to re-engineer both intra- and inter-organization processes involving people, systems, reinforcing collaborative culture, support decentralizing decision-making and a mindset towards adaptation and improvement.

Future work on this topic will be on measuring the effectiveness of the model deployment in a supply chain context with quantitative KPIs. The evaluation targets need to be set per case. This means that different supply chains will have their own operational needs, requirements and processes to be monitored and improved. Some generic (and indicative) criteria can be: improved time to market (for a new product development); early detection of a defect in the supply chain (early warnings, response times along the supply chain actors-CDTs); improvements due to the optimization model applied, etc. In parallel, using a qualitative analysis we will try to assess more "soft" aspects such as people satisfaction and improvement as well as increase of trust and collaboration among the different stakeholders.

Author Contributions: Conceptualization, K.K. and G.A.; methodology, K.K., J.R., A.K., D.K. and G.A.; writing—original draft preparation, K.K., J.R. and A.K.; writing—review and editing, K.K., J.R., A.K., D.K. and G.A.; visualization, A.K.; supervision, G.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by EU-funded SPIRE-2019 FACTLOG project (FACTLOG: Energy Aware Factory Analytics for Process Industries).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Work leading to this paper has been financed by the EU-funded SPIRE-2019 FACTLOG project (FACTLOG: Energy Aware Factory Analytics for Process Industries). The authors would like to thank project partners for sharing expert knowledge and case studies' information. The results presented in this paper reflect only the authors' views and the EU is not liable for any use that may be made of the information contained therein.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. WMF. The 2020 World Manufacturing Report: Manufacturing in the Age of Artificial Intelligence. Available online: https://worldmanufacturing.org/wp-content/uploads/WorldManufacturingForum2020_Report.pdf (accessed on 13 February 2021).
2. Pearson, H.; Noble, G.; Hawkins, J. *Redistributed Manufacturing Workshop Report*; EPSRC-Engineering and Physical Sciences Research Council, 2013. Available online: https://epsrc.ukri.org/newsevents/pubs/re-distributed-manufacturing-workshop-report/ (accessed on 13 February 2021).
3. Deloitte. Business Ecosystems Come of Age. 2017. Available online: https://www2.deloitte.com/content/dam/insights/us/articles/platform-strategy-new-level-business-trends/DUP_1048-Business-ecosystems-come-of-age_MASTER_FINAL.pdf (accessed on 18 January 2021).
4. EFFRA. Factories 4.0 and Beyond: Recommendations for the Work Programme 18-19-20 of the FoF PPP under Horizon 2020. 12 September 2016. Available online: https://www.effra.eu/sites/default/files/factories40_beyond_v31_public.pdf (accessed on 23 October 2020).
5. ElMaraghy, H.; Schuh, G.; Piller, F.; Schönsleben, P.; Tseng, M.; Bernard, A. Product variety management. *CIRP Ann.* **2013**, *62*, 629–652. [CrossRef]
6. Kiritsis, D. Closed-loop PLM for intelligent products in the era of the Internet of things. *Comput. Des.* **2011**, *43*, 479–501. [CrossRef]
7. Schuh, G.; Rebentisch, E.; Dölle, C.; Mattern, C.; Volevach, G.; Menges, A. Defining Scaling Strategies for the Improvement of Agility Performance in Product Development Projects. *Procedia CIRP* **2018**, *70*, 29–34. [CrossRef]
8. IDC. *IDC Manufacturing Insights*; IDC: Needham, MA, USA, 2014.
9. McKinsey. Industry4.0: How to navigate digitization of the manufacturing sector, McKinsey Digital. 2015. Available online: https://www.mckinsey.com/business-functions/operations/our-insights/industry-four-point-o-how-to-navigae-the-digitization-of-the-manufacturing-sector (accessed on 1 October 2020).
10. CGI. CGI Client Global Insights 2018 for Manufacturing, Summary. 2018. Available online: https://www.cgi.com/en/media/white-paper/manufacturing-client-global-insights-2018 (accessed on 2 February 2021).
11. Grieves, M. Digital twin: Manufacturing excellence through virtual factory replication. *White Paper* **2014**, *1*, 1–7.
12. Tao, F.; Qi, Q.; Wang, L.; Nee, A. Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. *Engineering* **2019**, *5*, 653–661. [CrossRef]

13. Gartner. Gartner Identifies the Top 10 Strategic Technology Trends for 2019. 2018. Available online: https://www.gartner.com/en/newsroom/press-releases/2018-10-15-gartner-identifies-the-top-10-strategic-technology-trends-for-2019 (accessed on 16 September 2020).
14. Qi, Q.; Tao, F.; Zuo, Y.; Zhao, D. Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE Access* **2018**, *6*, 3585–3593. [CrossRef]
15. DIGICOR. *DIGICOR H2020 Project: Decentralized Agile Coordination across Supply Chains*; DIGICOR. Available online: https://www.digicor-project.eu/ (accessed on 12 November 2020).
16. Heutger, M.; Kuechelhaus, M. *Digital Twins in Logistics: A DHL Perspective on the Impact of Digital Twins in the Logistics Industry*; DHL, 2019. Available online: https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/glo-core-digital-twins-in-logistics.pdf (accessed on 12 December 2020).
17. Rojas, R.A.; Rauch, E. From a literature review to a conceptual framework of enablers for smart manufacturing control. *Int. J. Adv. Manuf. Technol.* **2019**, *104*, 517–533. [CrossRef]
18. Kritzinger, W.; Karner, M.; Traar, G.; Henjes, J.; Sihn, W. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC Papers OnLine* **2018**, *51*, 1016–1022. [CrossRef]
19. Minerva, R.; Lee, G.M.; Crespi, N. Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models. *Proc. IEEE* **2020**, *108*, 1785–1824. [CrossRef]
20. Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In *Transdisciplinary Perspectives on Complex Systems*; Springer: Berlin, Germany, 2017; pp. 85–113.
21. Rozanec, J.; Lu, J.; Rupnik, J.; Skrjanc, M.; Mladenic, D.; Fortuna, B.; Zheng, X.; Kiritsis, D. Actionable Cognitive Twins for Decision Making in Manufacturing. 23 March 2021. Available online: https://arxiv.org/pdf/2103.12854v1.pdf (accessed on 24 March 2021).
22. Lu, J.; Zheng, X.; Gharaei, A.; Kalaboukas, K.; Kiritsis, D. Cognitive twins for supporting decision-makings of Internet of Things systems. In Proceedings of the 5th International Conference on the Industry 4.0 Model for Advanced Manufacturing, Belgrade, Serbia, 1–4 June 2020.
23. P. Industrie4.0. RAMI4.0: A Reference Model for Digitalization. 9 August 2018. Available online: https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/rami40-an-introduction.html (accessed on 24 November 2020).
24. Cheng, J.; Zhang, H.; Tao, F.; Juang, C.-F. DT-II: Digital twin enhanced Industrial Internet reference framework towards smart manufacturing. *Robot. Comput. Manuf.* **2020**, *62*, 101881. [CrossRef]
25. Qi, Q.; Tao, F.; Zuo, Y.; Zhao, D. Digital Twin Service towards Smart Manufacturing. *Procedia CIRP* **2018**, *72*, 237–242. [CrossRef]
26. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Ind. Inform.* **2019**, *15*, 2405–2415. [CrossRef]
27. Lu, Y.; Liu, C.; Wang, K.I.-K.; Huang, H.; Xu, X. Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robot. Comput. Manuf.* **2020**, *61*, 101837. [CrossRef]
28. Ellis, S.; Hand, L.; Ortis, I.; The Future of the Supply Chain: Disrupt or to Be Disrupted. IDC Sponsored by Oracle. September 2018. Available online: https://www.oracle.com/a/ocom/docs/industries/idc-disrupt-or-be-disrupted-wp.pdf (accessed on 7 February 2021).
29. Schützer, K.; Bertazzi, J.D.A.; Sallati, C.; Anderl, R.; Zancul, E. Contribution to the development of a Digital Twin based on product lifecycle to support the manufacturing process. *Procedia CIRP* **2019**, *84*, 82–87. [CrossRef]
30. Kalaboukas, K.; Lioudakis, G.; Koukovini, M.; Papagiannakopoulou, E.; Morabito, G.; Dellas, N.; Zacharias, M.; Quattropani, S.; Samarotto, M.; Jermol, M.; et al. Cognitive Logistics Operations through Secure, Dynamic and ad-hoc Collaborative Networks: The COG-LO Project. In Proceedings of the 6th International Physical Internet Conference, 9–11 July 2019, London, UK.
31. Suhail, R.; Hussain, R.; Jurdak, R.; Hong, C.S. Trustworthy Digital Twins in the Industrial Internet of Things with Blockchain. 2020. Available online: https://arxiv.org/abs/2010.12168 (accessed on 15 February 2021).
32. Defining Governance (IoG). Available online: https://iog.ca/what-is-governance/ (accessed on 17 January 2021).
33. Nochta, T.; Badstuber, N.; Wahby, N. On the Governance of City Digital Twins—Insights from the Cambridge Case Study; Centre for Digital Built Britain. 2019. Available online: https://doi.org/10.17863/CAM.41083 (accessed on 14 January 2021).
34. Otto, B.; Jurgens, J.; Schon, J.; Auer, S.; Menz, N.; Wenzel, S.; Cirullies, J. Industrial Data Space: Digital Sovereingty over Data. 2016. Available online: https://www.fraunhofer.de/content/dam/zv/en/fields-of-research/industrial-data-space/whitepaper-industrial-data-space-eng.pdf (accessed on 6 February 2021).
35. Schroder, J.; Held, B.; Neuhaus, F.; Kasser, M.; Klink, C.; Tatomir, S. *Fast Forwarding Last-Mile Delivery—Implications for the ECOSYSTEM*; McKinsey&Company, 2018. Available online: https://www.mckinsey.com/~{}/media/mckinsey/industries/travel%20logistics%20and%20infrastructure/our%20insights/technology%20delivered%20implications%20for%20cost%20customers%20and%20competition%20in%20the%20last%20mile%20ecosystem/fast-forwarding-last-mile-delivery-implications-for-the-ecosystem.pdf (accessed on 19 December 2020).
36. Saracco, R. Available online: https://cmte.ieee.org/futuredirections/2020/07/17/the-economics-of-the-digital-transformation-xii/ (accessed on 17 July 2020).
37. Joerss, M.; Neuhaus, F.; Schroder, J. *How Customer Demands Are Reshaping Last-Mile Delivery*; McKinsey&Company, 19 October 2016. Available online: https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/how-customer-demands-are-reshaping-last-mile-delivery# (accessed on 15 March 2021).

38. Bonnefon, J.-F.; Shariff, A.; Rahwan, I. The social dilemma of autonomous vehicles. *Science* **2016**, *352*, 1573–1576. [CrossRef] [PubMed]
39. Congress, L.L.-L.o. Supply Chain Regulation of Pharmaceutical Samples—European Union-Japan-Turkey. September 2019. Available online: https://www.loc.gov/law/help/pharmaceutical-samples/pharmaceutical-samples.pdf (accessed on 14 March 2021).
40. Taisch, M.; Casidsid, G.; May, T.; Morin, V.; Padelli, M.; Pinzone; Wuest, T. *World Manufacturing Report*; World Manufacturing Forum: Cernobbio, Italy, 2020.
41. Smart Specialization Platform. European Commission. Available online: http://s3platform.jrc.ec.europa.eu/ (accessed on 14 March 2021).