Technical University of Crete

School of Production Engineering and Management

Industrial and Digital Innovations Research Group

A Methodological Framework for Digital-Twin Driven Cognitive Manufacturing in the context of Connected and Agile Value Networks

Kostas Kalaboukas

Dipl. Production Engineer and Management, Technical University of Crete

MSc in Total Quality Management, University of Piraeus

A dissertation submitted in partial fulfilment of the requirements for the degree of

PHD in Production Engineering and Management

Doctoral Advisor: Associate Professor George Arampatzis

Supervisory Committee

1. George Arampatzis, Associate Prof., School of Production Engineering and Management, Technical University of Crete
2. Efstratios Ioannidis, Associate Prof., School of Production Engineering and Management, Technical University of Crete
3. Dimitris Kiritsis, Emeritus Professor of ICT for sustainable manufacturing, Ecole Polytechnique Federale de Laussane (EPFL)

Chania, 17 December 2024

Copyright Statement

Citation

If you would like to cite this work, please use:

Kostas Kalaboukas, "A Methodological Framework for Digital-Twin Driven Cognitive Manufacturing in the context of Connected and Agile Value Networks", Doctoral Dissertation, School of Production Engineering and Management, Technical University of Crete, Chania, Greece, 2024.

Technical University of Crete

School of Production Engineering and Management

Industrial and Digital Innovations Research Group

Doctoral Dissertation

A Methodological Framework for Digital-Twin Driven Cognitive Manufacturing in the context of Connected and Agile Value Networks

by

Kostas Kalaboukas

Examination Committee:

1. George Arampatzis, Associate Professor
   Technical University of Crete
   School of Production Engineering and Management
2. Efstratios Ioannidis, Associate Professor
   Technical University of Crete
   School of Production Engineering and Management
3. Dimitris Kiritsis s, Emeritus Professor
   Ecole Polytechnique Federale de Laussane (EPFL)
4. Eleftherios Doitsidis, Associate Professor
   Technical University of Crete
   School of Production Engineering and Management
5. Vasilios Kouikoglou, Professor
   Technical University of Crete
   School of Production Engineering and Management
6. Yiannis Mourtos, Professor
   Athens University of Economics and Business
   Department of Management Science and Technology
7. Pavlos Eirinakis, Associate Professor
   University of Piraeus
   Department of Industrial Management & Technology

ΕΠΤΑΜΕΛΗΣ ΕΞΕΤΑΣΤΙΚΗ ΕΠΙΤΡΟΠΗ

Τίτλος (ελληνικά/αγγλικά): Μεθοδολογικό πλαίσιο για υλοποίηση "γνωσιακών ψηφιακών διδύμων" σε ευέλικτες αλυσίδες αξίας παραγωγής / A Methodological Framework for Digital-Twin Driven Cognitive Manufacturing in the context of Connected and Agile Value Networks

ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

Κωνσταντίνου Καλαμπούκα

ΤΡΙΜΕΛΗΣ ΣΥΜΒΟΥΛΕΥΤΙΚΗ ΕΠΙΤΡΟΠΗ:

1. **Γεώργιος Αραμπατζής (Επιβλέπων)**
2. **Ευστάθιος Ιωαννίδης**
3. **Δημήτριος Κυρίτσης**

Εγκρίθηκε από την επταμελή εξεταστική επιτροπή την: 17/12/ 2024

1. **Αναπλ. Καθηγητής Πολυτεχνείου Κρήτης**
   Γεώργιος Αραμπατζής

   Georgios Arampatzis

2. **Αναπλ. Καθηγητής Πολυτεχνείου Κρήτης**
   Ευστάθιος Ιωαννίδης

   EFSTRATIOS IOANNIDIS
   17/12/2024 19:06

3. **Emeritus Professor Ecole Polytechnique Federale de Lausanne**
   Δημήτριος Κυρίτσης

4. **Αναπλ. Καθηγητής Πολυτεχνείου Κρήτης**
   Ελευθέριος Δοϊτσίδης

   ELEFTHERIOS DOITSIDIS
   17.12.2024 18:50

5. **Καθηγητής Πολυτεχνείου Κρήτης**
   Βασίλειος Κουϊκόγλου,

   Vasilis Koulkoglou
   2024.12.17
   18:19:54 +02'00'

6. **Καθηγητής Οικονομικού Πανεπιστημίου Αθηνών**
   Ιωάννης Μούρτος

   IOANNIS MOURTOS
   17/12/2024 19:29

7. **Αναπλ. Καθηγητής Πανεπιστημίου Πειραιώς**
   Παύλος Ειρηνάκης

   PAVLOS ERINAKIS

to *Valentini*, my inspiration for a wonderful world

to *Athina - Spyridoula*, my inspiration for a creative world

to *Maria*, my inspiration for a world full of happiness

to my father *Zisis* and my mother *Athina,* for what they have taught me

Acknowledgements

They say it is never too late to achieve your dreams. After finishing university, I never had the opportunity or time to pursue a PhD for various reasons. Despite having over 20 years of experience in the industry, and working on research and software solutions, achieving a PhD remained an unfulfilled goal for me. I would like to thank Associate Professor George Arampatzis who gave me this opportunity. He inspired me to pursue a PhD, guided me on the research aspects and together we did very interesting work in research projects that helped not only to fulfil my thesis but also to improve my knowledge and transfer to my work. But most of all, I thank him for his personality because he is not just a professor: he is a good friend who truly cares about people's growth.

Prof. Dimitris Kiritsis is another person who inspired and guided me in this research journey. I thank him for the collaboration and the exchange of ideas, knowledge, and many discussions on how research can be applied within the industry. He is a gentle person and a very good mentor.

When the idea about the PhD started to take form, I had my concerns regarding whether I could combine my research with my family and work time restrictions. I am grateful to Associate Prof. Stratos Ioannidis who encouraged me on this. But also for his experience and knowledge that helped me accomplish my work. He is very competent and passionate with his work.

I would also like to thank my colleagues from Gruppo Maggioli – Greek Branch We have been conducting applied research for ICT in various industries for a long time, and they have give me very good insights into the technical aspects of the architectural parts of my work. I feel very lucky to be working with them. They improve not only my knowledge but also contribute to my personal growth.

I am very grateful to be pursuing this PhD in the Technical University of Crete and the School of Production Engineering and Management. I had the best time in my life during my studies and I learnt a lot. But most of all I got an "engineering way" of thinking and skills that still help me in my work and my personal growth.

All the above would not have been possible without the full support of my family: my wife Valentini and my two daughters Athina-Spyridoula and Maria. They inspire me in everything I do.

Last, I thank for this thesis - as everything I do in my life - my father Zisis and my mother Athina. I owe them a debt of gratitude for their sacrifices and everything they have taught me.

Table of Contents

Table of Figures

List of Tables

List of Acronyms

Acronym	Description
AI	Artificial Intelligence
AAS	Asset Administration Shell
AR	Augmented Reality
CDT	Cognitive Digital Twin
DT	Digital Twin
GDPR	General Data Protection Regulation
HITL	Human in the Loop
IDS	International Data Spaces
REs	Rare Earths
REE	Rate Earth Element
RQ	Research Question
SC	Value network
VN-CDT	Value network CDT
VR	Virtual Reality
WEEE	Waste from Electrical and Electronic Equipment
XAI	Explainable AI
XR	Extended Reality

Disclaimer

Any statement written in this thesis with *"Italics"*, is an exact copy taken from the source.

Abstract (English)

Value network 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 value networks to become "cognitive", i.e., to able to predict trends and to be flexible enough in dynamic environments, ensuring optimized operational performance. Digital Twins (DT) are a promising technology, and a lot of work is done on the factory level. Additionally, the term "Cognitive Digital Twins" (CDTs) gets more attention as it encapsulates the cognition capabilities of a digital twin of which the analytics and AI services are realized.

However, when it comes to the adoption of CDTs in value networks there is little work and development on how we can model value network digital twins, which are the main capability and benefits, and how we are ensuring trust and good practices for operation. Furthermore, in the era of interconnected value networks, we need to define a roadmap with configuration principles, for any ICT solution that aims to incorporate features for various sectors. This thesis addresses the above considerations by elaborating on the following research principles:

- A reference framework for modelling value network CDTs as a network of inter-connected CDTs, each one representing the involved stakeholders and the materials/products that are flown across the network.
- A reference governance framework for value network CDTs integrating three different views:
  - ✓ business and sustainability,
  - ✓ data governance and
  - ✓ cognition (AI) model governance.
- A reference ICT architecture, which provides main functions and usage scenarios for the operation of the value network CDT.

The structure of this thesis is as follows:

Section 1 - Introduction: The introductory chapter provides an overview of the evolving dynamics of value network and introduces the concept of CDTs. It highlights the importance of agile, resilient, and connected value networks, the need for value network CDTs and finally outlines the research objectives (main research questions).

Section 2 - Research methodology: Presents the path from the inception of the thesis until the proposed approach and case validation.

Section 3 - Literature review: This section offers a comprehensive review of existing literature on the three main research objectives, exploring their evolution and state of the art along with potential experimentation or industrial cases.

Section 4 - Proposed solution framework: presents the research outputs and the proposed framework for modelling value network CDTs, the applicable governance and the ICT reference architecture for implementation.

Section 5 - Pilot Study: Magnet Circular Value network: This section applies the proposed frameworks to an industrial case on circular value networks, which transformed waste from electrical and electronic equipment into secondary resource material and magnet products.

Section 6 - Discussion: This section discusses the main findings, the value of our proposition together with limitations and risks that may impede the implementation of our approach.

Section 7 - Conclusions – Future Research: This section synthesizes the key findings, and suggests areas for future research in the field.

Abstract (Greek)

Η ευελιξία και η ανθεκτικότητα της αλυσίδας αξίας είναι βασικοί παράγοντες επιτυχίας των εταιρειών παραγωγής στην προσπάθειά τους να ανταποκριθούν στις διάφορες δυναμικές αλλαγές. Η κυκλική οικονομία, η ανάγκη για βελτιστοποιημένες ροές υλικών, ad-hoc απαιτήσεις, γρήγορη ανταπόκριση και εξατομίκευση, είναι μερικές από τις τάσεις που απαιτούν από τις αλυσίδες αξίας παραγωγής να γίνουν «έξυπνες», δηλαδή να μπορούν να προβλέψουν τις τάσεις και να είναι αρκετά ευέλικτες σε δυναμικά περιβάλλοντα, διασφαλίζοντας παράλληλα την βέλτιστη απόδοσή τους. Οι Ψηφιακοί Δίδυμοι (Digital Twins-DT) είναι μια πολλά υποσχόμενη τεχνολογία με αρκετές εφαρμογές στο επίπεδο μιας παραγωγής και εντός των ορίων μιας εταιρείας. Επιπλέον, ο όρος «Γνωσιακοί Ψηφιακοί Δίδυμοι» (ΓΨΔ) (Cognitive Digital Twins–CDT) δημιουργεί ένα νέο ερευνητικό πεδίο, καθώς ενσωματώνει τις γνωσιακές δυνατότητες ενός ψηφιακού δίδυμου μέσω των λειτουργιών της ανάλυσης και της τεχνητής νοημοσύνης.

Ωστόσο, όταν πρόκειται για την υιοθέτηση ΓΨΔ στις αλυσίδες αξίας παραγωγής, από ερευνητικής πλευράς, δεν υπάρχει ένα σαφές πλαίσιο στο πώς μπορούμε να μοντελοποιήσουμε ένα ΓΨΔ, ποιες είναι βασικές δυνατότητες/λειτουργίες του και πώς διασφαλίζεται η εμπιστοσύνη μεταξύ των μερών της αλυσίδας παράλληλα με τις ορθές πρακτικές λειτουργίας.

Επιπλέον, στην εποχή των διασυνδεδεμένων αλυσίδων αξίας, πρέπει να ορίσουμε ένα γενικό πλαίσιο παραμετροποίησης για κάθε λύση τεχνολογίας πληροφορικής που θα ανταποκρίνεται στις απαιτήσεις διαφορετικών τομέων.

Η παρούσα διατριβή ασχολείται με αυτές τις διαπιστώσεις, μέσω της εκτενής ανάλυσης των παρακάτω ερευνητικών πεδίων:

- Ένα μεθοδολογικό πλαίσιο αναφοράς για τη μοντελοποίηση των ΓΨΔ αλυσίδας αξίας παραγωγής ως ένα δίκτυο διασυνδεδεμένων ΓΨΔ, το καθένα από τα οποία, αντιπροσωπεύει τους εμπλεκόμενους φορείς και τα υλικά/προϊόντα που μεταφέρονται κατά μήκος της αλυσίδας αξίας.
- Ένα πλαίσιο αναφοράς διακυβέρνησης για τους ΓΨΔ της αλυσίδας αξίας που ενσωματώνει:
    - ✓ την επιχειρηματική λειτουργία και βιωσιμότητα,
    - ✓ την διακυβέρνηση των δεδομένων και
    - ✓ την διακυβέρνηση των εφαρμοσμένων μοντέλων τεχνητής νοημοσύνης και γνωσιακής συμπεριφοράς.
- Μία αρχιτεκτονική αναφοράς για πληροφοριακά συστήματα, η οποία παρέχει κύριες λειτουργίες και σενάρια χρήσης για τη λειτουργία των ΓΨΔ μιας αλυσίδας αξίας.

Η δομή της διατριβής αποτελείται από τα παρακάτω κεφάλαια:

Κεφάλαιο 1 - Εισαγωγή: Περιλαμβάνει μία σύνοψη της δυναμικής των αλυσίδων αξίας και εισάγει την έννοια του Γνωσιακού Ψηφιακού Διδύμου. Δίνει έμφαση στην ανάγκη για ευέλικτες, ανθεκτικές και διασυνδεδεμένες αλυσίδες αξίας, την ανάγκη για ΓΨΔ και τέλος παρουσιάζει τους ερευνητικούς στόχους (ερευνητικές ερωτήσεις).

Κεφάλαιο 2 – Μεθοδολογία έρευνας: Παρουσιάζει την διαδρομή ολοκλήρωσης της διατριβής: από την σύλληψη της ιδέας, τον καθορισμού του πλαισίου αναφοράς μέχρι και την εφαρμογή της σε μία αλυσίδα αξίας.

Κεφάλαιο 3 – Ανασκόπηση βιβλιογραφίας: το κεφάλαιο αυτό περιλαμβάνει μία εκτενή αναφορά στην υπάρχουσα βιβλιογραφία για τα ερευνητικά θέματα που πραγματεύεται η διατριβή, σε συνδυασμό με πιθανές εφαρμογές στην βιομηχανία.

Κεφάλαιο 4 – Προτεινόμενο πλαίσιο αναφοράς: Παρουσιάζει το αποτέλεσμα της έρευνας και το προτεινόμενο πλαίσιο μοντελοποίησης των ΓΨΔ αλυσίδας αξίας, το πλαίσιο αναφοράς για διακυβέρνηση και τέλος μία αρχιτεκτονική αναφοράς για υλοποίηση.

Κεφάλαιο 5 – Pilot Study: Magnet Circular Value network: Το κεφάλαιο αυτό παρουσιάζει την εφαρμογή των προτεινόμενων πλαισίων αναφοράς σε ένα βιομηχανικό σενάριο κυκλικής αλυσίδας αξίας, όπου οι μαγνήτες από χρησιμοποιημένες ηλεκτρονικές συσκευές μεταμορφώνονται σε δευτερεύοντα υλικά για την παραγωγή νέων προϊόντων μαγνήτη.

Κεφάλαιο 6 - Συζήτηση: Στο κεφάλαιο αυτό γίνεται συζήτηση των κύριων ευρημάτων της διατριβής, την αξίας των προτεινόμενων πλαισίων αναφοράς μαζί με τους περιορισμούς και ρίσκα κατά των εφαρμογή τους.

Κεφάλαιο 7 – Conclusions – Future Research: Στο κεφάλαιο αυτό παρουσιάζονται τα κύρια συμπεράσματα της έρευνας και προτεινόμενα πεδία για μελλοντική έρευνα.

Contribution to the Research Community

Innovation highlights

A new way of configuring value network CDTs as networks of interconnected DTs, of which, some of them have cognition capabilities and others not. This is realized through modelling the stakeholders' interactions, material and information flows. This approach is modular (by adopting specific enablers), replicable (to any value network contexts) but also scalable to other domains (at any type of networks, i.e. smart cities).

A comprehensive and holistic governance approach for the implementation of value network CDTs. This extends the current approaches, which focus only on the business aspects and integrates them with data and AI model governance since, in the context of connected value networks, we need to ensure that IT systems share the right information and any applicable AI service that processes data makes decisions in a fair manner and is trustworthy.

A reference ICT implementation framework for modelling and operating value network CDTs considering the latest trends in data sharing and interoperability and enhancing them with new concepts of shared CDTs among actors in the value network.

Publications

International Peer Reviewed Journals

- Kostas Kalaboukas, Dimitris Kiritsis and George Arampatzis. *Governance framework for autonomous and cognitive digital twins in agile value networks*. Computers in Industry, Volume 146, 2023. https://doi.org/10.1016/j.compind.2023.103857
- Kostas Kalaboukas, Jože Rožanec, Aljaz Košmerlj, Dimitris Kiritsis and George Arampatzis. *Implementation of Cognitive Digital Twins in Connected and Agile Supply Networks-An Operational Model*. Applied Science Volume 11, Issue 9, 2021. https://doi.org/10.3390/app11094103
- Pavlos Eirinakis, Stavros Lounis, Stathis Plitsos, George Arampatzis, Kostas Kalaboukas, Klemen Kenda, Jinzhi Lu, Jože Rožanec and Nenad; Stojanovic. *Digital Twins for Resilience in Production: A Conceptual Framework*. Information, Volume 13, Issue1, 2022. https://doi.org/10.3390/info13010033

Chapters in Edited Books

- Jože Rožanec, Pavlos Eirinakis, George Arampatzis, Nenad Stojanović, Kostas Kalaboukas, Jinzhi Lu, Xiaochen Zheng and Dimitris Kiritsis. *Cognitive Digital Twins in the Process Industries*. Chapter in "Handbook of Digital Twins", Edited by Z. Lyu, 2024. ISBN: 9781032546070. https://doi.org/10.1201/9781003425724
- Xiaochen Zheng, Jinzhi Lu, Rebeca Arista, Jože Martin Rožanec, Stavros Lounis, Kostas Kalaboukas and Dimitris Kiritsis. *Cognitive Digital Twins*. Chapter in "Handbook of Digital Twins", Edited by Z. Lyu, 2024. ISBN: 9781032546070. https://doi.org/10.1201/9781003425724

International Conferences

- Kostas Kalaboukas and George Arampatzis. *Process Industry Digital Transformation Using Cognitive Digital Twins*. European Big Data Value Forum, Prague, 21-23 November 2022.
- Kostas Kalaboukas and George Arampatzis. *Cognitive Digital Twins for Optimized Manufacturing Operations*. IoT Week Dublin 20-23 June 2022.

1 Introduction

1.1 Rationale and motivation

Digitization in manufacturing is a fact. Following the Industry 4.0 paradigm, a plethora of ICT solutions focusing on different levels of the RAMI reference model (Plattform Industrie 4.0, 2018), which defines the hierarchical levels and processes of a digital factory: Internet of Things solutions, Machine to Machine, Manufacturing Execution Systems, Enterprise Resource Planning, etc. Whereas such solutions allow the information flow and monitoring using digital models, the usage of DTs and their benefits in the industry still have not been integrated yet. In fact, Gartner has identified DTs as one of the top 10 strategic trends organizations need to explore in 2019 (Gartner, 2018).

In 2016, the European Factories of the Future Research Association released the recommendations for the Horizon 2020 work programme (EFFRA, 2016), which was fully adopted by the EC. One of the main strategic issues for manufacturing value networks is to **transform existing value network networks into ones that are more digitally connected and agile**. At the same time, manufacturing is becoming more distributed thus operating complex networks of suppliers and logistics chains.

The transformation of existing value network networks into more connected and agile ones is a key strategic goal of the Industry 4.0 paradigm. This comes as a response to various events that may disrupt the continuity (e.g. COVID) and the dynamics of the market and the need to act both globally (serving different geographical areas) and locally (being closer to the customer).

With the advancement of data-acquisition systems, information technology (IT), and network technologies, manufacturing has entered the digital age. The concept of a virtual, digital equivalent to a physical entity, or the **Digital Twin** (DT) that was first introduced by M. Grieves (Grieves Michael, 2015), is taking a central position in digital transformation (Tao, Qi, et al., 2019). We can simply state that a DT is a digital replica of a living or non-living physical entity (El Saddik, 2018) with various capabilities in the manufacturing industry (Kritzinger et al., 2018):

- A DT is a virtual model of a real entity.
- A DT simulates both the physical state and behavior of the entity.
- A DT is unique, associated with a single, specific instance of the entity.
- A DT is connected to the entity, updating itself in response to known changes to the entity's state, condition or context.
- A DT provides value through visualization, analysis, prediction, or optimization.

The usage of DTs in connected factories is very important. Through DTs, a manufacturing company can virtualize its assets and have better monitoring of their performance both at factory and intra-factory level. The company can also improve Production Planning and Predictive Maintenance (Qi & Tao, 2018), monitor virtual production lines by connecting all involved stakeholders(DIGICOR H2020 Project) and optimize Packaging, Materials and Logistics (Heutger Matthias & Kueckelhaus Markus, 2019).

While the concepts of Industry 4.0 and DTs are making rapid inroads into the manufacturing sector, there are several aspects that need to be incorporated in order to strengthen the goal of optimal process operations. One such aspect is the cognitive manufacturing element (Maier et al., 2010), (Zaeh et al., 2010), (Bonnaud Serge et al., 2019) where the process plants can learn from pattern recognition in historical data and adapt to changes in the process, simultaneously being able to predict unwanted events in the operation before they happen. The induction of cognitive capabilities into the digital twin concept led to the novel concept of the **Cognitive Digital Twin** (CDT), augmenting the capability of DTs to self-organize and offer solutions to unpredicted behaviors (J. Lu et al., 2020). Although any control loop can adapt to changes, current DTs are rather restricted in the sense of reacting to already known problems. CDTs use cognition services to resolve “unknown unknowns” (Bratianu, 2015), i.e**.**, to detect situations that cannot be modelled by design (e.g., encapsulated in models) or have not been experienced (i.e., they have not appeared in past data). Although there is a plethora of CDT definitions, we can assume that a **CDT is an extension of the Digital Twin (digital representation of a physical system with bilateral connections digital-physical system), where a CDT incorporates cognitive capabilities, multiple lifecycle phases and system levels (Zheng et al., 2022)**.

In value networks (SC), various factors create the need of CDTs to enhance resilience and adaptability. First, SCs need to improve or even just cope with potential disruption events (breakdowns due to war conditions, COVID restrictions, etc.). Moreover, the emergence of novel paradigms and shifts in organizational focus towards a more green and sustainable economy offers avenues for the reconfiguration of value networks through the promotion of circularity. This can be achieved by either redesigning materials and products to adhere to circular principles or by establishing waste value networks. A common denominator of the above is the ability of SCs to test new scenarios (strategic or operational), to simulate the impact and respond to such a dynamic environment.

According to the above, the role of CDTs is crucial. A CDT may refer to different granularities; a physical object (machine), processes, factories or even value networks. In the latter case, **a SC can be considered as a network of inter-connected CDTs**. In a value network CDT (VN-CDT), all involved actors (CDTs) can share information about products and operations, collectively learn, ensure proactive behavior and adapt to different changes. Such an alignment will come from an agreed collaboration rules and conditions for CDT operations, while at the same time ensuring sustainability and resilience.

To realize VN-CDTs, we need to rethink existing governance approaches, define a comprehensive **CDT Governance Model** and deploy it at both the whole (VN-CDT) and each of the contributing CDTs. In the existing literature there is very little work on Governance models for VN-CDTs. Many of the cases found refer to physical and business operations and not on how we can model a VN-CDT, define the interactions, rules of information sharing/liability and decisions/ actuations at the “Twin” level. Therefore, we need to address governance in a holistic view by incorporating a) the *business governance* view, where - in line with the sustainability goals - values, conditions and collaboration terms are defined; b) the *data* and *models governance* view, where business goals, agreements and collaboration terms are modelled. There is a need to address policies for data treatment and how AI (cognitive) models are modelled, trained, and improved to create trust to the end users.

1.2 Thesis goal, research questions and expected outcomes

In line with the above challenges, the main goal of this thesis is to investigate the usage and adoption of cognitive digital twins in the endeavor of manufacturing enterprises to enhance their agility and digital integration with their stakeholders. This thesis explores a holistic approach to CDTs at different hierarchical levels from the shop floor level (machine, assets) to workstations, processes and at (cross-) factory levels.

More specifically, the key research questions that will be addressed are:

1) Despite a lot of research work being done on the machine and asset digital twins there is little research on the broader context: to model value network CDTs and their belonging

entities.

Research Question RQ1*: how we can model a value network CDT? (as a network of inter-connected CDTs that allows agility and resilience in the value networks)*

2) For the above, a crucial aspect lies in the governance of CDTs. This means that since CDTs belong to different actors/ stakeholders in the value chain there are critical factors to consider with regards to liability, data ownership, code of collaboration and in general the governance of the involved CDTs.

   Research Question RQ2*: which are the key enablers of a CDT governance framework and how can it be deployed in different value chain contexts?*

3) Last, we need to materialize this framework into a reference ICT architecture. The main challenge is to make it modular, easy to configure to different usage contexts and be agnostic to (or even complement) any existing commercial ICT solution.

   Research Question RQ3*: Which are the main functional blocks and usage scenarios for ICT companies who want to implement the reference framework for modelling and governance of value network CDTs?*

2 Research methodology

The methodology from inception to the finalization of the thesis is presented in *Figure 1*.

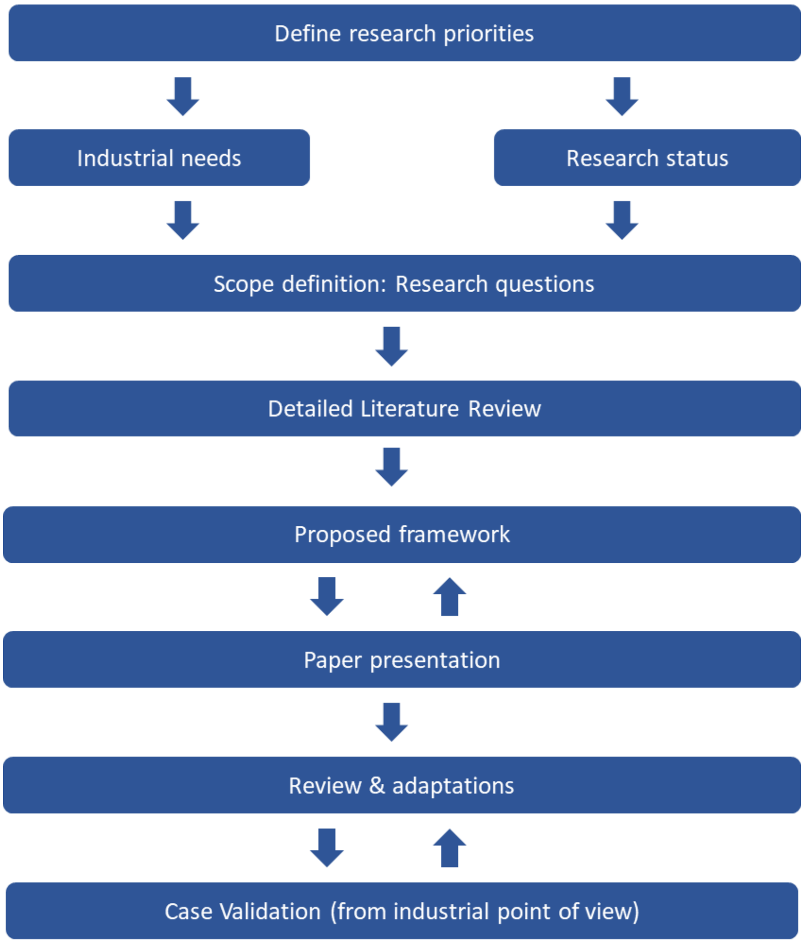


Figure 1: Thesis methodological approach

An initial literature review on the topic of value network digital twins has been conducted. **Relevant papers** and bibliography were collected, together with **market research studies**. The aim was to understand the industrial needs and potentials in value network digitization, the potentials of digital twins, the current level of adoption and prosperities. On the other hand, we to understand the current state of the art in research field on relevant topics to assess from conceptual or experimentation view, the available technologies, operational and industrial experimentations that were done in the literature. The output of this process was the following:

- To identify the trends in the industry on value network digitization and new models for Digital Twin adoption.
- To understand the gaps from the existing research.

The above led to the refinement of our research scope into the **three specific research questions**.

For all research questions, we followed a similar path:

We conducted a thorough literature review on:

- Scientific peer-reviewed papers.

- Market studies.
- Books.
- High impact articles from worldwide leading industrial companies.

The result of each Research Question literature review is presented in section 3 as follows:

- In line with RQ1, *section 3.1* presents the current status of value network digitization, cognitive digital twins and their potentials
- In line with RQ2, *section 3.2* presents the state of the art in different aspects of governance in value networks, considering the potentials of CDT adoption.

Research Question #3 was more horizontal than the first two, since for each of the CDT modelling and Governance Frameworks we examined the supporting architectures and technologies. The reason is that ICT is an important driver for RQ1 and RQ2 frameworks and could not be examined separately.

Based on the literature review findings, we formulated and propose a novel **framework** for each of the three research questions, which are presented in *sections 4.1, 4.2 and 4.3* respectively.

Our proposed frameworks were submitted as **papers in scientific journals** and were accepted, thus receiving approval from the scientific community. Any reviews and comments received, were adopted and a refined version of our approach was finalized.

The last phase was the **case validation** from the industrial perspective. Through the PLOOTO EU Horizon Europe Research Project we applied our methods in a value network focused on magnet circularity value network. We conducted dedicated meetings, visits to the factory and spoke to personnel from all stakeholders involved to understand the process, derive the needs and propose a configuration model for any ICT solution that may apply for the integration and interoperation of the value network as CDT.

3 Literature review

3.1 Cognitive Digital Twins in value networks

3.1.1 Existing status

Manufacturing is becoming global, distributed, and cognitive (World Manufacturing Forum, 2020), 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 impacts reduction (Pearson Hannah et al., 2013).

In the broader context, value networks 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 (Deloitte, 2017). This is recognized as key strategic goal by the Industry 4.0 paradigm, being described as "the trans-formation of existing manufacturing value network networks into more digitally connected and agile ones" (EFFRA, 2016).

The importance of connectivity and agility in value networks is justified by various factors.

First, the need for shortened product lifecycles together with growing product complexity, creates pressure to realize effective and efficient product development (ElMaraghy et al., 2013). The need for customization forces value networks 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) (Kiritsis, 2011), which are modular and highly customized 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 (Schuh et al., 2018).

Also, improved visibility and value network optimization is becoming more important to 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 enhanced 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 (IDC, 2014). Real-time value network optimization is shown to be a key factor able to reduce inventory costs by 20–50% typically (McKinsey, 2015), while in other studies cross-organization data interoperability in the manufacturing industry is recognized as the top trend (CGI, 2018).

Last, the need for resilience is critical and, given the COVID-19 experience, value networks need to find means of responding to different situations by disrupting the whole model and ensuring flexibility to changes. The need to ensure manufacturing and material flows require novel approaches with real-time information sharing, collaboration, and simulation/optimization models to assess alternative network setups, either on an ad-hoc basis, or even at the strategic level.

In response to the above, the transition to agile and connected value networks is highly dependent on the digital transformation of each participating actor. Whereas various ICT solutions allow the monitoring and information of flows using digital models, they are still compartmentalized and do not offer the full value network "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 (Grieves Michael, 2015), which is slowly taking a central position in the digital transformation (Tao, Qi, et al., 2019) and in the era of industrial internet (Cheng et al., 2020).

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 (Gartner, 2018). In the context of connected agile supply networks, the usage of DTs is especially important, since it allows a manufacturing company to virtualize its assets holistically and fully simulate, monitor and control their performance at the factory level. Moreover, DTs can potentially improve production planning and predictive maintenance (Qi & Tao, 2018), monitor virtual production lines by connecting all involved stakeholders and optimize packaging, materials and logistics (Heutger Matthias & Kueckelhaus Markus, 2019) or even be used together with VR functionalities in circular economy practices through disassembling and remanufacturing (Rocca et al., 2020).

However, the DT as an independent digital model is not sufficient to realize the dynamics and the needs of value networks as described above. The need for synchronization, knowledge sharing, responsiveness and optimization at the value network level requires inter-connected 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.

Current approaches to the implementation of DTs in manufacturing lack a thorough understanding of the CDT concept and, more importantly, a solid methodological framework. This impedes the development of genuine cognitive applications. At the same time, there is no systematic approach in scientific literature that applies the concepts of cognitive manufacturing to the organizational characteristics of agile product development and the design of a product development network.

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

- The inadequate understanding of the connotations of DT-driven cognitive manufacturing.
- A focus mostly on operation and maintenance of production lines and not on the value chain.
- The lack of application frameworks and reference models for CDTs (Rojas & Rauch, 2019).

3.1.2 Understanding CDTs

There are numerous DT definitions, each one focusing on different domains. According to a research study (Kritzinger et al., 2018), there are different levels of information integration between the DT and the physical object as follows:

- A *Digital Model* is just a visualization of the object without any data flowing from and to the object. In a *Digital Model,* we can simply run simulations without information exchange with the physical object.
- A *Digital Shadow* is a *Digital Model* but with some information flowing from the object to the model. In such cases, a change in the status of the physical object updates the status of the digital model.
- A *Digital Twin* is a digital replica of the physical system (e.g., the entire value network) or integral parts of it (e.g., a factory, a production line). It has a bilateral integration with the physical object by both receiving information from the object and controlling the physical object.

The DT 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 the manufacturing industry. Consequently, it must:

- Create and manage a virtual model of the system.
- Virtualize the behavior of the physical entity.
- Have different capabilities allowing to simulate, predict and optimize.
- Connect virtual (model) entities with physical ones, updating themselves 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" while taking into consideration the data, the states of the object and its behavior (Minerva et al., 2020). This means that a CDT is able to understand, promptly detect and predict the impact of different types of behavior observed (Grieves & Vickers, 2017):

- *The Predictable Desired (PD), which is the desired (normal) behavior of the system.*
- *The Predictable Undesired (PU), which are issues that are anticipated but elude comprehension regarding their occurrence.*
- *The Unpredictable Desired (UP), which is the "surprise" and benefits/good behavior of the system that were not anticipated.*
- *The Unpredictable Undesired (UU), which is a serious occurrence and relates to behavior that we did not expect, and we are unaware of the reasons behind their occurrence.*

A key difference 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 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 by relating different types of knowledge that are introduced to the CDT or that emerge from different models or components present in a DT (Rožanec Joze et al., 2020) (J. Lu et al., 2019). Besides the cognition capabilities, a CDT may have a more complex structure, consisting of multiple subsystems each one having its own lifecycle (Zheng et al., 2022).

3.1.3 CDTs positioning in the Value network

CDTs have been studied in different applications. In manufacturing systems, (Liu et al., 2022) proposed a multi-layered cognition knowledge graph model for CDT implementation and (Jinzhi et al., 2022) suggested a conceptual framework for CDTs from the model-based system engineering approach. Other research explored the implementation of CDTs in production scheduling (Eirinakis et al., 2022) and predictive maintenance (D'Amico et al., 2022). In a different domain, (Kor et al., 2022) investigated the contribution of deep learning-based DTs in the construction industry.

In agile value network networks, connectivity among all factory assets and value network entities is of the utmost importance. The RAMI industry 4.0 architecture (Plattform Industrie4.0, 2018) emphasizes how to connect different hierarchies of the factory from an individual asset up to connected processes, the enterprise level and the value network (connected enterprises). Such "assets" are orchestrated along the different product lifecycle phases (from development to product use and maintenance). Similarly, the Industrial Internet of Things Connectivity Framework is based on a hybrid interconnection in all product lifecycle phases and on a vertical (field device up to Service system) and horizontal level (value network) (Cheng et al., 2020). The common denominator of both approaches is the need for modelling all production assets in a way that ensures that:

- There is an up-to-date representation of the operational behavior, 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/value network as a dynamic system.
- Combining the behavior and the networking of such assets we can monitor, simulate and optimize its performance.

Large enterprises have already adopted the concept of DTs in different models and applications (Grieves & Vickers, 2017; Qi et al., 2018). Furthermore, different DT scenarios are introduced in the literature (Y. Lu et al., 2020; Minerva et al., 2020; Tao, Zhang, et al., 2019). In a literature study about the research on value network DTs and their implementations, (van der Valk et al., 2022) identified four main areas:

- *Visibility & Monitoring*: visualizing the process itself and benefiting from transparency.
- *Optimization*: analyzing data from the physical assets and optimizing the processes and flows within the value network.
- *Prediction*: forecasting the value network's behavior based on various data sources.
- *Simulation*: forecasting the value network's behavior based on experiments done in virtual models.

The importance of CDTs in the value network is that through their cognition capabilities we have a holistic view of the entire 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 can have a holistic approach of event detection, simulation, impact assessment and optimization (actuation) in complex value network networks. With the recent evolution of IoT, AI and blockchain technology, digitization of the value network is becoming more realistic as it provides the mechanisms for data capturing, understanding, and sharing in a decentralized way (Agrawal & Narain, 2023). (Garay-Rondero et al., 2019) proposed a reference model for digital value networks that use Cyber Physical Systems (CPS) technologies as main enablers for data capturing and value creation through enhanced services such as analytics, product life cycle management, information sharing, etc.

On the application areas (Bhandal et al., 2022) conducted a bibliographic study on articles related to the application of DTs in value networks and identified five main areas of value creation:

- Alternative manufacturing (e.g., additive or remanufacturing).
- Smart Manufacturing (production integration, prediction, simulation).
- Product development and lifecycle management.
- Value network resilience and risk management.
- Value network planning.
- Warehouse management.

These areas can also be utilized in material transportation management and last mile delivery (Tozanli Özden & Saénz Maria Jesús, 2023), where - for instance - different actors can form ad-hoc networks of collaborative parties for merging deliveries and improving operational efficiency (Miha Cimperman et al., 2021).

3.1.4 Digital threads supporting connectivity among CDTs

According to the American Institute of Aeronautics and Astronautics (Arnold Steven et al., 2023) a digital thread is "a *linked set of digital artifacts whose consistency is actively managed over the life cycle of a product, process, or system*". It ensures that in each phase of its lifecycle all artefacts are updated accordingly whenever there is a change in a specific phase. This ensures that information is traceable and accessible by all stakeholders in the product design, development and (re-) use. This comes in response to the trend that product lifecycle information is no longer exchanged through documentation but rather as data models, following Model Based Engineering (MBE) (J. Lu et al., 2022) (Lubell et al., 2012). Such information can be 3D models, CAD/CAM other specifications; all of them in electronic forms and format.

According to (Kwon et al., 2020) numerous commercial solutions for integrating data generated across the product lifecycle exist. "*However, these systems are typically expensive and tend to not target a diverse group of users, especially small-to-medium sized enterprises.*" This barrier can be overcome by enriching the standards using Knowledge Graphs (KGs).

The need for common ontologies and knowledge graphs is not new. Many case studies and models have been introduced for ontologies and KGs in different Product Lifecycle Management (PLM) phases and domains: in the Automotive industry (Matsokis & Kiritsis, 2010), in fluid transportation processes in process industries and mainly the oilfield industry (Yin et al., 2023) and in the shipbuilding industry (Jagusch et al., 2021). Similar studies on the use of KGs in process planning activities have been conducted. For instance, (T. D. Hedberg et al., 2020) proposed a method and prototype implementation of KGs in product assembly between the design, manufacturing, and quality domains of the product lifecycle. In a literature review, (Xiao et al., 2023) classified them into different areas such as: machinery planning, CNC machinery, production resource allocation and manufacturing safety.

We might consider that both concepts (digital twin and digital thread) are similar in action. In principle we can say that the Digital Twin is the mean of a physical asset representation and testing different scenarios and monitoring aspects on top of it, using a feedback loop between the digital and the physical worlds, connected to a single stream of data called the Digital Thread (Vickers Peter & Fojan Claudia, 2023) and with different stakeholders. This relationship is illustrated in the following figure (Ramesh et al., 2020).

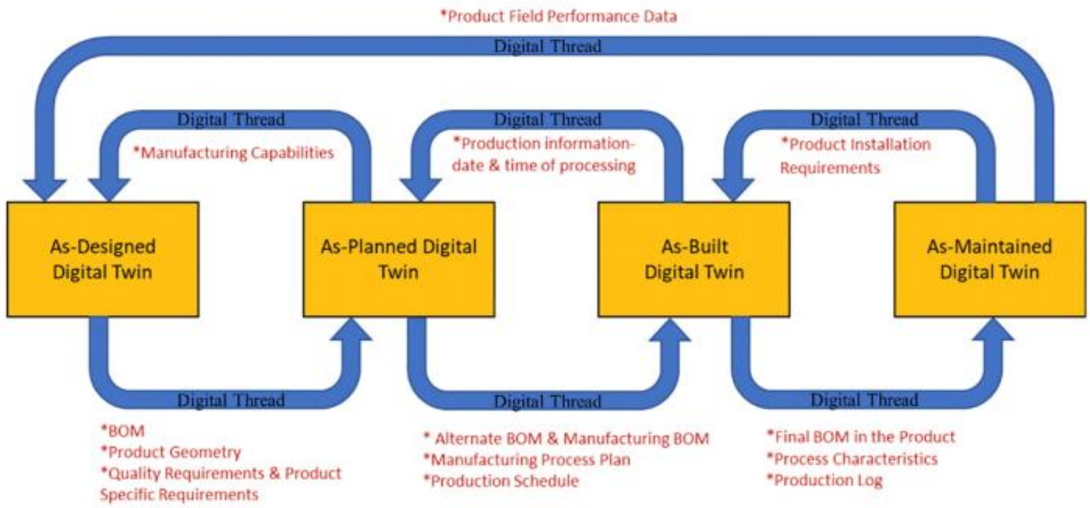


Figure 2: Digital Twin and Digital Thread

Apart from digitization in information exchange there are many other benefits. (T. Hedberg et al., 2016) tested the use of digital threads in three different cases using CAD/CAM/CIM models in both the model-based and drawing-based processes. They proved that using the digital thread, savings on cycle times for the manufacturing and inspection were achieved as well as improved the quality of specifications and models along the manufacturing phases. Business market studies also point out the value of digital threads. According to the Accenture report (Warlick John et al., 2021), businesses should develop a comprehensive thread strategy beyond narrow function-specific definitions, where they combine digital twins at all levels, include all available data sources and extend to the value network level. In this report Accenture reported (based on their findings) the following typical value propositions (depending on the industry):

Cost Optimization

- 20% – 40% reduction in costs for data duplication and overlapping toolsets.
- Up to 5x the speed of data capture and curation through thread automation.
- 2 – 3x data re-use through cross-functional access to data.
- 15 – 40% improvement in time to market via enhanced design team coordination.
- 10 – 50% reduction in product renovation activities through data-driven design.

Post-sales revenue growth

- 30 – 45% increase in accuracy in predicting service or spare parts needs.
- 10 – 25% reduction in customer churn through more focused customer offerings.
- Up to 5x increase in services revenue through new service offers targeted towards specific consumers.
- 10 – 20% increase in market share through superior service offerings.

3.2 Governance in value network CDTs

In a value network CDT (VN-CDT), all involved actors (CDTs) can share information about products and operations, collectively learn, ensure a proactive behavior and adapt to different changes. Such alignment will come from commonly agreed upon collaboration rules and conditions for CDT operations, while ensuring sustainability and resilience.

To realize this, existing governance approaches within value networks need to be reconsidered, a comprehensive **CDT Governance Model defined** and deployed at both the whole (VN-CDT) and each of the contributing CDTs.

With regards to SC governance, a lot of research is focused on operational aspects, and (?) collaboration issues with various suggestions of applicable frameworks. From a VN-CDT viewpoint, there are some studies focusing on cases of implementation, but little work on how a *holistic value network governance framework* should apply. (Srai Jag et al., 2019) introduced the main characteristics of a value network digital twin and key examples of future implementations. There are also some suggestions for the deployment of the value network digital twin model in risk management and resilience (Ivanov & Dolgui, 2021) and planning (Y. Wang et al., 2020). An interesting case is Cambridge as a Digital Twin (Nochta Timea et al., 2019) with a governance framework, where all involved parties have been modelled and clear decision-making policies, rules and conditions are defined.

Our governance approach assumes that in connected value networks, we have CDTs of all the involved stakeholders, their critical processes and affecting assets, which are linked by sharing information, and we apply decision-making (cognition) using specific norms, criteria, and other operational conditions. In this way, a governance framework should first fulfil the United Nations generic principles of governance (Economic and Social Council, 2018): i) effectiveness; ii) accountability and iii) inclusiveness.

In line with the above principles, we studied the background of the different pillars of CDT operation, from:

- the *business/sustainability view*.
- the *data governance aspects*.
- *the AI models governance* applied to the embedded models of CDTs.

<table>
<tr><th colspan="2" rowspan="2">UN governance principles
(Economic and Social Council, 2018)</th><th colspan="3">CDT value network governance enablers</th></tr>
<tr><th>Business Collaboration & Sustainability</th><th>Data Governance</th><th>AI models Governance</th></tr>
<tr><td rowspan="3">Effectiveness</td><td>Competence</td><td>X</td><td></td><td></td></tr>
<tr><td>Sound policy making</td><td>X</td><td></td><td></td></tr>
<tr><td>Collaboration</td><td>X</td><td></td><td></td></tr>
<tr><td rowspan="3">Accountability</td><td>Transparency</td><td>X</td><td>X</td><td>Explainable AI</td></tr>
<tr><td>Integrity</td><td>X</td><td>X</td><td rowspan="7">Neutral, non-biased algorithms for knowledge extraction and fair decision-making respecting ethical and societal issues</td></tr>
<tr><td>Independent oversight</td><td></td><td>X</td></tr>
<tr><td rowspan="5">Inclusiveness</td><td>Leaving no-one behind</td><td rowspan="5">• Trust, ethical principles, applicable norms/ policies in business collaborations
• Compliance with regulations and guidelines</td><td></td></tr>
<tr><td>Non-discrimination</td><td></td></tr>
<tr><td>Participation</td><td></td></tr>
<tr><td>Subsidiarity</td><td></td></tr>
<tr><td>Inter-generation equity</td><td></td></tr>
</table>

Table 1: Basic pillars for our proposed governance model in line with the principles of effective governance

3.2.1 Business Perspectives in collaborative value networks

3.2.1.1 Operational and collaboration aspects

From an operational point of view, value network governance can be defined as a *set of coordination mechanisms, constructed for a specific purpose including policies, guidelines and rules, monitoring, and verification procedures along with exercise of authority in decision making* (J. Wang & Ran, 2018). In this context, a plethora of studies can be found on SC governance.

From a **strategic and value chain creation** point of view, new omni-channel networks are introduced where customers and products complement each other and there is a fragile balance between trust and conflict of interest (Gupta Sunil, 2018). Resilience and customer value excellence are becoming increasingly critical, and are threatened by decoupling, i.e., when an external entity breaks the value creation process and creates better value for the customer (S. Teixeira Thales & Piechota Greg, 2019).

Given the nature, complexity and dynamics of the value network, there are different **factors and conditions that drive the interactions and governance** among the involved entities in terms of alignment of roles/responsibilities, information sharing, mechanisms for structuring the collaboration and the dynamics of inter-dependency among its members (Richey et al., 2010). The role of trust among entities is critical. (Y.-H. Chen et al., 2014) analyzed the factors that affect trust in value network transactions and (Bachmann & Zaheer, 2008) studied the role of trust from economic and sociological perspectives as a key element in inter-organizational business relationships.

The structure of a value network can also be considered as *centralized***,** where a single firm (i.e. the focal company) makes decisions for the firms belonging to the value network, or *decentralized*, where each company manages its own decisions (Giannoccaro, 2018). In a comparative study, (Chiu & Kremer, 2014) concluded that a decentralized value network scenario is advantageous for the time performance of the value network network, whereas the centralized value network scenario demonstrates superiority on the cost performance. In line with these structures, different approaches to **governance frameworks** have also been introduced. (Ryciuk, 2020) classified them according to the drivers that force the entities interrelations and trust, on the procedures and structures for formal/informal governance and the level of power imposed on each value network member. (Garcia-Torres et al., 2019) identified both formal and informal mechanisms that shape the structure of value network governance: the formal are the ones that are imposed by regulations, compliance, and certifications; informal are the ones that are based on trust supported by practices such as campaigns, informal visits to suppliers/factories, etc.

However, the choice of an appropriate governance framework is not often a matter of selecting one or another; it is rather a combination of those in a way that satisfies the particularities of the interactions among the organizations in the value network networks (Alvarez et al., 2010).

3.2.1.2 Value network sustainability

Organizations operate in a broader context, and they need to engage their suppliers and customers with a holistic approach to sustainability. For instance, in the consumer sector, the incorporation of a sustainability plan throughout the entire value network results in a magnified impact on environmental resources. (Bove Anne-Titia & Swartz Steven, 2016). On the other side and from consumer's point of view, there are studies showing the increasing interest towards sustainable products and services (Nguyen Hoang & Dsouza Rishad, 2021; Simon Kucher & Partners, 2021); however, in some cases, this does not mean that consumers indeed pay more for such offerings (White Katherine et al., 2019). This is critical for the results of a sustainability model: a careful examination of the most important factors at value network level with the right interventions can ensure responsiveness to environment and societal challenges without any price increase.

The evaluation of supply performance has been widely discussed, and various established methods have been implemented. (Estampe et al., 2013). In a review paper, (Reddy. K et al., 2019) found that the Value network Operations Reference model – SCOR (APICS, 2017) has acquired the most attention by researchers.

Longo et al., (2023) proposed a simulation-based decision-making framework for enhancing resilience and sustainability focusing on a value network DT response to different COVID-19 scenarios. (Katiyar et al., 2018) identified five main value network functions (planning performance, sourcing performance, manufacturing performance, delivery performance, and sustainability performance) that positively affect value network performance and sustainability.

(Kaplan R.S. & Norton D.P., 1992) were the first to introduce a balanced scorecard approach in organization performance by linking four main perspectives: financial, customer, internal business, innovation, and learning. Based on this concept, various studies proposed BSC KPIs and performance criteria focusing on the value network context (De Sousa et al., 2020); indicatively we mention the work from (Bhagwat & Sharma, 2007) and for the Agri-Food value networks the study from (Cunha Callado & Jack, 2015).

Sustainability is also the focus of global and national policy initiatives. In line with the 17 Sustainability Development Goals (SDGs) (*Sustainable Development Goals*, 2015) we have the EU Green Deal with specific actions and targets that organizations have to fulfil. In line with this, Environmental, Society and Governance (ESG) is also getting more attention to sustainability by optimizing assets (sustainable plants, equipment), resources (energy, water, etc.) leading to optimized cost, reputation (social, environmental credibility) and less regulatory and level interventions (Henisz Witold et al., 2019). The World Economic Forum (Moynihan Brian & Schwab Klaus, 2020) has also adopted a 4-pillar metrics approach to organizations who want to align their mainstream reporting on performance against environmental, social and governance (ESG) indicators and track their contributions towards the SDGs on a consistent basis: Principles of Governance, Planet, People and Prosperity.

The World Business Council for Sustainable Development - WBCSD (WBCSD, 2019) has also underlined the importance of business climate resilience, i.e. a set of strategies focusing on first assessing the dependencies of their operations and value to nature and society and then develop a climate risk, mitigation, and continuity plan for resilience.

Linked with sustainability, circularity has also been a point of attention both from nations and from businesses. There are various national (China, Japan, India, Brazil, Jordan) and broader (EU) circularity programs with specific goals targeting key domain areas: cities, mobility, construction, etc. (WBCSD, 2018). (Ellen Macarthur Foundation, n.d.) developed the Material Circularity Index (MCI) which applies to organizations and value network contexts. This MCI is a set of indicators associated with a toolkit to assess the circular effects of a product (reusability, environmental issues, recyclability, etc.). WBCSD has also proposed a similar circularity framework for value chains focusing on three main groups of indicators (WBCSD, 2020):

- Closing the loop (circularity inflow, outflow, water and energy circularity).
- Optimizing the loop (% of critical material, % of recovery type).
- Value the loop (Circular material productivity).

Various sustainability evaluation models have been introduced in the past, which, according to a study can be tailored to different value network characteristics (Estampe et al., 2013). A very good example is the Mars Company, which deployed a sustainability programme along its value network supporting local farmers in more efficient and environmental-friendly production with significant benefits: by improving farmer income by 30%, they achieved a water reduction of 30% and a cost structure reduction of 30% (Askew Katy, 2018).

3.2.1.3 Value network traceability and information models

According to ISO Standards, *traceability is the ability to trace the history, application, or location of a product in relation to the origin of its materials and parts; the processing history; and the distribution and location after delivery*.

(J.-Y. Chen, 2022) explored via game theory strategies the implications and interactions between responsible sourcing and traceability and their impact on buyers' perspectives. Similarly to the impact factor, in a literature study, (Razak et al., 2023) classified the benefits of introducing traceability to value networks as follows:

Category	Benefits of traceability
Impact on crisis management	• Improved monitoring and visibility • Efficient recall management • Assurance of product safety and quality • Elimination of counterfeiting and fraud
Impact on firm & SC performance	• Reduced operations cost • Reduced risk of SC disruption – stockouts, inventory inaccuracy • Real-time asset tracking • Enhanced SC trust and confidence (collaboration) • Improved reliability and security • Improved brand image
Impact on consumers & society	• Improved attraction and retainment of new customers • Evidence of sustainable/ ethical production/ sourcing methods • Improved reverse logistics and remanufacturing

Table 2: Classification of Value network traceability benefits (Razak et al., 2023)

Different traceability information models have been introduced as guidelines for value networks to track necessary information. Some examples are connected to the health value network (Barbosa et al., 2018), the coffee value network (Bashiri et al., 2021) and waste from electrical and electronic equipment (Li et al., 2023). Such models provide structures and semantics in specific domains, which cannot be generalized horizontally due to the following challenges (Maro et al., 2021):

- The complexity of the products and their related activities (e.g. tracking and maintenance, progress monitoring).
- Complexity due to company size and their distribution.
- Complexity due to long lasting products and how to maintain their evolution and history.

A key driver that boosts the need for traceability, is the **Digital Product Passport** (DPP) introduced by the European Commission, which will contain information about the product sustainability (European Commission, 2023a). The information models and the structure of such

DPP is still under consultation and a first implementation is expected in the battery domain. The implementation of the DPP is anticipated to be an emerging necessity for critical value networks, thus, the utilization of Value network Digital Twins is becoming increasingly crucial for monitoring and traceability of the material/product flow along its lifecycle and its value chain. Some first industrial initiatives on this are:

- The product circularity data sheet – a reference format document to be shared among stakeholders in value networks ensuring common principles in product circularity capability (PCDS, 2020).
- The pilot implementation of the DPP in the battery sector from the global battery alliance and in three proof-of-concept car model value networks (*Global Battery Passport Pilot*, 2023).

Developing an information data model in data sharing is not enough; for traceability and for the DPP to work smoothly it is essential that all IDs are globally unique and, by design, fully interoperable (Patorska Julia et al., 2022). Standards are very important because they align information systems and organization processes in the attempt to achieve traceability. Reference architecture standards for product identification and traceability have been developed by GS1 (GS1 Institute, 2017), however, there are still obstacles from organizations to adopt traceability solutions due to ICT maturity, trust in cloud storage of sensitive information and lack of market maturity (Verzijl Diederik et al., 2015).

From the ICT perspective, the introduction of trust enabling technologies (e.g. **blockchains**) addresses the issue in decentralized networks of ensuring secure information transaction without concern about data manipulation when certain nodes within the network cannot be trusted.(Khanna et al., 2020)(Feng Tian, 2016). In the literature we can find many applications of blockchains in digital value networks ensuring trust and information security: in pharmaceutical (Gruchmann et al., 2023), food (Pandey et al., 2022) and many other sectors/ industries (Risso et al., 2023). Most of the studies on blockchain or related trust technologies conclude in terms of its benefits in decentralized value networks as follows (Batwa & Norrman, 2021):

- *They enable trust in the technology through trusting the records (e.g. contracts, agreements)*
- *They enhance trust in SC partners through openness in information sharing.*
- *They enhance trust in SC partners through credibility.*

3.2.2 Data Governance and Sovereignty

Data governance refers to the entirety of decision rights and responsibilities regarding the management of data assets (Otto Boris, 2011). The information to be shared in value network data sharing differs per case. Data are heterogeneous from different sources that come either from the actors' systems (sensors, manufacturing applications) or the external environment (social media, lifecycle inventory databases, standards, etc.). In such contexts, organizations need not only to specify the roles and responsibilities regarding *what information is shared with value network partners*, but also *with which partners value network information is to be shared*, and *via which methods it is to be exchanged* (In et al., 2019).

In the literature, we find references to different models for data sharing and governance, (Abraham et al., 2019) (Alhassan et al., 2016). (Micheli et al., 2020) analyzed four emerging data governance models where data is shared for different purposes and conditions resulting in different economic and social benefit. From an industrial perspective, we have suggestions from leading organizations like Gartner (Judah Saul, 2019) and Deloitte (Sohail Omer et al., n.d.).

Data must be treated in line with the applicable regulation and norms such as the Data Governance Act European Parliament (European Commission, 2023b) updated with the measures proposed in the Data Act (European Commission, 2022a) and the FAIR principles (Force11, n.d.).

One of the most well-known approaches in the EU is the International Data Spaces (IDS) reference architecture (IDSA, 2019), which describes the necessary blueprints, roles and reference models for information annotation and sharing in a secure way. Data sovereignty in IDS is ensured only when data owners decide, control and monitor what happens to their data, who receives it and what the purpose of use is. For this purpose, IDS has defined the necessary roles as presented in *Figure 3*:

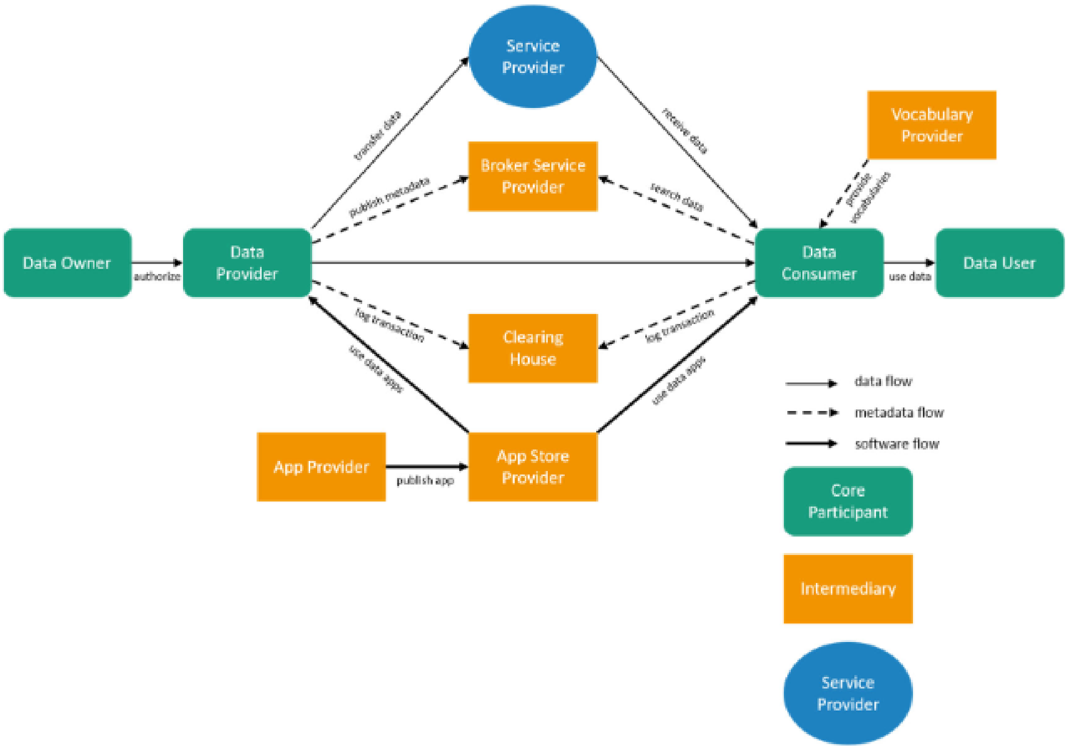


Figure 3: Data governance and sovereignty: IDS roles and interactions (IDSA, 2019)

Core Participants:

- *Data Owner*: the legal entity or person creating and/or controlling data
- *Data Provider*: makes data available (public) in order to be exchanged between a Data Owner and a Data Consumer
- *Data Consumer*: the one receiving the data. The person/entity who can search for the data by making an inquiry to a broker service provider.
- Data *User*: the legal entity or person who has the legal right to use the data from the data owner according to the usage policy or contract signed between them.
- *Application Provider*: the one who creates data apps compliant to the system architecture proposed by the IDS.

Intermediaries (Trusted entities)

- *Broker Service Provider*: stores and manages information about the data sources available, making them searchable by the data consumers.
- *Clearing House*: is responsible for all settlement, financial and data exchange transactions.

- *Identity Provider*: Offers a service that creates, maintains, manages, monitors, and validates identity information of and for participants in the data space.
- *App Store Provider*: the store that provides data apps.
- *Vocabulary Provider*: manages vocabularies (ontologies, models, etc.) that can be used to annotate and describe the data sets.

Software/ Service Providers

- *Service Provider*: Offers infrastructure for data hosting or additional services on top of the data shared (e.g. integration, cleansing, semantic enrichment)
- *Software Provider*: Offers software to implement the necessary functionalities proposed by the IDS architecture.

Governance Bodies

- *Certification Body and Evaluation Facilities:* are in charge of the certification of the participants and the core technical components applied in the data space.
- *International Data Spaces Association*: offers and supports the IDS reference architecture.

In line with the IDS development, the GAIA-X European initiative offers architecture guidelines for data sharing in value networks through data spaces with the first deployments on manufacturing, health, mobility, and other domains (GAIA-X, 2019). GAIA-X provides the data and infrastructure ecosystem ensuring openness and transparency, interoperability, federation as well as authenticity and trust. While in some parts these frameworks seem to overlap (as both ensure sovereignty), in a technical report (Otto Boris et al., 2021) an integrated approach allows data spaces operations and smart domain-specific services. More particularly, as illustrated in Figure 4, GAIA-X focuses on cloud services sovereignty and cloud infrastructure with federated data catalogues, while the IDS focuses on data sharing and data sovereignty.

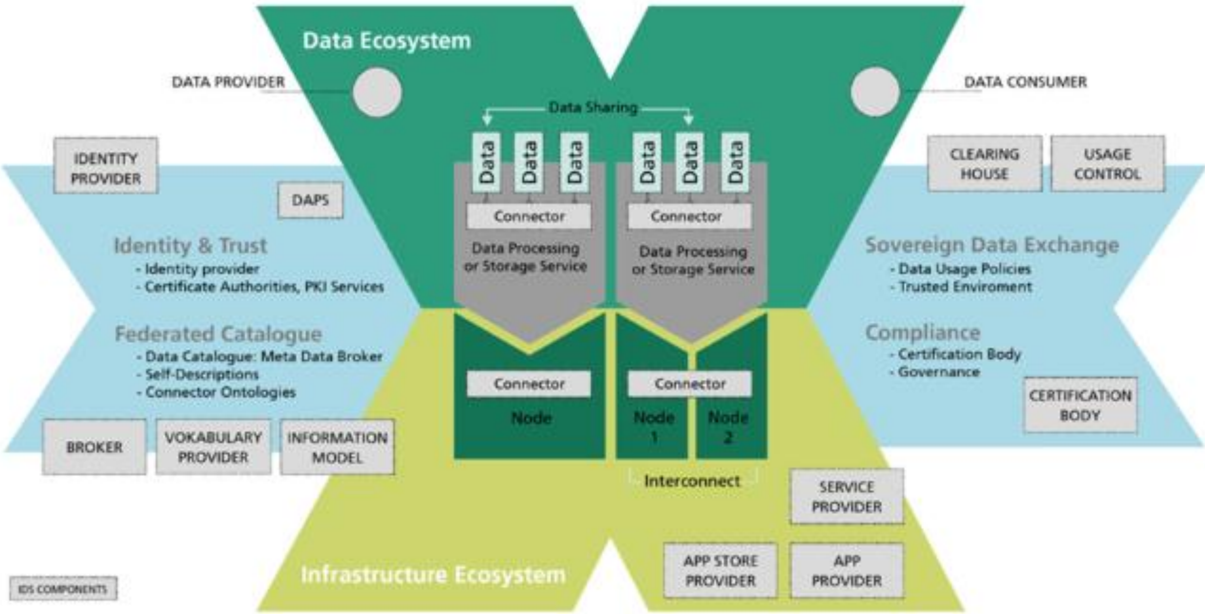


Figure 4: Proposed integrated IDS and GAIA-X approach (Otto Boris et al., 2021)

In this section we described the existing approaches and focused mainly on the IDS and GAIA-X data governance and sovereignty. If we extend this to the value network context, we assume that data which is shared has the structure/ format and quality as agreed between the shared parties.

This is a very important assumption and implies that at the inter-organizational level there must be a lot of effort in harmonizing the data and ensuring quality. Data assurance is also noted by McKinsey (Petzold Bryan et al., 2020), proposing that data governance should be associated with data quality assurance mechanisms, which will result in significant savings in time and effort from employees in non-value-added tasks. Such mechanisms should also include organizational roles and assignments, data prioritization for governance (to avoid complexity) and relevant policies.

3.2.3 AI Governance

AI governance focuses on ensuring the trustworthiness of AI models and establishing liability directly on the models themselves. Trustworthiness 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 trustworthy holistic framework (Suhail et al., 2021). This includes data security, traceability, transparency, confidentiality and integrity.

This section is organized around two main pillars:

- Existing frameworks and ethical principles in the use of AI.
- Mechanisms for AI model explainability, transparency and human engagement (human in the loop).

3.2.3.1 Ethics and codes of use

Several initiatives and studies have proposed reference governance, social and ethics frameworks of AI models, which need to be codified to regulate the behavior of AI systems (Leenes & Lucivero, 2014). One of the most well-known cases is Singapore's AI governance framework (Personal Data Protection Commission, 2020) - a set of guidelines with the principles for AI governance including stakeholder interaction and communication, incorporating transparency and explainability, putting humans and all actors in the loop, and finally ethical evaluation of the AI models. China is also adopting an Artificial Intelligence Development Plan with a rollout plan from 2025 (Roberts et al., 2021).

(Gasser & Almeida, 2017) proposed a model for AI Governance in 3 different layers: i) *Society and legal*; ii) *Ethical aspects*; iii) *Technical, algorithm accountability and data governance*. Societal aspects (putting the human in the loop) can drive collective feedback and actively participate in ethics and other AI models governance issues (Rahwan, 2018). Although the role of society and human intervention is critical, there is a need for studies examining how these can be implemented in practice (Taeihagh, 2021).

The role of ethics in AI governance has also been extensively examined. The European Commission (European Commission, 2018) issued the ethics guidelines for trustworthy AI highlighting the need to "*develop, deploy and use AI systems in a way that adheres to the ethical principles of: respect for human autonomy, prevention of harm, fairness and explicability*".

Many countries have also launched relevant ethical guidelines and initiatives. (Jobin et al., 2019) studies 84 documents from various countries worldwide and clustered them around eleven overarching ethical values (*Table 3*). However, these ethical initiatives are merely guidelines, and they lack detailed procedural structures when compared to the law (Larsson, 2020).

Ethical Principle	Elements
Transparency	Transparency, explainability, explicability, understandability, interpretability, communication, disclosure, showing
Justice and Fairness	Justice, fairness, consistency, inclusion, equality, equity, (non-)bias, (non-)discrimination, diversity, plurality, accessibility, reversibility, remedy, redress, challenge, access, and distribution
Non-maleficence	Non-maleficence, security, safety, harm, protection, precaution, prevention, integrity (bodily or mental), non-subversion
Responsibility	Responsibility, accountability, liability, acting with integrity
Privacy	Privacy, personal or private information
Beneficence	Benefits, beneficence, well-being, peace, social good, common good
Freedom and autonomy	Freedom, autonomy, consent, choice, self-determination, liberty, empowerment
Trust	Trust
Sustainability	Sustainability, environment (nature), energy, resources (energy)
Dignity	Dignity
Solidarity	Solidarity, social security, cohesion

Table 3: Clustering of ethical principles in ethical guidelines and principles (Jobin et al., 2019)

3.2.3.2 Explainable AI (XAI) and Human in the Loop (HITL)

Trust in AI algorithms is a critical issue. In value networks, important actions are taken by decision makers regarding operations. In various cases of operations monitoring (simulation, process optimization, anomaly detection, etc.) there should be clear evidence about how any alert, recommendation, or other result (coming from an AI-based system) has been generated. The right level of trust depends on the explanations provided to humans about an AI's prediction or result because humans often fail to trust an AI when they should, and they often follow an AI when they should not (Schmidt et al., 2020).

Transparency and explainability of AI systems is one of the main AI principles defined by OECD (OECD.AI, 2019), which states that an AI system should "*incorporate the necessary information, appropriate to the context, and consistent with the state of art:*

- *to foster a general understanding of AI systems,*
- *to make stakeholders aware of their interactions with AI systems, including in the workplace,*
- *to enable those affected by an AI system to understand the outcome, and,*
- *to enable those adversely affected by an AI system to challenge its outcome based on plain and easy-to-understand information on the factors, and the logic that served as the basis for the prediction, recommendation, or decision."*

In line with the above, different goals for explainability have been introduced. (Barredo Arrieta et al., 2020) suggested that the most common are:

- *Understandability* (being the most used): the ability of a model to make a human understand its function – how it works – without any need for explaining its structure or how the algorithm processes data.
- *Comprehensibility*: ability of a Machine Learning (ML) model to represent its learned knowledge in a human understandable fashion.
- *Interpretability*: to explain the model in understandable terms to a human
- *Transparency*: a model is transparent if by itself it is understandable.

The need for explainability differs among actors participating in the development, training, implementation and use of AI models. (Liao & Varshney, 2021) classified their needs as follows:

User group	Need for XAI
Model developers	Improve or debug the model
Business owners or administrators	Assess an AI application's capability, regulatory compliance, etc. to determine its adoption and usage.
Decision-makers, who are direct users of AI decision support applications	Form appropriate trust in the AI and make informed decisions
Impacted groups, whose life could be impacted by the AI	Seek recourse or contest the AI
Regulatory bodies	Audit for legal or ethical compliance such as fairness, safety, privacy, etc. by people

Table 4: Different user groups and needs for XAI (Liao & Varshney, 2021)

There are numerous XAI techniques available, each designed for specific purposes. (Barredo Arrieta et al., 2020) classified the XAI approaches proposing a taxonomy of main challenges and how they contribute to the principles of responsible AI. The results are shown in *Figure 5*.

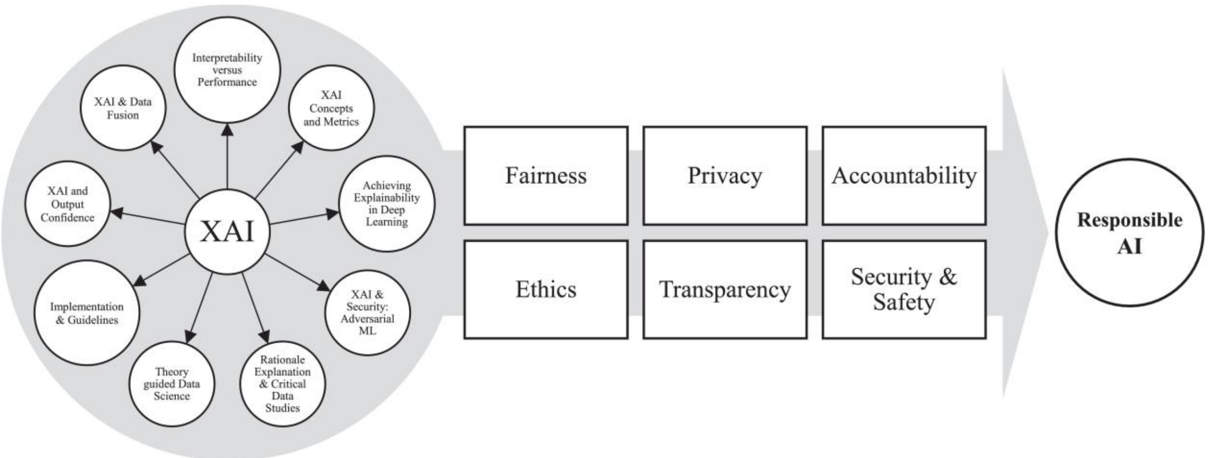


Figure 5: Summary of XAI challenges impact on the principles for Responsible AI (Barredo Arrieta et al., 2020)

In the research domain, we can find applications of XAI in various domains. In a review study (A. & R., 2023) found that the recent developments of XAI models referred mainly to healthcare, fewer targeted financial social media, computer vision, signal processing and agriculture. On industrial applications there are some studies of XAI mainly at the intra-factory level. (Terziyan & Vitko, 2022) developed an XAI model demonstrated in condition monitoring, diagnostics and predictive maintenance; (Rehse et al., 2019) conducted a test lab case study on XAI in process prediction in the DFKI smart factory testbed; (Sun et al., 2020) used it for fault detection through vision analysis in water pumps.

In a literature review paper (Mugurusi & Oluka, 2021), found that in the value network management there is little development on XAI, which focus on AI models for demand forecasting, logistics, transport, supplier selection, order fulfilment, vehicle routing, etc.

From the user perspective (the one who receives and uses the results of an AI model) the term user centered XAI (UCXAI) is receiving more attention. More specifically, as XAI by default targets – among others – end users, according to a socio-technical study by (Ehsan Upol & Reidl Mark O., 2020), the UCXAI has better understanding of "who the human is", the needs and how to provide the information in a more interpretable and reliable way for them. In line with the UCXAI, in a user field study, (Liao & Varshney, 2021) collected common questions users ask across 16 ML applications and developed an XAI Question Bank, with more than 50 detailed user questions organized in 9 categories:

- *How (global model-wide): asking about the general logic or process the AI follows to have a global view.*
- *Why (a given prediction): asking about the reason behind a specific prediction.*
- *Why Not (a different prediction): asking why the prediction is different from an expected or desired outcome.*
- *How to be That (a different prediction): asking about ways to change the instance to get a different prediction.*
- *How to Still Be This (the current prediction): asking what change is allowed for the instance to still get the same prediction.*
- *What if: asking how the prediction changes if the input changes.*
- *Performance: asking about the performance of the AI.*
- *Data: asking about the training data.*
- *Output: asking what can be expected or done with the AI's output.*

Besides the various studies on AI explainability researchers also agree on putting the human in the loop. (Meng, 2023) defined human-in-the-loop (HITL) as *"the need for human interaction, intervention, and judgment to control or change the outcome of a process, and it is a practice that is being increasingly emphasized in machine learning, generative AI, and the like"*.

(Mosqueira-Rey et al., 2023) in an HITL state of the art paper, classified the HITL approaches based on the level of human control to an AI system as follows:

- Active Learning (AL): where the AI system remains in control of the learning process and treats humans more as "oracles", (i.e. a teacher who provides some initial training to the model) to annotate unlabeled data.
- Interactive Machine Learning (IML): there is a closer interaction between the AI system and human, where humans interact in a more focused, frequent, and incremental way,

compared to the AL.

- Machine Teaching (MT), where human domain experts have full control over the learning process of the AI system.

With regards to the interaction process, a human in the IML or the MT process can interfere in every step of the AI process: training, computation, explanation of result. This means that a human can be active either in the process of suggesting a result and/or at the end of the process by evaluating/correcting/improving the result of the AI model.

3.2.4 Standards supporting digital twin modelling and operation

Many standards have been proposed for the representation of physical entities, in terms of data needed and other aspects of digital twins and value network digitization. (Kung Antonio et al., 2023) and (K. Wang et al., 2022) created landscapes of all applicable standards that support digital twin creation and operation at both the asset and value network level. The CircThread European H2020 research project (*CircThread H2020 Project*, 2023) created a standardization toolkit for all relevant standards, regulations and norms affecting circularity and information to be monitored in both organizational and value network level.

An indicative list of well-known standards and initiatives in asset/product/value network digital twins is presented below.

Asset administration shell: Following the RAMI4.0 reference architecture, the Asset Administration Shell (AAS) provides submodules for modelling assets such as digital twins. The models include information about its features, properties, statuses, data and capabilities, among others. It originated in Germany and has been expanding throughout Europe, aided by different European research funding programs.

https://www.plattform-i40.de/IP/Redaktion/DE/Downloads/Publikation/AAS-ReadingGuide_202201.pdf?__blob=publicationFile&v=1

Industrial Ontologies Foundry (IOF) *https://industrialontologies.org/welcome-to-the-iof/#* *:* The IOF is a group working to co-create a set of open reference ontologies to support the needs of the manufacturing and engineering industry and to advance data interoperability.

The IOF ontology version 1 has been launched with the support of the value network working group in February 2023 and includes a reference ontology for value networks

(https://github.com/iofoundry/ontology/tree/202301/supplychain)

Industrial Internet Consortium (IIC)*:* The IIC has published a whitepaper (Industrial Internet Consortium, 2020) providing guidelines for modelling digital twins related to:

- The defining characteristics of a digital twin.
- Relations among digital twins to form composite systems.
- The role of digital twins in the lifecycle of entities, considering the scenarios with and without digital twins and the business value of digital twins.
- Digital twin internal design.
- A detailed description of various design decisions.

- An overview of standards for digital twins, which could be considered in their design.
- Example of digital twin use in various industries.

https://www.iiconsortium.org/

OntoCommons*:* OntoCommons is a research project funded by the EU which focuses on the standardization of data documentation in different domains. Through the Industrial Domain Ontology, the project tries to implement mechanisms for intra- and inter- organization interoperability on materials and manufacturing with respect to the FAIR principles.

(https://ontocommons.eu/)

ISO 23247: Automation systems and integration - Digital twin framework for manufacturing*:* the standard for digital representation of assets along with an information model and reference architecture.

https://www.iso.org/standard/75066.html

ISO 10303: Product data representation and exchange: ISO 10303 provides a representation of product information along with the necessary mechanisms and definitions to enable product data to be exchanged. It incorporates information about the product representation along its lifecycle: from design to production, use, and final disposal.

https://www.iso.org/obp/ui/#iso:std:iso:10303:-1:ed-2:v1:en

IPC-2551: International Standard for Digital Twins: This data exchange and interoperability standard has been in the works since 2022 before being officially released in 2023. IPC-2551 is the first international standard on digital twins and targets the creation of smart value chains with standardized data formats.

(https://shop.ipc.org/ipc-2551/ipc-2551-standard-only/Revision-0/english)

Digital Twin Consortium*:* Digital Twin Consortium brings together industry, academia and governmental bodies to facilitate common vocabularies, reference architectures, security and interoperability of digital twin technologies. There is an interesting work on common vocabularies and a work-in-progress glossary for digital twins:

https://www.digitaltwinconsortium.org/about-us/
https://www.digitaltwinconsortium.org/glossary/glossary/

GS1 Standards *(https://www.gs1.org/):* Provides a common language and information models to seamlessly share data about a product (key, location, code, etc.) among different stakeholders. The main recommendations are briefly presented in *Figure 6*.

GS1 IDENTIFICATION KEYS AT YOUR FINGER TIPS

KEY	IDENTIFY
GTIN	**Global Trade Item Number** Products such as consumer goods, pharmaceuticals, medical devices, raw materials at any packaging level (e.g., consumer unit, inner pack, case, pallet). Services such as equipment rental, car rental, ... Individual trade item instance(s) by combining the GTIN with batch / lot number, serial number. **Note: Compatible with ISO/IEC 15459 - part 4: individual products and product packages**
GLN	**Global Location Number** Physical Locations: An organisation's geographical addresses such as Ship From, Ship To, Read Point. In combination with the GLN extension also internal physical locations such as storage bins, dock doors, bar code scan / read points. Parties: An organisation's legal and functional entities engaging in business transactions. **Note: Recognized in ISO standard 6523, international code designator (ICD) for GLN is '0088'**
SSCC	**Serial Shipping Container Code** Logistic units such as unit loads on pallets or roll cages, and parcels. The SSCC enables the unique identification of any combination of trade items packaged together for storage and/or transport purposes. **Note: Compatible with ISO/IEC 15459 – part 1: unique identifiers for transport units (the ISO licence plate)**
GSIN	**Global Shipment Identification Number** Shipments, comprised of one or more logistic units intended to be delivered together. The logistic units belonging to a particular shipment keep the same GSIN during all transport stages, from origin to final destination. **Note: Meets the WCO requirements for UCR (Unique Consignment Reference).** **Compatible with ISO/IEC 15459 – part 8: grouping of transport units.**
GINC	**Global Identification Number for Consignment** Consignments comprised of one or more logistic units (potentially belonging to different shipments) intended to be transported together for part of their journey. Logistic units may be associated with different GINCs by carriers or freight forwarders during subsequent transport stages.
GRAI	**Global Returnable Asset Identifier** Mostly used to identify Returnable Transport Items (RTI) such as pallets, roll containers, crates. The GRAI identifies the type of returnable asset, and if needed also the individual instances of the returnable asset via the optional serial number.
GIAI	**Global Individual Asset Identifier** Fixed assets such as office equipment, transport equipment, IT equipment, vehicles. The GIAI identifies individual asset instances regardless of the type of asset.
GSRN	**Global Service Relation Number** Service provider relationships of an organisation and the provider of the service, such as the doctors employed by a hospital. Service recipient relationships of an organisation offering a service and the recipient of the service such as the loyalty account of a customer with a retailer, the registration of a patient at a hospital, the account of a customer with an electricity company. In combination with the Service Relation Instance Number (SRIN) it can identify service encounters, such as the phases of a medical treatment.
GDTI	**Global Document Type Identifier** Physical documents such as certificates, invoices, driving licenses. Electronic documents such as digital images, EDI messages. The GDTI identifies the type of the document, and if needed also the individual document instances via the optional serial number.
GCN	**Global Coupon Number** Coupons (paper or digital). The GCN identifies the coupon offer, and if needed the individually issued coupons via the optional serial component.
CPID	**Component / Part Identifier** Components and parts such as drive motor for washing machine, fan assembly for a jet engine, starter motor for vehicle, wheel axle. Individual components or parts, by combining CPID with a serial number. **Note: The CPID identifier shall not be used in open supply chains. It is restricted to use by mutual agreement.**
GMN	**Global Model Number** The Global Model Number enables users to uniquely identify the product model through the entire life cycle of the product: design - production – procurement – use – maintenance - disposal **Note: The GMN has currently only been approved for regulated healthcare identification of medical devices. Other applications may be added in the future.**

Figure 6: GS1 standards for asset identification (*source GS1*)

4 Proposed solution framework

This section presents the findings of the main research questions (*section 1.2*).

4.1 A reference framework for modelling and operating VN-CDTS

All findings in this section have been published in the following papers:

- Kostas Kalaboukas, Jože Rožanec, Aljaz Košmerlj, Dimitris Kiritsis and George Arampatzis. *Implementation of Cognitive Digital Twins in Connected and Agile Supply Networks-An Operational Model*. Applied Science Volume 11, Issue 9, 2021. https://doi.org/10.3390/app11094103
- Pavlos Eirinakis, Stavros Lounis, Stathis Plitsos, George Arampatzis, Kostas Kalaboukas, Klemen Kenda, Jinzhi Lu, Jože Rožanec and Nenad; Stojanovic. *Cognitive Digital Twins for Resilience in Production: A Conceptual Framework.* Information, Volume 13, Issue1, 2022. https://doi.org/10.3390/info13010033

and they have been utilized in the following European Union's Research projects:

FACTLOG — Energy aware factory analytics for process industries - *European Union's Horizon 2020 research and innovation programme under grant agreement no. 869951*

Plooto — Product Passport through Twinning of Circular Value Chains - *European Union's Horizon 2020 research and innovation programme under grant agreement no. 101092008*

4.1.1 Modelling a CDT value network as a network of interconnected CDTs

To begin with our approach, it is necessary to explain the concept of a value network CDT (VN-CDT). We consider a VN-CDT as a network of interconnected CDTs, each one representing the main actors (*stakeholder's flow*) and inputs/outputs (*material flow*) in the value network (*Figure 7*).

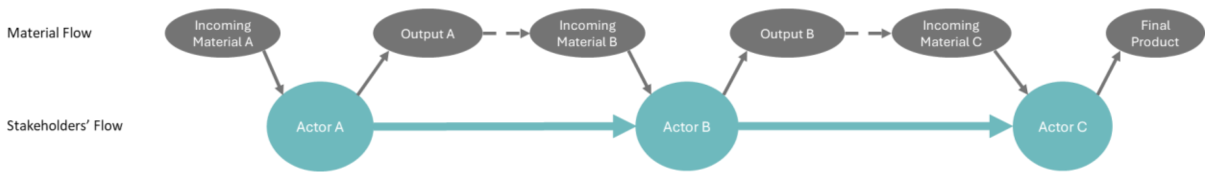


Figure 7: Basic model of a value network CDT (material and stakeholders' flows)

More specifically, in the above example, each *Actor* is a generic representation of the stakeholder (Actor CDT), who in the context of the value network is transforming incoming *material* (material CDT) into a specific *output* (output CDT).

Each CDT can share only the necessary with other CDTs based on the agreements among the stakeholders. In this way we model also the information flow among the different CDTs. For instance, *Actor A* can share information only about its production capacity or time needed to deliver a particular quantity of *Output A*. *Output A's* shared information is encapsulated in its Output A CDT and may include various characteristics of the product: testing results, lot number and more, which in the real operation is shared through the documentation associated with the delivery of the order.

Each CDT also has specific cognition capabilities: from basic understanding (e.g., information transmitted through the Output A CDT) to autonomous decision making and actuation (e.g., Output A CDT understands an anomaly during its transportation and informing the affected stakeholders about a potential quality failure).

In a similar way, each organization/actor can monitor **its own assets and operations** at different hierarchies, from machines to processes, i.e. network of machines and inputs/outputs. The organization has its own ICT systems where information is generated (e.g., SCADA, MES, ERP, Sensors) and such information characterizes the performance of assets and process CDTs. The organization aggregates this information and creates a shared set of data which is transmitted in the value network.

Therefore, we have at both the intra-organizational and the inter-organizational (value network) level a dynamic, living system of "cognitive digital twins" representing all assets, operations and actors involved: factory, logistics service provider (LSP), trucks, warehouses, etc. as illustrated in Figure 8.

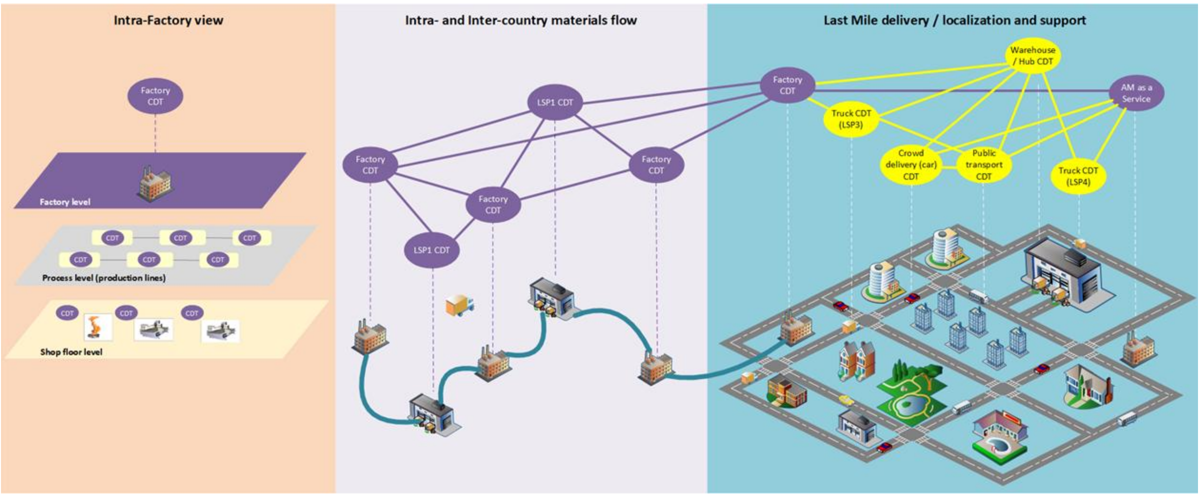


Figure 8: Agile value networks as network of interconnected CDTs

To deploy a VN-CDT we need first to get a detailed view of a CDT, how it works and how cognition applies to its operation.

4.1.2 Basic enablers for CDTs and cognition process

A Cognitive Digital Twin is a DT which has specific cognition capabilities that are realized by AI services. In more detail, a CDT has a set of enablers that characterize its identity, networking and behavior as illustrated in *Figure 9*.

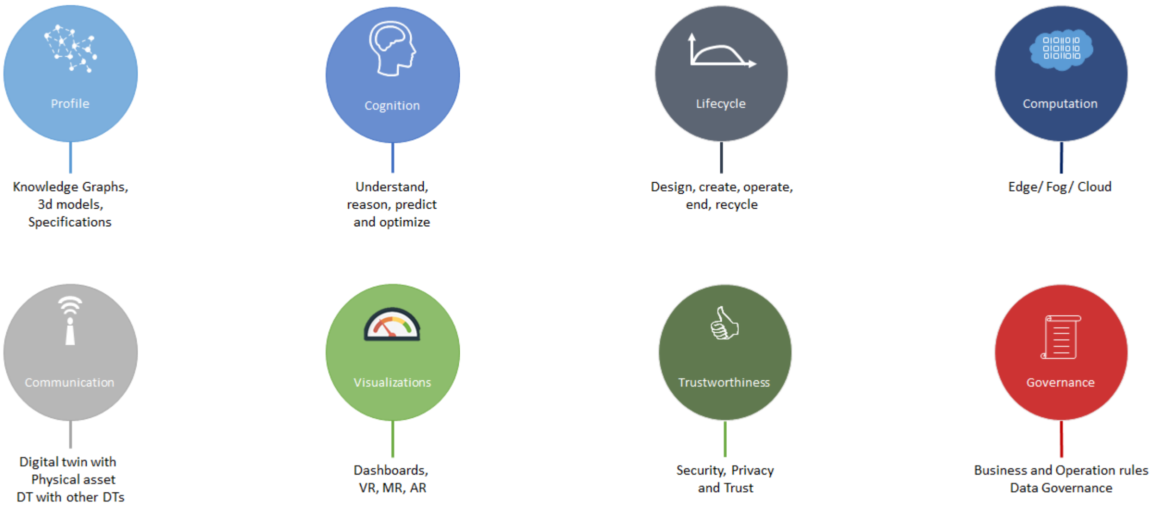


Figure 9: Basic enablers of Cognitive Digital Twins

Profiling: This provides the necessary knowledge about the physical asset's status, behavior, specifications, and any other information that characterizes the asset. Besides the textual information, the profile can also contain representation models of the asset that is being twinned. Some model examples can be:

- Product CAD model
- Machine/robot 3d models

Cognition: The ability to understand context, reason on top of existing information, predict and optimize behavior. This refers to all analytics and cognition services and each Digital Twin can have different cognition capabilities (from basic sensing and understanding to complex detection and optimization). The basic blocks of Cognition are the following:

a) *Reasoning services,* which are responsible for understanding a context and generating knowledge based on data streams

b) *Simulation and Prediction Services,* which propagate the behavior of a DT in the future to detect whether an anomaly is about to happen.

c) *Optimization services*.

Lifecycle: This refers to the ability and the actions to monitor and control DT behavior through its entire lifecycle:

- *Generation*: how the CDT is being created and under which knowledge: which are the data to be used to develop a baseline behavioral model that will evolve through its operation? How are we testing and ensuring a robust twin with regards to the data flows and the associated AI models?
- *Operation*: how is the CDT fed with new data and how does it update its behavior? how is knowledge being generated and how does a cognition process apply to get the maximum benefits of the CDT operation?
- *End of life*: how can existing knowledge be formalized and transferred to the design and operation of other CDTs with similar behavior?

Depending on the application, we might have different DT lifecycles from the creation, duration, and end of life perspective.

First, we have *static DTs,* e.g. in a production line inside a factory, a machine that has a long lifetime and is part of a fixed process (the behavior of which can of course be upgraded but as an entity remains essentially unchained). In such a case, the production line is a network of such fixed DTs.

We might also have the case of an *ad-hoc and more dynamic DT*: This is a case where in existing production of value network networks there is a disruptive event that needs to change the structure and operation of the value network (e.g., need to find a local operator, a local producer, a logistics provider). In this scenario, we are creating CDTs on an ad-hoc basis for temporary actors, and it is crucial to evaluate if their actions align with the requirements and objectives of the value network.

Computation: Refers to the ability to carry out calculations, taking into account the functions and calculations that need to be performed. This capability is associated with the capacity to operate certain services in either the cloud and/or edge.

Communication*:* Is the ability of a CDT to communicate with its physical asset and with other DTs as part of the network it belongs in (e.g., Workstation A with Workstation B, which belong to the same production line). Communication services are supported through a ***message bus*** responsible for the interoperation and information exchange.

Visualization: Refers to the ability to monitor the performance and lifecycle of a DT (using dashboards, or immerse technologies such as VR, MR, XR).

Trustworthiness: Refers to the security/privacy and trust services/policies applicable to the operation of a DT and its ability to exchange information with other DTs.

Governance: Refers to all necessary agreements on business/sustainability goals, ownership and liability on generated data and applicable AI models. Governance frameworks are described in detail in *section 4.2*.

4.1.3 Cognitive Digital Twins Operational Model

The above enablers function together in an integrated concept where for each of the DTs we can monitor the flow of information from collection to understanding and behavioral alerting as indicated in the figure below:

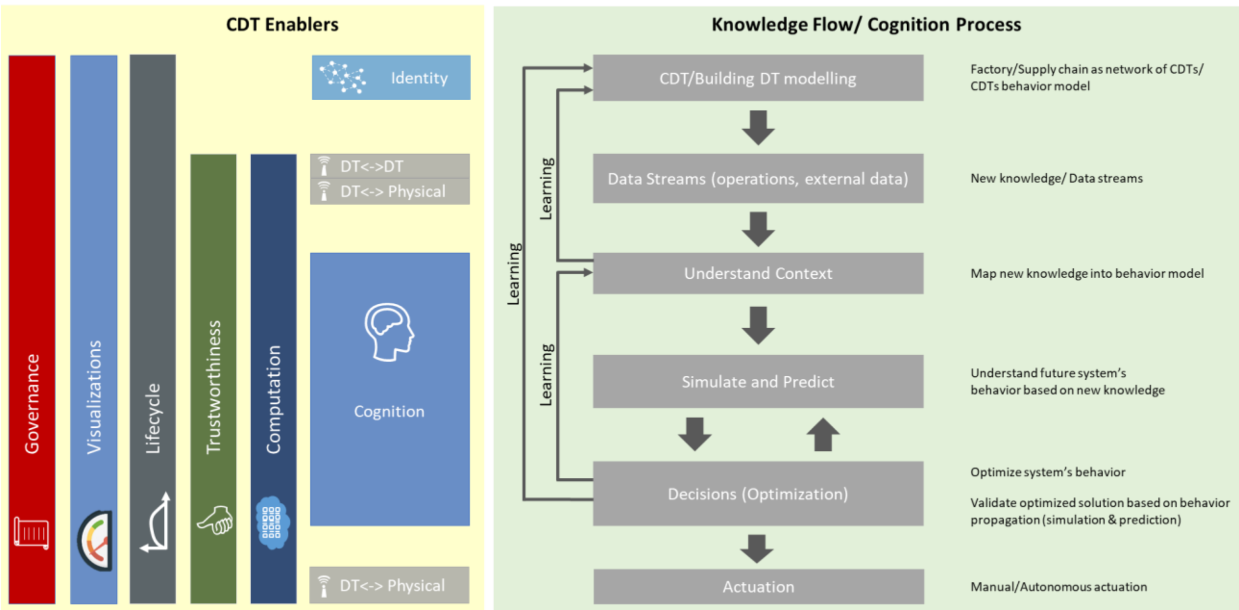


Figure 10: CDT Operational Model

The main steps are:

Step #1: Modelling: this is the configuration phase, where we can model a factory or any hierarchical structure of a factory/ value network as a network of interconnected DTs.

Applicable Enablers:

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

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

Applicable Enablers:

- **Communication**: Communication capabilities of the DT that define the sources of the data streams (either from the physical assets and/or from other DTs 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 assets/DTs.
- **Visualization**: Data stream visualization
- **Lifecycle**: Monitor status of the DT.
- **Governance:** Apply governance policies.

Step #3: Understand Context: Once data is collected, this is mapped against the DT's behavioral model. Through cognition services, the DT will be able to understand potential trends, anomalies or create new knowledge (in the form of new rules, associations, etc.).

Applicable Enablers:

- **Cognition:** Analytics based on existing behavior 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/DTs.
- **Visualization**: Knowledge visualizations.
- **Lifecycle**: Monitor status of the DT.
- **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 behavior of the DT in the future and should predict potential failures in the future. Simulation is performed based on root-cause analysis and using the existing behavior model (propagating the behavior of the system in the future using the new data).

Applicable Enablers:

- **Cognition:** simulation and prediction services propagating the system's behavior with the new knowledge to the near future to 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/DTs.
- **Visualization**: Simulation and prediction visualizations.
- **Lifecycle**: Monitor status of the DT.
- **Governance:** Apply governance policies.

Step #5: Decisions (optimization): after simulating and predicting the DT's behavior, robust optimization services will offer suggestions for improvements**.** Optimization services will propose a new state of the DT's behavior, which should be validated using the simulation and prediction services. This feedback loop will consider the new DT's behavior inputs, simulate and predict its behavior in the system and assess the performance (is the problem solved? Is the trend fixed? Other issues?). If the solution is not verified, the optimization services must be rerun, and the feedback process will continue. *Applicable Enablers:*

- **Cognition:** Robust optimization services to identify new behavior parameters. Simulation and prediction services propagating the new (proposed) system's behavior in the near future and potential anomalies identified.
- **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 assets/DTs.
- **Visualization**: Behavior visualization.
- **Lifecycle**: Monitor the status of the DT.
- **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 behavior accordingly.

- **Communication:** DT 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 DT to the physical asset.
- **Visualization**: monitor the status of the actuation (confirmed or not, other).
- **Lifecycle**: Monitor status of the DT.

- **Governance:** Apply governance policies.

4.1.4 Deploying the framework and operational model

In the previous sections we analyzed the concept of the VN-CDT model, the basic CDT enablers and how CDTs operate in the VN-CDT context.

The methodology for deployment and configuration of the above into different value networks depends on the context and is in line with the CDT lifecycle enabler.

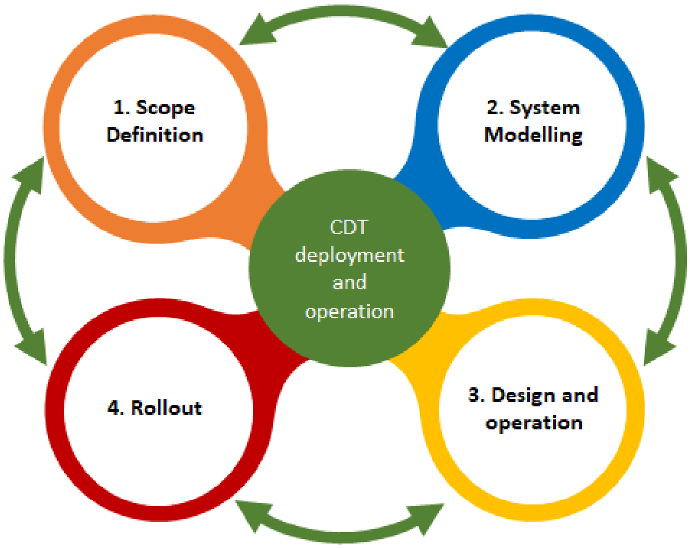


Figure 11: VN-CDT framework deployment approach

More specifically, the main steps are:

#1: Scope Definition

This is the first phase in which we define the case for monitoring and improvement of the agile value network. We need to analyze 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 value network?
- Why is it critical to monitor the value network? 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? At this point it is necessary to define our system boundaries (either focusing on a specific supplier tier or selecting the most important supplier in multiple tiers).
- Define and select the focus of the process: Depending on the challenge, we need to identify the critical process(es), which will be the focus for modelling and operation.

#2: System Modelling

Once the problem and the case are identified, we need to understand how the collaborative value network processes work, where the needs for CDTs are and understand the different capabilities/needs in relation to the CDT enablers. After that, we will be able to configure the cognition operational model process (presented in *Figure 10*).

More particularly, the issues that must be addressed 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 value network has to be modelled as CDT. We may establish either a 1-to-1 connection between CDT and entity or a collection of interconnected CDTs.
- Elaborate on the CDT enablers: For each CDT identified, we need to understand how the enablers apply. This is a time-consuming process 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 model performance over time.
- Deploy the necessary optimization algorithms for decision making.

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

#3: Design and Operation

After the modelling phase, we move to the design and operation which involves 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 performed for testing.

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

#4: Rollout

In the rollout we extend the operation to the rest of the CDTs and scenarios in the operational model (defined in the 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.

4.2 Governance Framework

All findings in this section have been published in the following paper:

- Kostas Kalaboukas, Dimitris Kiritsis and George Arampatzis. *Governance framework for autonomous and cognitive digital twins in agile value networks*. Computers in Industry, Volume 146, 2023. https://doi.org/10.1016/j.compind.2023.103857

and they have been applied in the following European Union Research projects:

Energy aware factory analytics for process industries - *European Union's Horizon 2020 research and innovation programme under grant agreement no. 869951*

Product Passport through Twinning of Circular Value Chains - *European Union's Horizon 2020 research and innovation programme under grant agreement no. 101092008*

4.2.1 Overall

Our model incorporates five basic blocks (*Figure 12*).

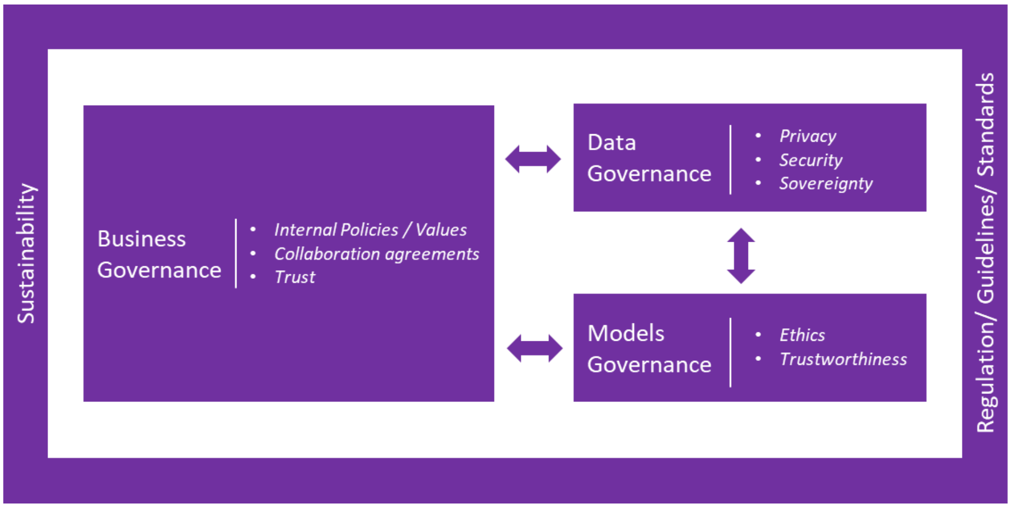


Figure 12: A holistic approach to CDT Governance Framework for Connected Value networks

The first is to define the **Business Governance;** to reach an agreement among the involved stakeholders regarding the SC configuration:

- Agree on the stakeholders' flow (see *Figure 8*): Define main actors and material flows.
- Define goals, conditions, and principles for the operation of the value network.
- Define the information that needs to be shared among the SC members and who will have access to it.
- Agree on the structure of the data to be shared in the SC context.
- Understand which assets/ operations will be modelled as CDTs with cognition capabilities.

Information needs and applicable privacy/ confidentiality policies will be the input to the **Data Governance**, which formalizes (as services on top of each CDT) the rules, policies, and transactional conditions where information is exchanged and processed. The main issues to be addressed are:

- Role and responsibility definition for data generation and usage
- Access and usage policy definition of the data shared along the value network.

AI models' governance incorporates all necessary steps for ensuring that data processing is done with principles of AI FAIR treatment and explainability to the end users.

The **Sustainability** block defines the main priorities of value networks operation. These vary depending on the nature of operations and can include circularity, social impact, economic benefits, community wealth, etc. This incorporates **applicable regulation, norms and standards** to which all SC operations and info sharing/processing need to adhere.

The below graph illustrates the main inter-relationships among the different blocks.

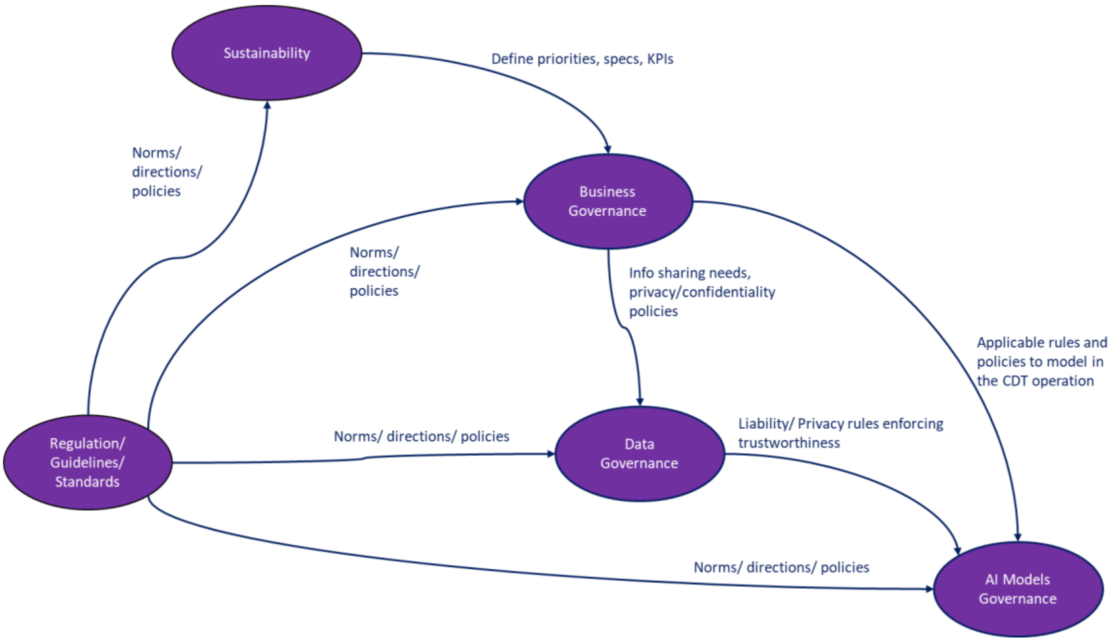


Figure 13: Governance Framework block inter-relations

In the sections below, we present each of the framework blocks along with the main issues to consider. It should be noted that each SC has its own context and particularities, so there will be different deployments depending on the agreements of the collaborative entities.

4.2.2 Business Governance

At this stage, the rules of collaboration in the value network must be agreed upon and modelled in the CDT. These rules describe the operation of the physical entities which will then be modelled as CDTs; a) input-output of each CDTs; b) inter-relation with other CDTs; c) specifications and acceptance conditions; d) agreement of information to be shared, and processing; e) ethical, legislation and other applicable rules and norms.

More specifically, such agreements will address the following:

- Understand the context: model operations, inputs, and outputs of the value network.
- Define involved actors, i.e. any entity involved in the operation of the value network such as factories, machines, people, systems.

- Agree on the SC sustainability goals. These goals will reveal needs for monitoring, simulation and common decision-making through the operation of CDTs. The goals need to be agreed upon by all involved actors.
- Identify the actors listed above who play a role in achieving the value network objectives and requirements for operating CDTs. These actors will later be represented as CDTs. Define roles for each CDT, i.e., the main functionalities in the context of the VN-CDT.
- Define interactions among the involved CDTs (inputs/outputs), information sources, constraints, and other conditions of operations.
- Define decisions to be made by each CDT and needs for AI models for decision-making.
- Decide the level of CDT autonomy in the decision-making and actuation processes. Will it be assisted by humans and in which phases? For example, in a material flow optimization problem, does the model perform autonomously or need some input from the end user?
- Outline the rules and criteria for every decision made by the CDT: how these decisions align with the value network objectives and current policies, norms, and Service Level Agreements (SLA). Formalize how reputation and experience affect trust and future transactions. This will be done through the necessary norms, rules and other criteria driving the decision-making process at each node of the value network. For example, in a case of an ad-hoc outsourcing scenario (Manufacturing as a Service) the organization needs to establish the rules/criteria that adhere to the principles and SLA of the value network.
- Agree on liability and legislation issues: this is done through the definition and monitoring of an operational risk plan for the CDTs usage. The risks will come from information sharing, data governance and model governance by addressing the following:
    - *Evaluate the trade-offs between specific risk and benefit: Understand how this risk impacts the reliability, business objectives, and ethical aspects of the CDT operation. In certain situations, the risk may escalate significantly for an autonomous CDT operation, making human intervention more preferable. Agree on liability*: who is liable for any malfunction of the CDT? How is responsibility shared with regards to the data acquisition, data processing and actuation?
    - *Agree on mitigation actions:* How can we ensure a proactive approach to CDT behavior assessment in line with the data and model governance principles?

The outputs of this stage are:

- A list of entities' involvement and identification of what is to be modelled as a CDT.
- Value network interactions, which are translated into inputs-outputs in an inter-connected VN-CDT.
- The level of CDT autonomous decision-making and actuation.
- The rules of collaboration to be considered in the applicable AI models.
- Information sharing needs for monitoring and decision making (relevant to the data and models governance).

4.2.3 Data Governance

Once the operational CDT agreements are established, a data governance plan will address the following:

- Define data inputs/ processing and outputs per individual CDT.

- Agree on confidentiality/privacy and other data sharing policies/ principles.
- Agree on data authorization, ownership, and accountability per CDT with regards to raw data (i.e., inputs in the CDT decision making process).
- Ensure a fair treatment of data from each CDT, according to the principles of security, privacy and applicable regulations.
- Agree on meta-data ownership/liability with regards to the processed data of the CDT.
- Monitor a continuous risk management plan in the overall VN-CDT and their subsequent inter-connected CDTs.

The output of this phase is a complete set of responsibilities, ownership and liability of both raw data and meta-data processed by the CDTs, including a risk management plan.

4.2.4 AI Models Governance

AI models realize the cognition part of the CDT. In VN-CDTs the behavior and the information processed by a CDT may affect the behavior of the rest and ultimately the value network. Therefore, agreeing on the norms and rules of the model operations is crucial to ensuring liability and compliance to the overall business collaboration agreement.

At each node of the value network and for the associated AI models there should exist ways to ensure explainability, feedback loops and continuous improvement (learning actions) from the usage to the model itself. In a VN-CDT we can have different AI models/systems, each serving different purposes and functionalities. From the models' development perspective, we believe that the selection of the XAI technique is up to the model's provider. When it comes to the VN-CDT serving as a hub for AI services, we can create an XAI approach from the user perspective of view by providing a clear explanation to end users on how the model operates, ultimately building trust in the outcomes. This will be done through an AI certificate service in addition to each CDT participating in the value network. The main functions of the AI certification will be:

- To provide the necessary (user-centric) explainability of how the models work and under which assumptions/rules
- To ensure HITL feedback loops from the user to the AI model (new knowledge or even updating existing knowledge)

Following the work by (Liao & Varshney, 2021) in the UC-XAI and the XAI questions repository, the main elements of such certification were drafted and are presented in the figure below. It should be noted that depending on the model, different questions and issues can be addressed in this certificate.

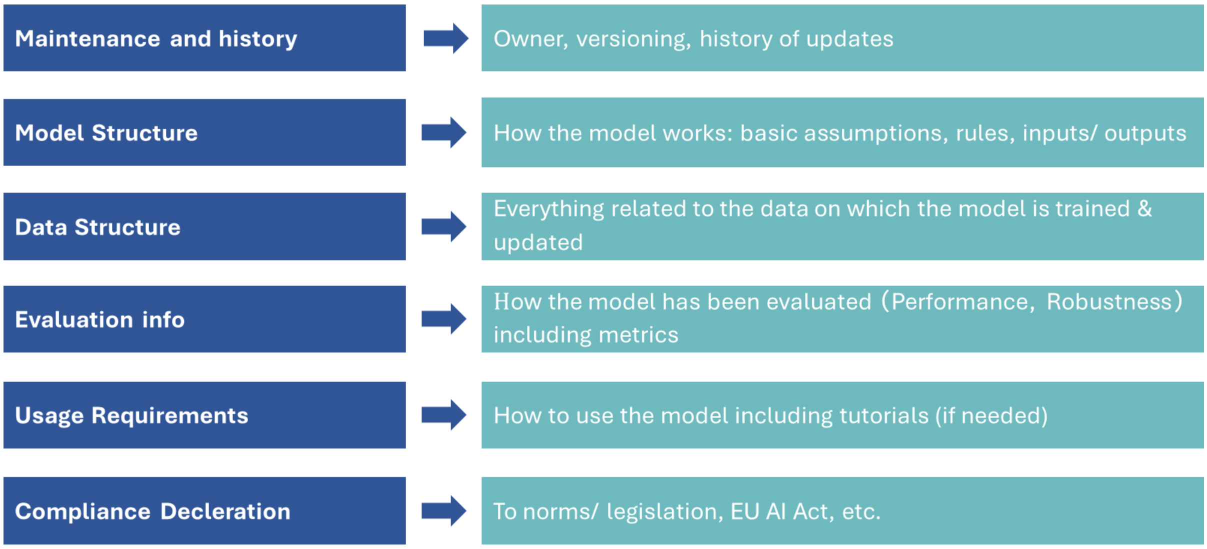


Figure 14: AI certificate elements

The output of this phase will be:

- All necessary procedures for AI model construction, training and improvement (during operation) by involving all actors (humans and/or other CDTs) in the value network.
- The AI model passport associated with each CDT separately and shared among the affected value network stakeholders.

4.2.5 Sustainability

Sustainability will define the basic criteria and KPIs which the value network will follow. Based on the business collaboration agreement, all involved stakeholders will have to agree on the KPIs that address not only economic but also environmental and societal perspectives. These KPIs will be translated into specific metrics/ KPIs for the performance of each CDT and criteria for its cognition process.

The output of this phase will be a set of agreed upon KPIs at the global (value network CDT) and local (materials and operation CDTs participating in the VN-CDT) scales.

4.2.6 Regulation/ guidelines/ standards

Each value network operates under a specific legal framework or supporting guidelines. These dictate the rules, constraints, and specifications for all aspects that need to be monitored (operations, product quality, etc.). In addition to business considerations, it is essential to also take into account and adhere to regulations and standards related to data and AI model governance, ensuring they are agreed upon, documented, and monitored for compliance across all SC operations. Some examples are:

- *Business Collaboration*: standards and regulations affecting the product characteristics (e.g., food treatment and transportation).
- *Data governance*: Information sharing and knowledge extraction on the product from production to retailer (Data Governance Act, GDPR with regards to consumer usage information)
- *AI Model governance*: declaring and ensuring compliance with ethics, the EU AI Act and other directives addressing a FAIR treatment of data collected and processed).

- *Sustainability*: circularity indexes based on ESG goals.

The output of this phase will be:

- A list of applicable norms/ laws/ guidelines
- Documentation of compliance in different forms (Business agreements, AI certificates, etc.).

4.3 Reference modelling architecture for VN-CDTs

All findings in this section have been applied in the following European Union's Research project:

Plooto

Product Passport through Twinning of Circular Value Chains - *European Union's Horizon 2020 research and innovation programme under grant agreement no. 101092008*

4.3.1 Overview – basic assumptions

In this chapter we will try to materialize the value network CDT framework and the governance model into a reference ICT architecture and its main functionalities.

The main assumption for this was that since value networks are heterogeneous and in most cases are not led by one company (power is distributed) we consider the network to be distributed, having the following characteristics:

- The starting point for the implementation of such an ICT framework is the **business agreement among stakeholders** involved, as described in *section 4.2.2*.
- Every company involved in the network operates with its own operating systems and sources of information. These systems gather and process data in their own specific formats and structures.. This means that such a framework should ensure **interoperability of these systems**.
- In line with the above assumption the ICT framework should consider a **distributed - and not centralized - approach to information sharing**. This means that stakeholders should share information using commonly agreed vocabularies and data structures.

The proposed model is presented below. And comprises two main pillars:

- The **business perspective**: this includes all "soft" commonly agreed aspects of the collaboration that provide the input for the modelling and operation of the VN-CDT.
- The **system perspective**, which includes the main usage scenarios for modelling and operation of the VN-CDT.

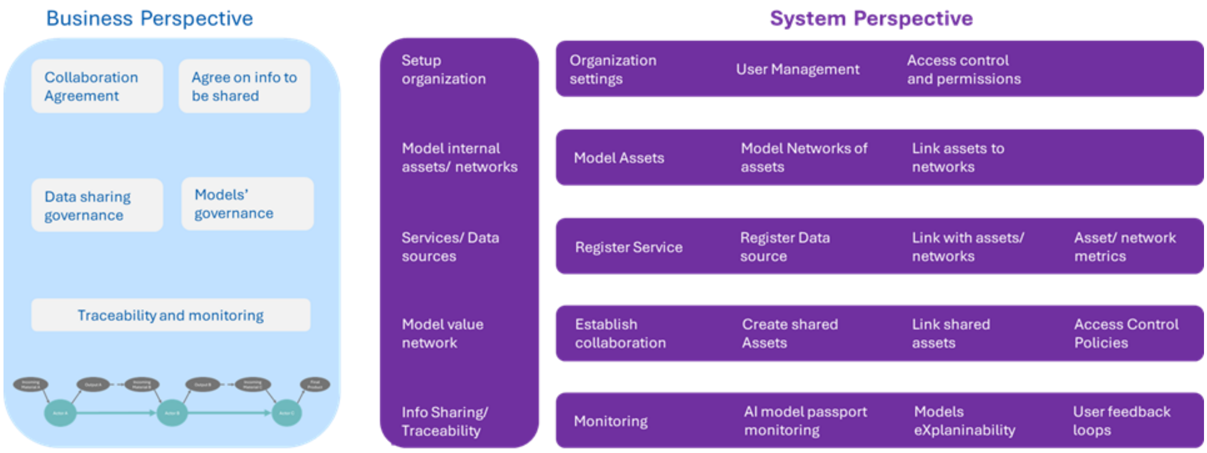


Figure 15: ICT Reference framework: from business to system modelling and operation

The main usage scenarios are detailed in the following sections.

4.3.2 Setup Organization

This is the organization configuration page. Here, each organization has its own instance of the VN-CDT solution and proceeds with the necessary settings for:

- Creation of the organization profile
- User management: Monitoring internal users, roles and permissions per user.

4.3.3 Model Internal Assets/ Networks

This usage scenario incorporates all necessary activities for modelling the organization's assets and operations/processes as CDTs. The difference between an asset and a network CDT is the following:

- By *asset CDT*, we refer to the entities, which represent the physical assets or a group of assets that we need to monitor.
- By *network CDT* we refer to the group of asset CDTs (or group of network CDTs) and their interactions within the network context.

As a reference case for the CDT model of an asset or operation, we propose the following information entities (in the manufacturing case).

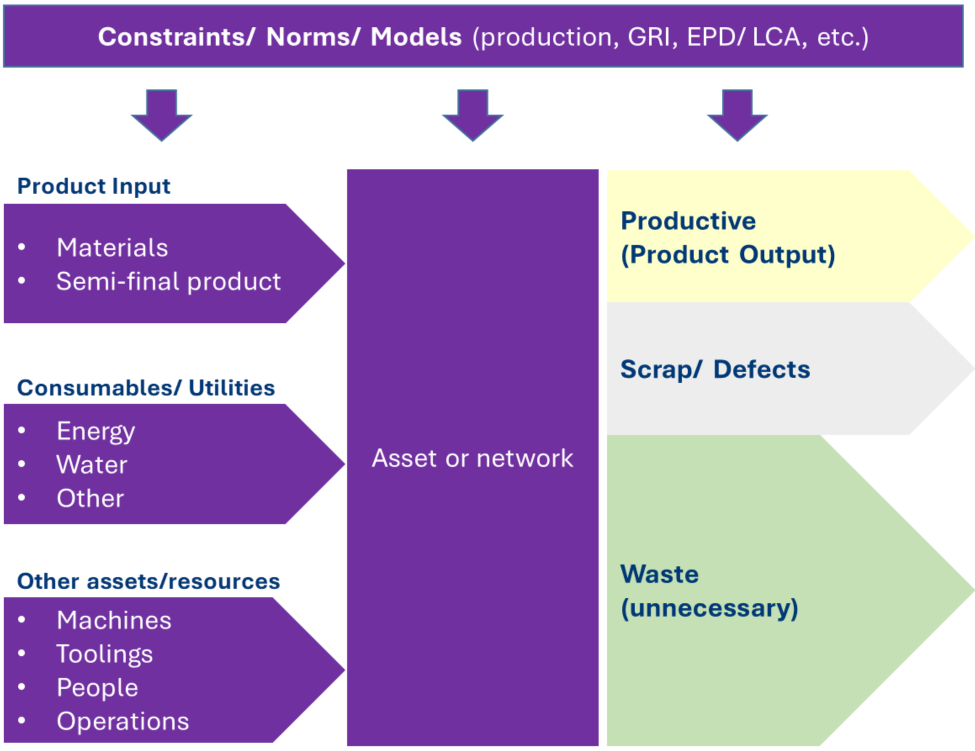


Figure 16: Modelling Asset or Network CDT (information entities)

Inputs:

- *Product Inputs*: Materials or semi-final products, which are used for the particular production step.
- *Consumables/ Utilities:* energy, water, soil, or other resources that are used or spent for the operation of the step.
- *Operational Assets:* these include the machines, toolings (tools associated or attached to the machine), people, and operations (design, logistics, etc.) responsible for the proper execution of this step.

Outputs:

- *Productive outputs*: are the expected (semi-) final products according to the quality specs.
- *Scrap/ Defects*: Failures/scrap in materials, semi- or final product. Defects can also be located in a machine or toolings.
- *Waste (unnecessary)*: is the waste of product inputs, consumables/utilities and assets/other resources which is caused by a defect/ failure in the inputs.

External factors: Are legal/ regulation/ norms or other constraints that impose rules of operation. Furthermore, they include any KPIs pertaining to production steps: environmental (e.g. Environmental Product Definition – EPD, Life Cycle Assessment - LCA), social (GRI guidelines), etc.

Using the entities mentioned above, we can moder an organization through various levels of hierarchy, starting from the shop floor and moving up to individual production lines, grouped lines, or the entire factory operation. (see example *in Figure 17*).

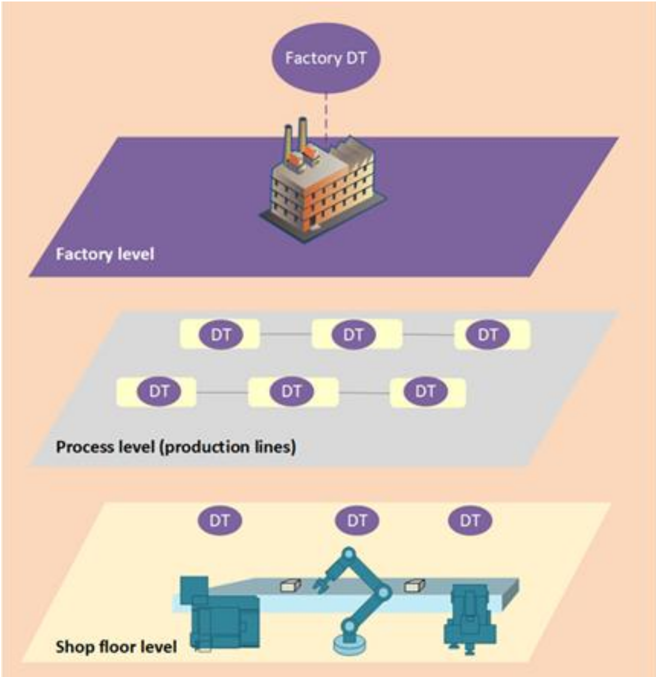


Figure 17: Intra-factory CDT modelling

In more detail, if we want to create a CDT profile in an application system, this will include the following attributes:

Entity	Description
Profile	Basic (descriptive) info about the asset and its behavior
Properties	Basic drivers that characterize the behavior of the particular asset: Some examples are: • *environmental:* incorporates all metrics that measure the environmental performance of the asset • *machine performance:* incorporates metrics that monitor the performance of the particular asset (operating times, daily shift, temperature of operation, etc.)
Metrics	Are measures that belong to properties and come from different information sources. Those metrics feed the asset CDT according to the cognition scenario illustrated in *Figure 10*.
Information sources	Here we define/ integrate the necessary information sources, which feed the particular asset's CDT metrics. These sources can be (indicatively): • Sensor data (e.g., temperature) • Data from specific services (e.g., predicted capacity of a machine)

Entity	Description
	• Data from existing solutions in the organization (SCADA, MES, ERP).
Services	Any service (cognition or not) that runs on top of the data used by the particular asset CDT
Location	Location of the asset

Table 5: Basic entities of an asset CDT

In a similar way, a network CDT has the following entities

Entity	Description
Profile	Basic (descriptive) info about the network and its behavior
Properties	Basic drivers that characterize the behavior of the network: Some examples are: • *environmental:* incorporates all metrics that measure the environmental performance of the network (e.g. energy spent in a particular production line per day) • *Operational:* incorporates metrics that refer to the operation of the network (e.g. daily production orders, total production cost).
Metrics	Are measures that belong to properties and come from different information sources. These metrics feed the network CDT according to the cognition scenario illustrated in *Figure 10*.
Information sources	Here we define/ integrate the necessary information sources, which feed the network CDT. These sources can be (indicatively): • Sensor data (e.g. an energy meter that shows the energy spent in the area where the production line is located) • Data from specific services (e.g. production scheduling) • Data from existing solutions in the organization (ERP).
Network graph	Is a process model of the network where we link the assets to the network. This is done through a workflow editor where we include the involved asset CDTs and their inter-relations within the network context.
Services	Any service (cognition or not) that runs on top of the data used by the particular network CDT
Location	Location of the network

Table 6: Basic entities of a network CDT

4.3.4 Monitor Services/ Data Sources

In this scenario we need to register and monitor all information sources that feed the asset or network CDT with data. The ICT solution should have a *service registry* where all information sources are located, monitored, and then assigned to the asset or network CDTs.

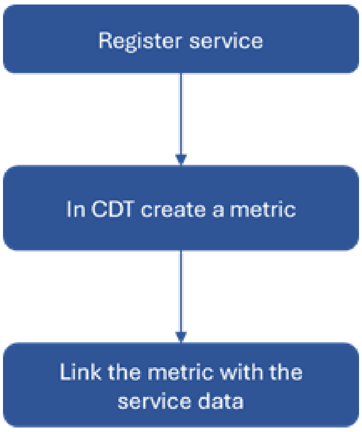


Figure 18: Registering services/ data source into Asset or Network CDT

After registering the services/information sources we need to link them with the CDT and the metric which will be fed into the CDT operation.

This is a very important step since we are defining how each metric will be fed with data by a specific information source.

4.3.5 Model Value Network

Once each organization is configured along with its internal assets and networks, we need to establish the value network CDT in terms of material and stakeholders' flows. The main steps are the following:

- **Establish collaboration** among the stakeholders.
- **Create shared assets**: Each organization creates a shared view of the asset CDTs (representing the materials that are flown in the value network).
- **Link shared assets**: Stakeholders are linked in the context of the network by linking output material (shared CDT) with input material (shared CDT).

In the following subsections we will present in detail the process for value network CDT modelling. We will provide the main workflows considering the case of two partners (partner A and Partner B). We also assume that these partners have their own internal systems.

4.3.5.1 Establish collaboration

Establishing collaboration is about agreeing on the business terms and principles for two stakeholders to work together. In line with the business collaboration principle (see governance framework on *section 4.2.2*), partners need to share principles, specifications, and they must have a record of each other in their respective systems.

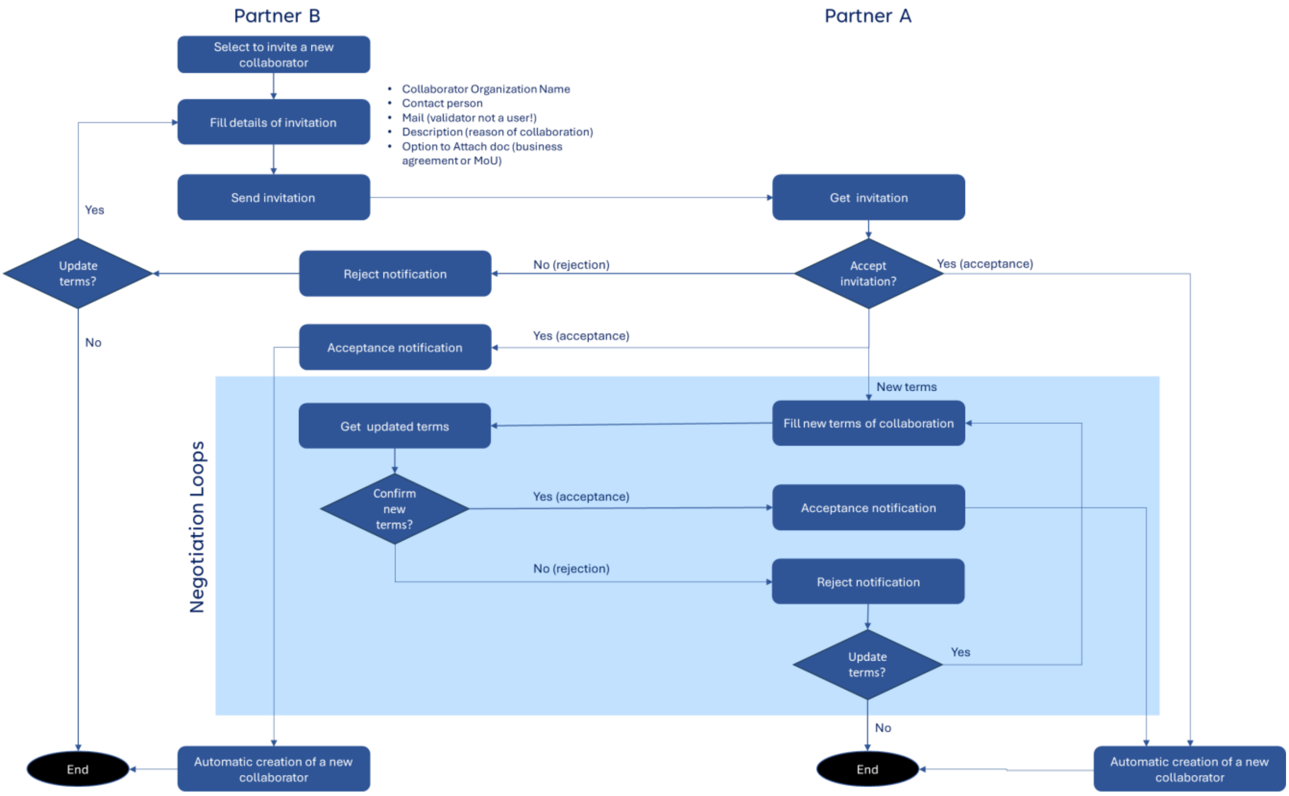


Figure 19: Establishing collaboration

As illustrated in the figure above, partner B wants to establish a new collaboration with partner A as the supplier. The process for this is the following:

- Partner B opens up a form in the system and puts all details of the collaboration including:
  - Identity information (profile of partner A)
  - A description of the collaboration including any terms, clauses, and goals to be commonly agreed.
- Partner B sends this form as an invitation to Partner A.
- Partner A receives the invitation and either accepts or rejects it.
- If the invitation is accepted, then the record of the collaborator is created in both systems.

There are also cases of various loops of negotiation (see highlighted box in *Figure 19*), where both partners A and B request new terms of collaboration. In such cases, both parties need to agree on them, and the process finishes either when there is an agreement (which means a new record of collaboration is created) or not (in such case, nothing happens).

4.3.5.2 Create a shared asset

The main link in value network is the input/output as illustrated in the materials flow. This means that organizations – once they model their internal assets/networks – should create a shared view of the asset that will be offered as an output to another organization. A shared asset is considered an asset only when specific permissions are granted to external organizations for access.

This is in line with the access control policies for all internal assets and operations which will be described in *section 4.3.5.3*. Each organization should have a specific repository of its shared assets in order to monitor:

- With whom do they share those assets.
- In which value networks these assets are shared and under which conditions/ terms.

4.3.5.3 Access control policies

Access control policies are very important and ensure that the pertinent information is shared to the appropriate stakeholders in the value network.

Dedicated permissions are given to the data which feeds the asset CDT. In line with the International Data Spaces and GAIA-X frameworks, each organization needs to create its own data space with other stakeholders by addressing the following:

- What data coming from the internal systems are generated within a particular CDT and are aggregated in the data space.
- Which of these data will be shared with other external stakeholders.
- How those data will be treated and check if there are dedicated permissions for use. (e.g. FAIR treatment. Specific rules may apply with regards to:
    - Duration of data usage
    - Constraints on data usage (how to process, ethics issues, etc.). Such constraints will be formalized in the contract agreement during the shared asset exchange (see *section 4.3.5.3*) as attachments or in the form of smart contracts.

Access control policies are given at the CDT level. This means that for a particular CDT, which becomes shared in a value network, these functionalities will lie on top of the CDT and apply only to this and to the value networks that they may refer to (we might have more than one value network in which the asset is shared).

4.3.5.4 Link shared assets

This is the main step for establishing a bilateral collaboration in a specific value network and the overall process is presented in *Figure 20*.

In this process, we have Partner B who needs an asset as incoming material for the value network. Partner B invites Partner A to “connect” the particular asset from Partner A and the latter accepts the invitation and assigns its shared asset to be connected in the value network.

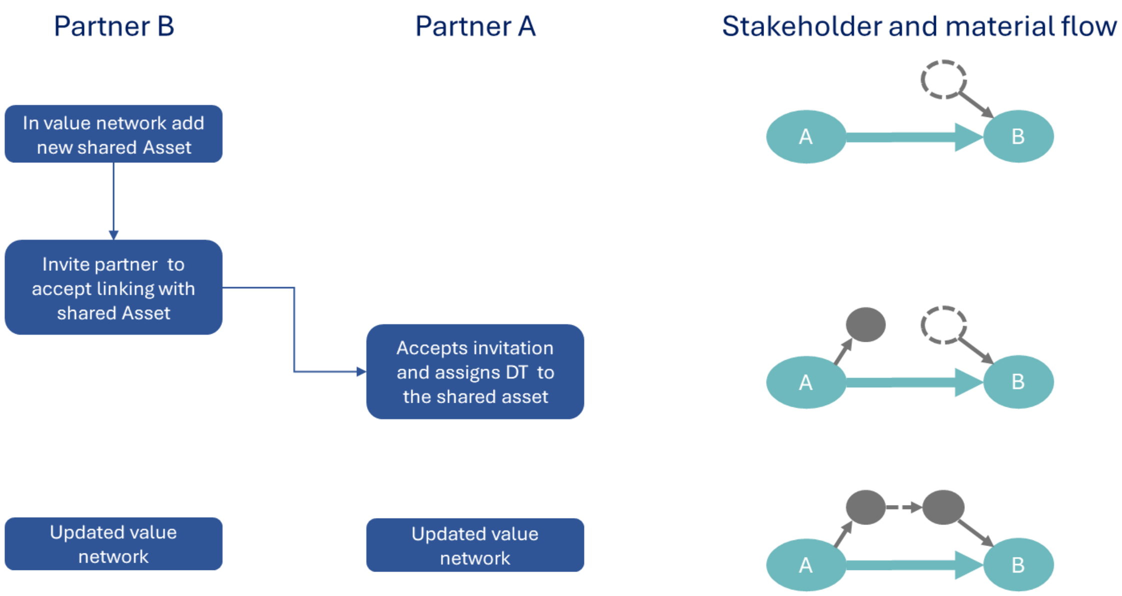


Figure 20: Linking shared assets in value network CDT (high-level view)

In more detail the activities for such connections are the following (*Figure 21*):

Partner B creates and sends an invitation

- Partner B creates a network CDT.
- Partner B assigns its shared asset CDT and relationship with the other stakeholder in the network.
- Partner B needs incoming material from Partner A. For this purpose, B chooses to create an invitation to A? about the particular asset need.
- Partner B selects the collaborator and fills in the details of the shared asset that need to be connected as "input" to A. These details can be:
    - A specific description of the asset.
    - The network details (code, name, description).
    - Terms of collaboration in the form of an attached document or textual description.
    - Any specifications/ thresholds for the asset to be connected.
    - The information/metrics to be shared from the external asset. Such metrics will come from Partner A's existing systems.
- Partner B sends the invitation.

Partner A receives the invitation and assigns the shared asset

- Partner A receives the invitation.
- Partner A accepts the invitation. In such a case partner A has to assign a particular internal shared asset in this invitation.
- Partner A assigns the necessary access control policies (see *section 4.3.5.3*) for the shared asset and for Partner B. This means that Partner A selects which information/metrics from the CDT will be shared and how through Partner B and for the network that they are connected to.

- Partner A sends the confirmation together with the shared asset info.

Negotiation loops

In processes such as this there can be also negotiation loops in which partners B and A propose alternative terms for the usage of the shared assets. These terms can be rules of usage or characteristics of the material/product (Asset DT) to be shared. This is a iterative process which might end in an agreement or a rejection and ultimately the termination of the shared asset process.

Partner A and B create the same instance of the shared network

Once an invitation is accepted and shared asset info shared, then:

- Partner A has a new entry in the list of shared assets (external shared asset that is input to A).
- In Partner A there is a new shared asset as incoming material in the material flow.
- Partner B has the option for the particular asset:
    - To create a new network CDT with the same network information received in the invitation.
    - To put in an existing network. This is the case where we link or merge different shared networks into an enlarged network (described in *section 4.3.5.5*).

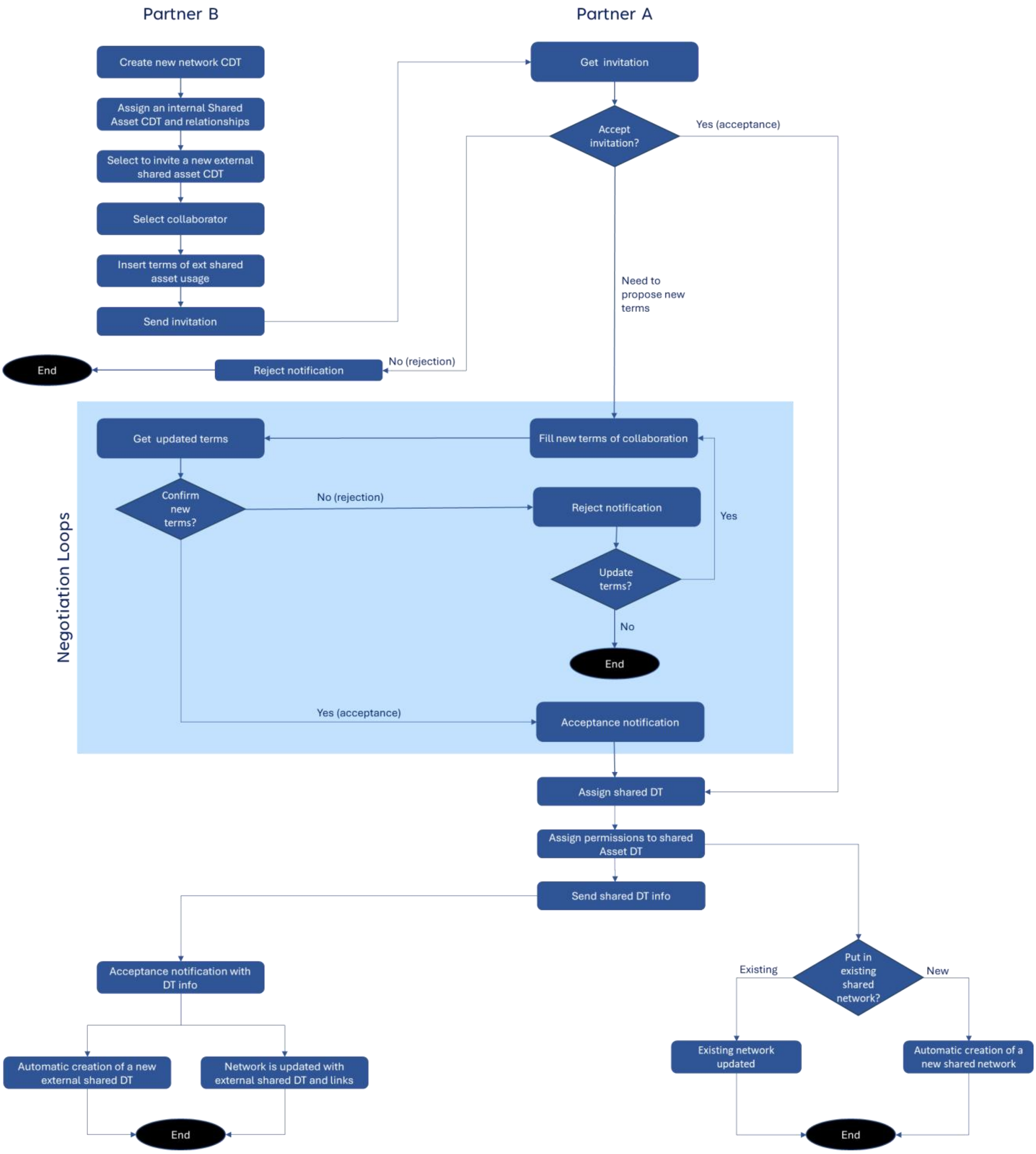


Figure 21: Detailed process for linking shared assets in value network CDT

4.3.5.5 *Linking different networks*

Another important aspect in value network CDT modelling is the complexity and scalability of the network. More specifically, we might have cases where some partners are already part of existing value networks and must be "merged" into an extended network. There are several reasons for which this can happen:

- Traceability of the whole value network (which is the result of merging activities)
- Specific services that need to understand the relations within the whole network. An

example can be an optimization service, where a waste material - depending on its characteristics - can go to different routes and paths inside the circular value network.

Let us take the example of Figure 22: We have partner B that is part of two networks:

- Network A->B with network id: A1
- Network B->C with network id: A2

Figure 22: Linking different network CDTs

In case Partner B wants to integrate these networks, it needs to be done in a way that the ICT solution will understand that A gives input to B and its output goes to C. This can happen in two ways:

- **Both network ids should be the same**: this is rather difficult since in a network of > 2 partners it requires that all partners must change the network id. The problem becomes bigger in cases of large value networks.
- **We create a linked code** in the merged value networks: this means that we keep the original id, and we establish a link to the value networks by a linked id. In our example B has value network id as follows:

Value network ID	Linked Network ID	Relationship
A1	A2	A1 gives input to A2 (A1->A2)
A2	A1	A2 gets input from A1 (A1->A2)

Table 7: Creating linked codes in value network CDTs

The concept of linked codes has an advantage as it does not require changes in different ICT systems; it is simpler and can be replicated to more complex value networks where we have either many nodes or multiple relationships as shown in *Figure 23*.

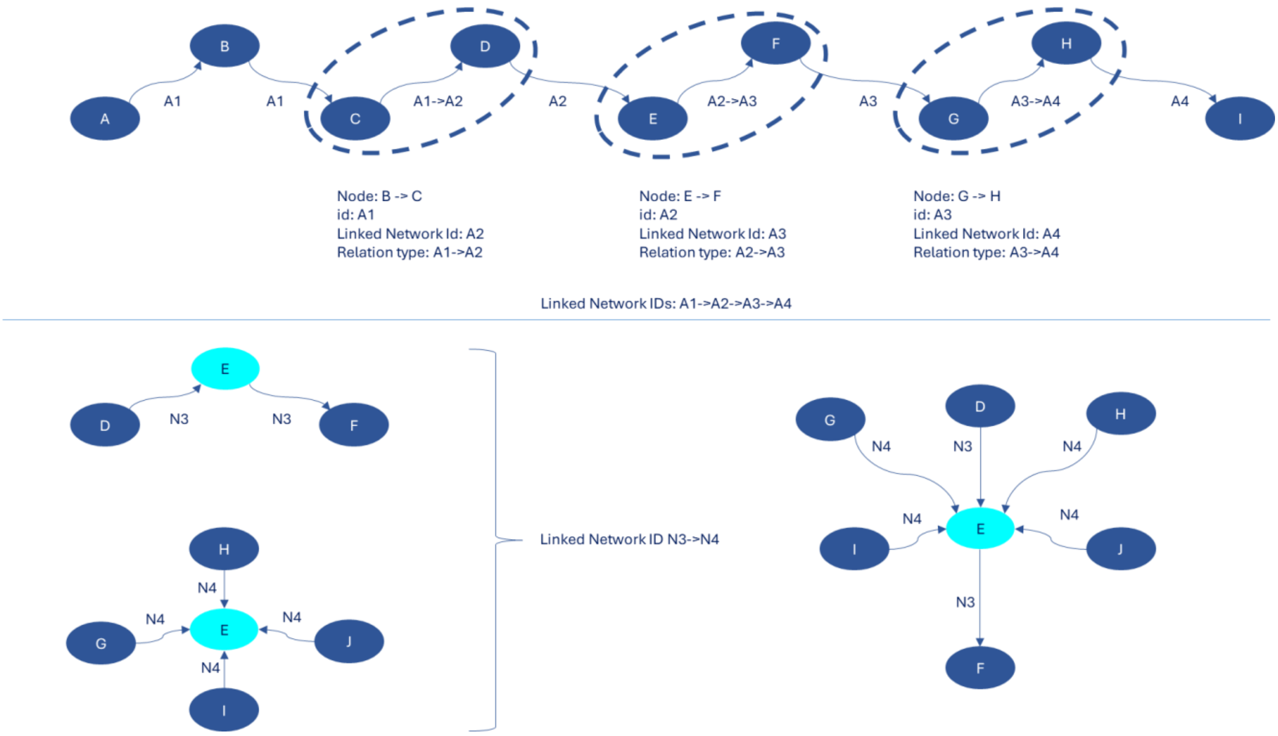


Figure 23: Example: Linking complex networks (linked networks IDs)

4.3.6 Information sharing in Value network CDTs

One of the most important aspects of connected value networks is information sharing. This is one of the main advantages of a value network CDT as it facilitates the execution of what-if scenarios and various services on top of the value network (simulation, optimization, traceability, etc.). Some examples are:

- Tracing the actual status of products in logistics processes (positioning, estimated time of arrival, other related information).
- Tracing (backwards) the final product characteristics and specific attributes along its value network. This is the case with the recently introduced Digital Product Passport (European Commission, 2022b) according to which the product has to provide information to the customers about specific characteristics from the whole value network.

In this section we will address how information can be shared among a CDT value network that is modelled as both stakeholder and materials flow (*Figure 7*).

We assume that the issue of interoperability in the assets CDT codes among the different ICT systems of the collaborative partners is resolved. In practice, this can be done through the following:

- A unique identification code based on the GS1 standard and its architecture for product traceability.
- Collaborative parties agreeing on common codes.
- Using the linked code approach in a similar way for the linked value networks.

We will examine the case of a value network CDT, illustrated in *Figure 24*:

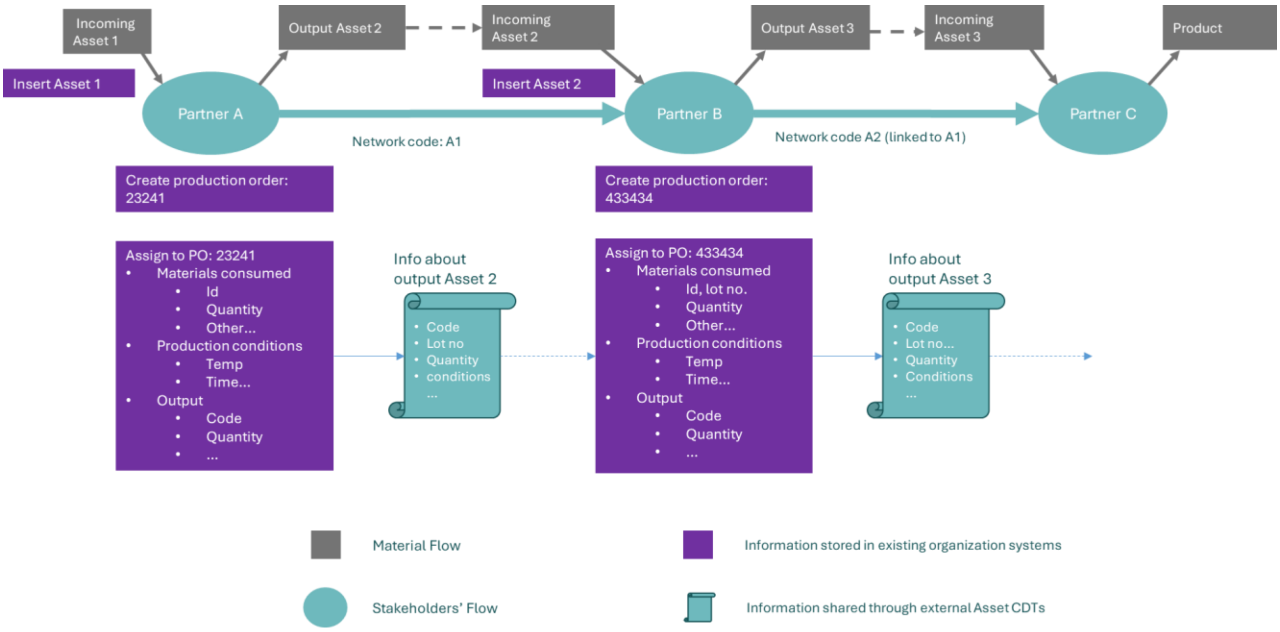


Figure 24: Traceability scenario in Value network CDTs

In this case we have information that is monitored in each partner (organization) system. Currently the way that information is sent and handled in each organization is the following:

- Information about incoming material is sent through an associated documentation (e.g., by document dispatch or similarly).
- A person is entering (manually) this information into the existing application (ERP or similar).
- The material is stored in the warehouse.
- For a specific production line there is always a production order which in principle describes the following:
    - Code of product to be produced.
    - Production phases.
    - Bill of materials (which material and how much is needed in each of the production steps).
- In each phase of the production – and for the specific production order - the following information is recorded (either automatically through sensors or SCADA, MES system or manually)
    - Material consumptions (what and how much).
    - Production conditions (e.g., temperature, shock levels, humidity, operation times).
    - Output produced (what and how much).

With the use of a value network CDT the above process and information sharing is performed using the *concept of External Asset CDT and shared metrics*. This means that in our case each partner A has to extract the **agreed set of metrics and information** (following the process of the Shared Asset 2 CDT in *Figure 21*). Then as the Asset 2 CDT is shared between Partner A and B the information is sent through a messaging service to Partner B and is recorded automatically into its existing systems.

In a similar way, Partner B creates a production order, creates receiving partner uses the shared Asset 3 CDT with the right information to be sent to Partner C.

Following the above approach, we ensure the following:

- *Information is communicated among the partners* and according to the agreements made.
- *Traceability of the value network,* which is achieved in two ways:
  - First, at inter-organizational (network path) level, where knowing the network codes (A1 and A2 linked to A1) we know the material flow (i.e., the path along the value network).
  - Second, at intra-organizational level we can track the conditions and other information where a material (asset CDT) has been produced. Knowing the ID of the Asset CDT (either lot number or unique ID or linked code) the producer of the asset can query the necessary information from its internal systems, having in mind the unique identification code used for its production (i.e., production order).

With regards to data extraction, we have a very complex landscape of heterogeneous information sources at the intra-organizational level. These can vary from ERP, MES, Sensor data or other external systems which produce data about operational conditions and the asset itself. Interoperability in this case if a very know problem and we are adopting the paradigm of data spaces where each organization creates data spaces with its collaborative partners where they agree on the information to be shared, the correct data structures and access rights (those can also be part of the collaboration agreement).

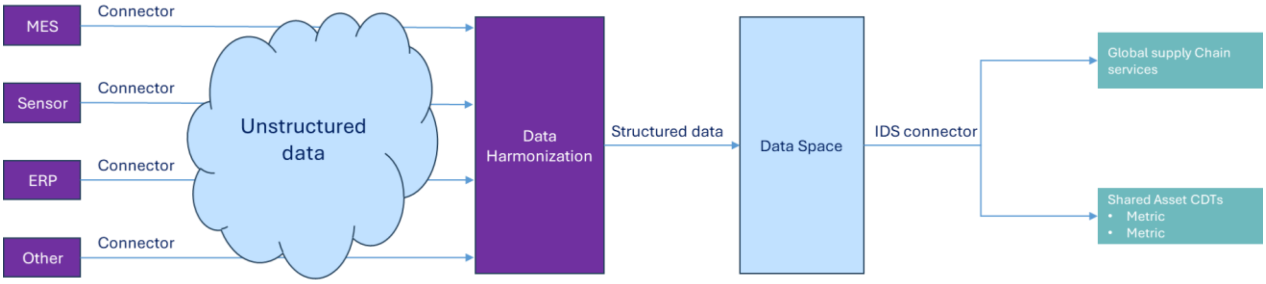


Figure 25: Sharing information through Data Spaces and External Asset CDT

As *Figure 25* depicts, using the data spaces, each organization is responsible for generating the data (with internal connectors) from the information sources and for storing them as raw data into a data lake. The organization also has to develop the necessary harmonization services (including cleaning) where information is converted to the desired structure/format to be used in the data space.

The above is an important assumption in organization and system interoperability. More specifically, it compels the organization to generate the data in the format that is commonly agreed. Then, the organization can create Data Spaces Connectors where these data (either raw or structured) can be shared with other organizations. Data Space Connectors can be developed using the reference framework and architecture proposed by IDS and GAIA-X (please refer to *section 3.2 - Governance in value network CDTs*).

The data that are exposed by the organization and defined following the access control policies, can then be integrated into specific asset metrics (please refer to the asset modelling approach in *section 4.3.3*), thus ensuring the continuous flow and data streams that feeds the Asset metric.

In addition to the shared asset metrics, data spaces can also be used in the case where a value network **has global services that require information from all involved stakeholders irrespective of their relations.** Some indicative cases are:

- An actor needs to understand the impact on the value network of a potential anomaly or deviation identified in the shared asset specifications (whether it is in line with the business agreement or not).
- We might have a case of material optimal flow identification. wherein this case we have value networks with different paths (stakeholder and material flows) and depending on the status of the asset the stakeholder needs to call for an optimization, simulation, or impact assessment service to identify the optimal forward path.

In conclusion, for the data sharing and information exchange governance we propose a hybrid approach, in which access control policies and rules of usage can be defined either at the **shared asset level** or the **data space** level. The main principles are the same, however they differ in implementation.

Both approaches are correct, and it is up to an organization to decide the optimal path. For example, for an organization that has an ICT platform that monitors internal asset operations and external value networks, it is more convenient to use the **shared asset permission-based approach** as there is only one point of defining rules of information sharing. Having a shared asset, the organization can also use it for any internal process where it describes in more detail how the incoming material is used to produce the desired output.

If the organization has no software for monitoring internal assets and processes, then the **data spaces approach** is more convenient as the organization publishes a set of data with rules that is accessible to other stakeholders.

The following table illustrates the potential usages for each of the models above.

<table>
<tr><th>Data governance</th><th>Governance principles</th><th>Applications</th></tr>
<tr><td>Data spaces</td><td rowspan="2">In line with IDS and GAIA-X framework</td><td>• Where we have global services on top of value network CDTs
• For organizations that do not use any solution to monitor internal assets/ operations</td></tr>
<tr><td>External assets</td><td>Where an organization also monitors internal assets/ operations and integrates external Asset CDTs into internal operations</td></tr>
</table>

Table 8: Data spaces and shared external asset usage in info sharing

4.4 Reference Framework Application areas

Our reference framework as described in the above sections is easy to be used in different contexts as it ensures:

Modularity: we can model internal organization processes and value network CDTs with different complexity levels.

Configurability: we have provided the necessary configuration entities (e.g., how to model an asset or operation as a CDT in section 4.3.3) which can include any type of information and parameter that can be used in different cases/domains.

ICT Agnostic: the ICT reference framework is not bound to any technology. Rather, it incorporates a more "agnostic approach". This means that all ICT scenarios/storyboards can be used by any software solution in the design and implementation of a new functionality for modelling and monitoring the operations of value network CDTs.

The model is also applicable to many manufacturing and value network scenarios. Indicatively we mention the following:

Optimizing Material Flows in Circular Value networks

Circular economy is becoming increasingly important, and many initiatives have been launched in cities, 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 value network (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 networks and factory planning. A more detailed case is presented in the reference case study in section 5.

Virtual Value network Production Lines

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

Optimize Material Flows in the Value network

This situation deals with the logistical elements, focusing on optimizing the flow of products from the factory (deliveries) and the incoming materials. This leads to enhanced demand forecasting and coordinated planning. (World Manufacturing Forum, 2020).

We can model all involved actors (LSP, origin supplier, factory and other external LSPs) as CDTs that 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 for optimal solutions to minimize delivery 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 extends beyond each CDT status.

Localization: Ad-Hoc or Constant Collaborations with Local Manufacturers

One of the key factors for resilience in value network 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) (European Commission, n.d.) 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 behavior and in such simulation scenarios, we can assess the behavior of the network.

In the short term, we can also have ad-hoc decision making for a specific part that is not in the production pipeline (e.g., for 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.

Manufacturing as a Service/ Re-configurable value networks

In a broader sense of the localization, we have Manufacturing as a Service model, where organizations can create an ad-hoc collaboration with an external partner and reconfigure the value network. in such cases, organizations can digitize and servitize their manufacturing processes, with mechanisms to supervise resource matching and service composition to be indexed by others and establish collaboration for a particular problem (e.g. product configuration, redesigning the value network to deal with disturbances, etc.)

Through our approach, a company can augment machine utilization, product availability as shared assets, introduce sharing of resources to create products in a sustainable manner, and support resilience in value chains.

5 Pilot Study: Magnet Circular Value network

In this section we will implement the solution framework described in section 4 in a value network where different stakeholders are connected to transform WEEE into bonded magnets (pellets) and then use the pellets to produce magnetic products.

All findings in this section have been the output of Plooto Horizon 2020 research project

Plooto

Product Passport through Twinning of Circular Value Chains - *European Union's Horizon 2020 research and innovation programme under grant agreement no. 101092008*

5.1 Case Description

5.1.1 Background

There is a rapidly increasing demand for permanent magnets (PMs) in modern technological applications with a 7% annual increase, mainly boosted by electric vehicles and green energy technologies. One of several processes for making magnets is the injection in magnetic plastic. Injection molding is a method employing a polymer as a solid blinder plus the magnetic material. Plastics are first assembled in an injection unit and then injected into a high-pressure mold. When the mold is cooled, the liquid plastic solidifies and can be removed from the mold. With this technique, millions of magnets in a wide variety of shapes can be produced in an automated way.

This type of magnet production typically makes use of Neodymium Iron Boron (NdFeB) as a raw material. Neodymium is a light rare earth element (REEs) and is vital in building magnets for motors and in many other applications. The main global supplier of Nd is China (86% of extraction and 99% of processing). The produced magnets can serve the production of a wide range of magnetic solutions for industrial magnetic systems (e.g., magnetic filtration, recycling, transport systems), electromagnets and electrical systems with applications in sectors such as automotive, electronics, motor and wind energy, aeronautics, medicine, recycling, mining, robotics and building. At the end of life of these products, magnets and motors become part of what is known as Waste from Electrical and Electronic Equipment (WEEE).

5.1.2 Overview

Our case focuses on a circular value network, aiming at increasing the reuse of NdFeB and Strontium-ferrite (Sr-ferrite) permanent magnets (PMs), recovered by WEEE from magnet products.

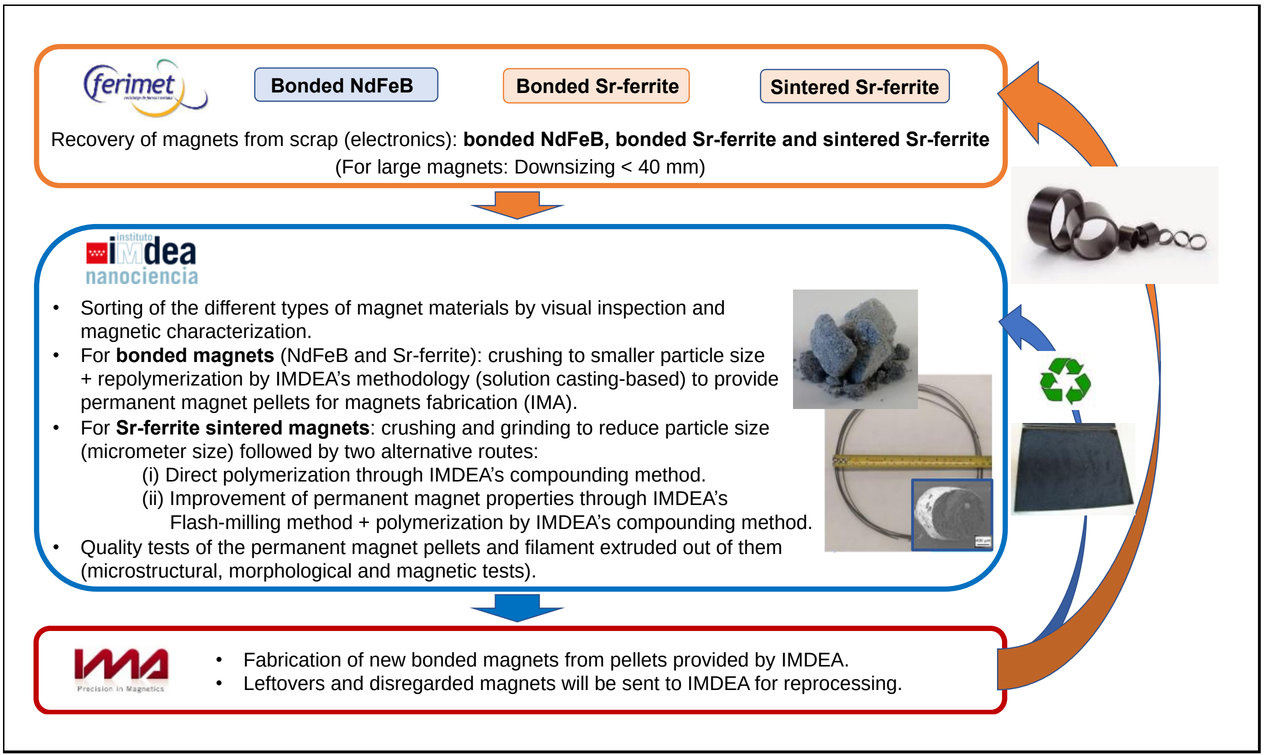


Figure 26: the process for WEEE transformation to permanent magnets

The possibility to recover NdFeB PMs from WEEE brings many competitive advantages such as a decreased dependency on other countries for the obtention of Nd (a rare earth element, i.e., a critical raw material) to manufacture magnets in Europe, the obtention of a competitive secondary raw material source and the valorization and reduction of WEEE landfilled. Given the unstable prices of rare earths over recent years, and together with the improved design of devices by manufacturers making possible the substitution of NdFeB magnets by ferrites in more and more applications, Sr-ferrite magnets have received a renewed interest from both the scientific community and industry, including magnet manufacturers and end-users from automobile, renewable energy technologies, home appliance and electronics.

Nowadays WEEE arrives mixed and crumbled. After arrival, different processes are applied to sort ferrous and non-ferrous materials. However, the Nd found in the different electrical motors is currently not recovered. IMDEA has developed a method for recycling permanent magnet residue resulting from the manufacture of PMs at an industrial plant (Bollero et al., 2017), which allows the recycled powder to be used for the fabrication of injected magnets. Additionally, application of IMDEA's self-developed methodology (flash-milling) (Bollero A. et al., n.d.) to ferrite recycled powder has been demonstrated to increase the PM properties well beyond those of the brand-new-commercial powder, thus creating the possibility of fabricating an improved permanent magnet material. As for the fabrication of PM/polymer composites for injection, IMDEA has developed a state-of-the-art scalable solution-casting method, successfully applied to diverse permanent magnet materials (including NdFeB, ferrite and MnAlC) (Palmero et al., 2018). **This method allows the possibility of using solution-casting in the preparation of a PM/polymer compound with a very high load of PM content (above 90 % PM content) to be used for injection and extrusion.**

The above requires:

- accurate and reliable data concerning composition, quantity available and cost of the recovered PM material,

- an increase and optimization of the use of the secondary raw material in the magnets production from the magnets' producer perspective (IMA).

From the recycling plant perspective (FERIMET, IMDEA), it needs intelligent systems providing recommendations and supporting decision-making tailored to the diversity of motors and magnets found in WEEE to select which elements from WEEE are technically and economically worth processing to extract Nd with conventional methods.

5.1.3 WEEE to magnet products transformation process description

The underlying scenario includes a magnet production process (IMA) from PM pellets, extracted through a recycling process (IMDEA) of bonded (NdFeB and Sr-Ferrite) and Sr-Ferrite sintered magnets recovered (FERIMET) from scrap, i.e., electrical motors or similar components. The whole transformation process is presented in *Figure 27*.

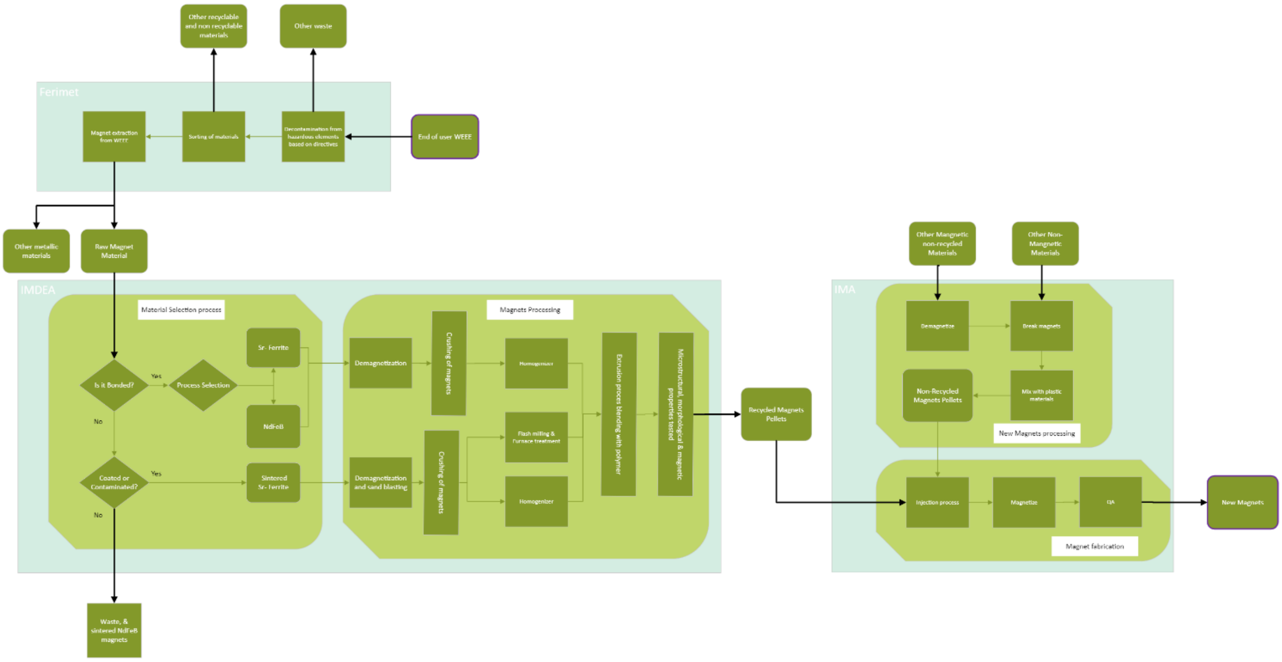


Figure 27: Detailed process for WEEE transformation to magnet products

The need is to create CDTs for each of the processes involved, such as processing WEEE to extract PMs, recycling bonded (NdFeB and Sr-Ferrite) and Sr-Ferrite sintered magnets, manufacturing bonded magnets (IMA) by fabricating new ones and re-processing disregarded ones, in order to connect the secondary raw material supplier (FERIMET) with the raw material consumer (IMA) while continuously assessing and evaluating the various steps in recovering PMs from WEEE using conventional methods. In more detail, WEEE processing CDTs will select the more profitable components and equipment from WEEE to extract magnets, assessing different options e.g., the use of Hyperspectral Cameras or the use of magnetic sensors that can identify which components contain magnetic materials. **Once the potential WEEE component is selected, WEEE processing CDTs will support the extraction of the magnetic component from its housing**. Motors and magnetic components can be found in many ways in many different types of electrical and electronic equipment. Different automation strategies with available technology for a mechanical extracting process of the magnets will be assessed for different kinds of electrical and electronic equipment, and once the magnetic component is accessible it will assess its composition in Ferrite and NdFeB PMs and recover both separately and once the NdFeB component is recovered, the recycling CDT will process the crumbling to powder in a controlled atmosphere so as to prevent oxidation of the magnetic material and to become a suitable raw material in IMA manufacturing process CDT. In the case of ferrite, the complete process can be carried out in air.

The orchestration of the above CDTs will support the traceability and certifications concerning policies and processes (e.g., determining whether the recycling technology does what it is supposed to do) as well as outcomes and products (e.g., certifying the origin of the NdFeb PMs) and will lead to the provision of a magnet passport containing all information on raw material composition, origin and standards.

Cognition services within the process CDTs include predictive and prescriptive systems to provide automated **support to FERIMET's decision on whether to recover or not WEEE magnets depending on each electrical and electronic equipment**. The developed tools will use integrated sensors (hall sensors, multispectral cameras, etc.) in the recycling plant together with external data from material prices and demand to establish the total revenue obtained from extracting the neodymium. A forecast of the expected amount of neodymium, to be obtained over a defined period (each week, month, etc.), will be shared with interested customers. **As a part of collective cognition, the CDT federation will allow potential customers to set procurement orders in time for the moment in which a new batch of neodymium is available for delivery**. This process will **increase the circularity index of WEEE**.

Last, in line with the new EU Digital Product Passport, there is a need to ensure traceability and information sharing along the value network in terms of specific information.

5.2 Implementation approach

Given the above case and needs, we will proceed with the configuration of our proposed framework by:

- Modelling the value network CDT (stakeholder and material flows)
- Understanding the information needs
- Defining the applicable governance principles

5.2.1 Value network CDT modelling

To begin with our modelling approach, we need first to clarify the main flow and involved stakeholders. This is presented in *Table 9*.

Stakeholders	Process	Roles
FERIMET	WEEE Magnet Extraction	Starts the recycling value network. Receives WEEE to extract the magnets present in different components.
IMDEA	Magnet Pellet production	Transformation of the raw material (extracted magnets) into a secondary product (pellets).
IMA Magnets	Magnet production	Transformation of the secondary product (pellets) into the final product (new magnets).

Table 9: Value network stakeholders and flow description

Therefore, we have three main assets (materials or products) that are processed and shared in the value network (*Figure 28*):

- **WEEE**, which in our case are the starting point and may come from different organizations.

- **Extracted Magnets**, which is the outcome of FERIMET and incoming material for IMDEA
- **Magnetic Pellets**, which are the outcome of the IMDEA transformation process and are used as incoming material to IMA
- **Magnetic Product,** which is the final product from IMA.

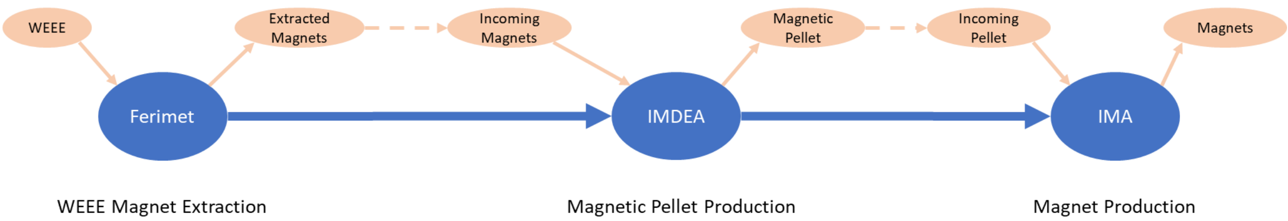


Figure 28: VN-CDT Model: Materials and Stakeholders' flows

The next step is to define the necessary configurations for assets or networks, following our approach in *section 4.3.3*. *Table 10* presents the overall modelling configuration, for an ICT solution on value network DTs where for each step (entry in the solution) there are two concepts:

- Network/Asset: Means that the particular entry in the configuration table is characterized as an:
  - Asset, i.e., a material or a particular step in the process.
  - Network: Representing the whole operation of a particular stakeholder.
- Shared or private: is whether the entry is monitored at the intra- (private) or Inter- (shared) organization level.

Step or material	Stakeholder	Network/ Asset	Name	Shared or private	Type
FERIMET (from WEEE to extracted magnet)					
WEEE	FERIMET	Asset	WEEE	Private	Material
Magnet Extraction from WEEE	FERIMET	Network	Magnet Extraction from WEEE	Shared	Operation
Classification/ Extraction	FERIMET	Asset	Classification/ Extraction	Private	Operation
Extracted Magnet	FERIMET	Asset	Extracted Magnet	Shared	Material
IMDEA (from extracted magnet to magnet pellet)					
Incoming magnets	IMDEA	Asset	Incoming extracted magnet	Shared	Material
Magnet Pellet Production	IMDEA	Network	Magnet Pellet Production	Shared	Operation
Material selection	IMDEA	Asset	Material selection	Private	Operation
Bonded material	IMDEA	Asset	Bonded material	Private	Material
Coated or contaminated	IMDEA	Asset	Coated or contaminated	Private	Material

Step or material	Stakeholder	Network/ Asset	Name	Shared or private	Type
Demagnitizer	IMDEA	Asset	Demagnetizer	Private	Operation
Crushing	IMDEA	Asset	Crushing	Private	Operation
Homogenizer	IMDEA	Asset	Homogenizer	Private	Operation
Extrusion	IMDEA	Asset	Extrusion	Private	Operation
Morphological and microstructural testing	IMDEA	Asset	Testing	Private	Operation
Magnet Pellet	IMDEA	Asset	Magnet Pellet	Shared	Material
IMA (from magnet pellet to magnet product)					
Incoming pellet	IMA	Asset	Incoming pellet	Shared	Material
Magnet production	IMA	Network	Magnet production	Shared	Operation
Magnet	IMA	Asset	Magnet	Private	Material

Table 10: Modelling shared and internal assets processes in the value network

Having the above configuration needs, we can proceed to the rest of the actions in the modelling of the value network CDT as mentioned in *section 4.3.5*. Table 11 shows the different entries in each stakeholders' ICT solution.

VN-CDT Modelling Step	FERIMET	IMDEA	IMA
Collaboration establishment (*section 4.3.5.1*)	New Collaborator: IMDEA	New Collaborators: IMDEA, IMA	New collaborator: IMDEA
Create shared asset (*section 4.3.5.2*)	New **outgoing** shared asset: *Extracted Magnet*	New **incoming** shared asset: *Extracted Magnet* New **outgoing** shared asset: *Magnet Pellet*	New **incoming** shared asset: *Magnet Pellet*
Access control policies (*section 4.3.5.3*)	See Governance configuration in *section 5.2.3*		
Link shared assets (*section 4.3.5.4*)	Linked shared asset: **Extracted Magnet** • Owner: FERIMET • User: IMDEA	Linked shared asset: **Extracted Magnet** • Owner: FERIMET • User: IMDEA Linked shared asset: **Magnet Pellet** • Owner: IMDEA • User: IMA	Linked shared asset: **Magnet Pellet** • Owner: IMDEA • User: IMA

VN-CDT Modelling Step	FERIMET	IMDEA	IMA
Linking different networks (*section 4.3.5.5*)	**Network id: A1** FERIMET -> IMDEA	**Network Id: A1** FERIMET -> IMDEA **Network id: A2** Linked Network id: A1 IMDEA -> IMA	**Network id: A2** IMDEA -> IMA

Table 11: Configuration entries in the stakeholders for the magnet VN-CDT

5.2.2 Information sharing needs and Digital Product Passport

Having all the VN-CDT configuration details, we need to understand and model the information sharing needs. The main drivers in our value network are the following:

- The need to share the necessary information between the collaborating parties about the shared asset (outgoing-incoming material). This is mainly for internal purposes, with a focus on how to make the best use of this product from the quality (e.g. selection of different paths based on the type of magnet received in IMDEA) and the operational point of view (e.g. understanding magnetic properties and configuring the optimal parameters in the bonded magnets transformation steps at IMDEA).
- The Digital Product Passport. This will define the information to be visible from the end point of the value network (i.e., IMA) and some of the datasets will come from the previous WEEE transformation processes and stakeholders.

5.2.2.1 Shared Asset information

For the first case, the following information is needed from FERIMET to IMDEA and from IMDEA to FERIMET.

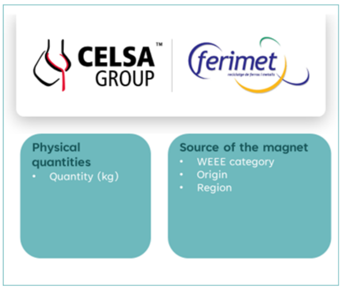
Data	Type and metrics/units	Owner	Source	Used in
FERIMET -> IMDEA				
Type of Material	Type: Text • NdFeB • Sr-Ferrite	-	FERIMET	IMDEA, IMA
Quantity of raw magnet material	Type: Number Unit: Kg	-	Ferimet	IMDEA
Origin	Type: Text Values: • white appliances • engines • WEEE	-	Ferimet	IMDEA

Data	Type and metrics/units	Owner	Source	Used in
IMDEA -> IMA				
Type of Material	Type: Text • NdFeB • Sr-Ferrite	-	FERIMET	IMA
Quantity of pellets	Type: Number Unit: Kg	IMDEA	IMDEA	IMA
Physical properties	Dimension of the pellets (shape, length, weight)	IMDEA	IMDEA	IMA
Magnetic properties	Remanent magnetization (emu/g), Coercivity (kOe), strength of magnet $(BH)_{max}$, (kJ/m^3)	IMDEA	IMDEA	IMA
Chemical properties	Chemical composition and corrosion resistance of the pellets.	IMDEA	IMDEA	IMA

Table 12: Information sharing overview

5.2.2.2 Digital Product Passport and Information Sharing needs

The digital product passport envisaged for this value network contains the following information from all involved stakeholders:



PARAMETERS	UNITS (S.I.)/ text
Physical Quantities	Quantity
Source of the magnet	• WEEE Category (Nd or FeB) • Origin (supplier) • Region of origin

Material Safety Data Sheet (MSDS)

PARAMETERS	UNITS (S.I.)/ Text
Material Name	Nd or FeB (FERIMET)
Polymer Base	%wt
Magnetic Powder	%wt
Magnetic Properties	
• Br	T
• Hc	kA/m
• BHmax	kJ/m³
Material density	kg/m³
Maximum Temperature	ºC
Personal Protective Equipment	EPIs (Safety needs)
Temperature to Decompose	ºC

Data Sheet (MSDS)

PARAMETERS	UNITS (S.I.)
Required drying time	s
Pre-drying Temperature	ºC
Maximum Temperature	ºC
Temperature to Decompose	ºC
Temperatures for each injection zones	ºC
Temperatures nozzle	ºC
Required time for each injection zone	s
Required time wait before open the mold	s

PARAMETERS	UNITS (S.I.)/ text
Informative message	"In order to improve the sustainability of the magnets, IMA is using magnetic material recovered from different EOL WEE. In this magnet contains magnetic materials from different recycled sources."
% wt of recycled material	%wt
Source of the magnet	Nd or FeB (FERIMET)

Figure 29: Decomposition of the DPP from end point to origin

The DPP will be included in the lot number of each shared asset. This means that the tagging method for the material flow will be the lot number.

As can be seen, the common information along the value network is the type of magnet material (Nd or FeB) that is shared among the three stakeholders.

5.2.2.3 Traceability through the VN-CDT

In this section we will configure the information to be shared through the external assets. The basic configuration setting for the shared assets is the following:

Shared asset Name	id	Linked id	Tagging method
FERIMET			
WEEE	WEEE	-	N/A
Extracted Magnet	Extr-Magnet	-	Lot
IMDEA			
Incoming extracted magnet	Extr-Magnet	-	Lot
Magnet Pellet	Mag-Pellet	-	Lot
FERIMET			
Incoming pellet	Mag-Pellet	-	Lot
Magnet	Magnet	-	Lot

Table 13: Shared Asset codification and tagging methods

For the sake of simplicity, we made the following assumptions:

- We consider that the codification of incoming and outgoing assets is the same, which means that there will be no linked ID in the asset code.
- The tagging method is the lot number

Figure 30 shows the flow of information sharing among the external assets in the stakeholders' and materials flow. We have added the "system" entity to illustrate how this information is stored in a value network DT solution.

The detailed data tables for information monitoring per production asset and materials that support the flow below are presented in *Annex A*.

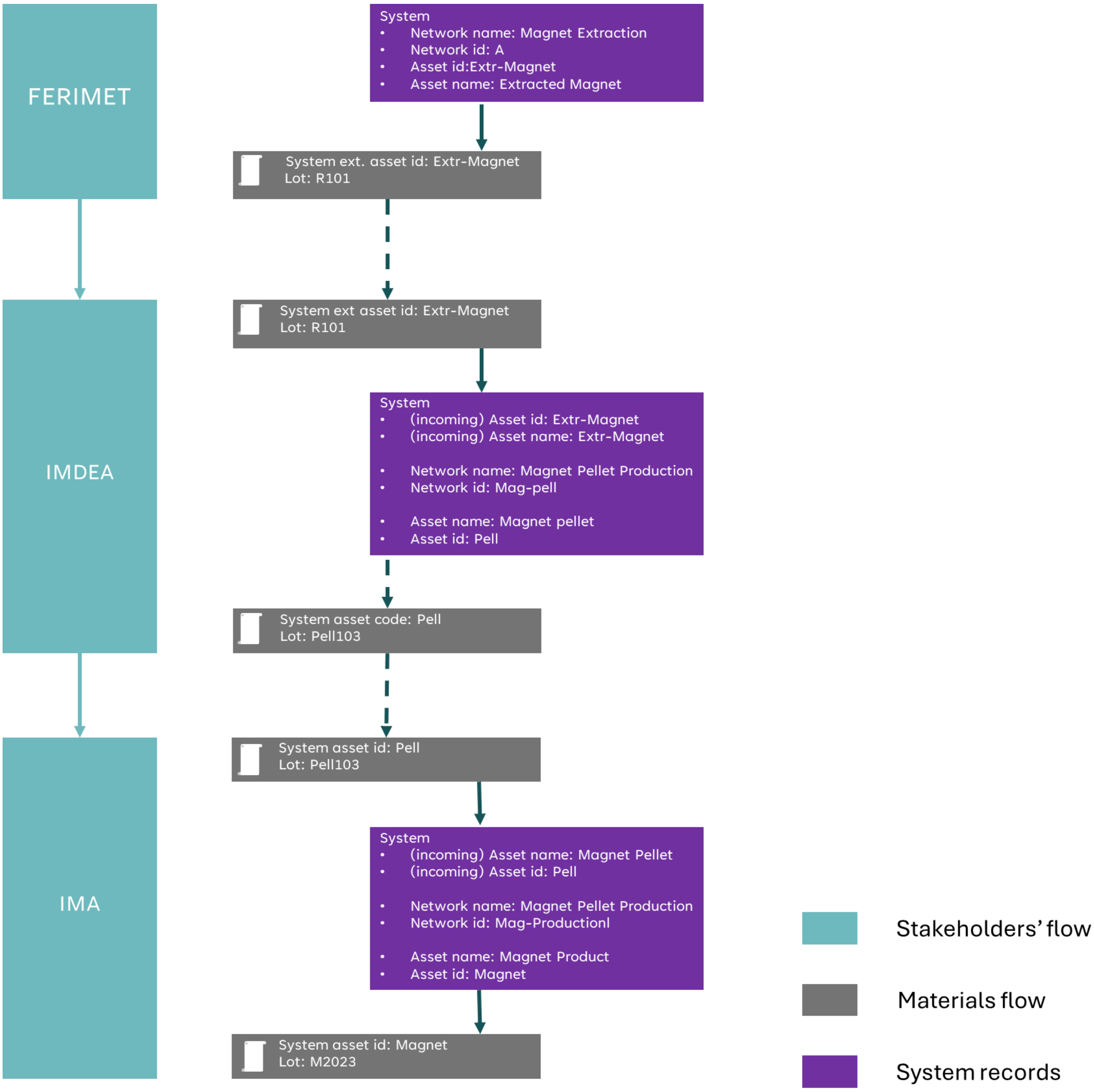


Figure 30: Digital Product Passport information sharing in the circular magnet value network

Based on this flow, the operational and system steps are the following:

FERIMET

Magnet extraction from WEEE by FERIMET

Operational Step #1: Magnet Extraction - Create *production order ID: WEEE-06* (From ERP)

System gets data sources/ telemetries (from sources)

- Production conditions (sensors, time,....).
  - Timestamp

  - Production ID
  - Conditions
- Material ID consumed.
  - Timestamp
  - Production ID
  - Conditions

System stores them as data sources/telemetries in network ID "**A**".

Operational Step #2: Create outgoing Asset lot and DPP

System creates a DPP for the asset "Extracted Magnet" with info:

- ID: Extr-Magnet
- Lot: R101
- Textual descriptions
- Telemetries referenced to the order ID from which the *Lot ID: R101* is created

System already has the link between *Lot: R101* and *Production ID: WEEE-06*

IMDEA

Magnet Pellet is generated by IMDEA

Operational Step #1: Material receipt: Record incoming material ID (manually, ERP, reader, ...)

System gets a DPP in shared *asset ID Extr-Magnet*

- Timestamp
- *Asset lot R101*
- DPP info of the *asset Lot R101*

Operational Step #2: Production - Create *production order id: Pell-2023-04* (From ERP)

System Gets data sources/ telemetries (from sources)

- Production conditions (sensors, time, ...).
  - Timestamp
  - Production id
  - Conditions (see Material Safety Data Sheet and Data Sheet in IMDEA DPP - *Figure 29*)
- Material ID consumed.
  - Timestamp
  - Production id

  - Conditions

System stores them as data sources/telemetries in *network id Mag-Pell*.

Operational Step #3: Create DPP

System creates a DPP for the *Asset id: Pell103* with info:

- Lot: Pell103
- Textual descriptions
- Telemetries referenced to the order ID from which the *Lot id: Pell103* is created

System has already the link between *Lot: Pell103* and *Production ID: Pell-2023-04*

IMA

Magnet Pellet is used by IMA to generate magnet product.

Operational Step #1: Material receipt: Record incoming material id (manually, ERP, reader,...)

System gets a DPP in Asset code M1

- Timestamp
- Asset Lot *Pell103*
- DPP of the Asset Lot *Pell103*

Operational Step #2: Production - Create *production order id: M-prod-2023* (From ERP)

System Gets data sources/ telemetries (from sources)

- Production conditions (sensors, time, ...).
  - Timestamp
  - Production id
  - Conditions (data measured for the sustainability: CO_2, see IMA DPP format in *Figure 29*)
- Material ID consumed.
  - Timestamp
  - Production id
  - Conditions

System stores them as data sources/telemetries in *Network id: Mag-Prod*.

Operational Step #3: create output: final product.

- Output Lot: M2023.
- Link ID with production order ID (in ERP or manually).

- DPP of the Asset *Lot M2023*

System already has the link between *Lot M2023* and *Production ID: M-prod-2023*

In summary, the main connection points between the modelled assets and networks are presented in *Table 14*.

Asset/Network Name	id	Lot number	Reference Production ID	Info to monitor
FERIMET				
WEEE	WEEE	-	WEEE-06	Quantity/type
Network: Extracted Magnet	A		WEEE-06	Production conditions
Extracted Magnet	Extr-Magnet	R101	WEEE-06	DPP
IMDEA				
Incoming extracted magnet	Extr-Magnet	R101	Pell-2023-04	Quantity/type
Network: Magnet Pellet Production	Mag-Pell		Pell-2023-04	Production conditions
Magnet Pellet	Mag-Pellet	Pell103	Pell-2023-04	DPP
FERIMET				
Incoming pellet	Mag-Pellet	Pell103	M-prod-2023-04	Quantity/type
Network: Magnet production	Mag-Production		M-prod-2023-04	Production conditions
Magnet	Magnet	M2023	M-prod-2023-04	DPP

Table 14: Overview of main connection points in magnet SC traceability

5.2.3 Applicable governance framework

In line with the Governance framework (*section 4.2*) the main elements to be configured are:

5.2.3.1 Business Collaboration

At the business collaboration we have all the agreements for the information sharing and DPP described above.

In any system this can be formalized with a contract (collaboration Agreement file) that is shared at two levels:

- The high level of collaboration among the two parties.
- Shared asset-specific collaboration agreement (information to be shared in the shared asset).

In both cases, when the agreement is finalized, we can transform it into a smart contract through a blockchain infrastructure, where all agreements will be stored and can be retrieved at any time by the collaborating parties.

5.2.3.2 Decision making at the CDT level

In our case apart from monitoring and information sharing functionalities, each partner in the value network has different cognition needs to optimize its performance.

For IMDEA the case is to have an optimal configuration of the internal extracted magnet-to-pellet process. This applies to the following steps in IMDEA (see *Table 10*):

- Demagnitizer
- Crushing
- Homogenizer
- Extrusion

Such a cognition functionality is realized through 2 different services:

- A b**ehavioural model** is established to enable continuous learning, in which various configurations can be achieved in the aforementioned steps based on the characteristics of the magnet extracted through the material selection process.
- An **optimizer**, where for a particular extracted magnet lot we will define the optimal configuration of the pellet production process (configurations in the four above cases). Such configurations have to do with defining the optimal set of parameters used in each phase. This is crucial because the setup relies heavily on the magnetic characteristics of the extracted magnet and the measurements obtained during the process selection phase (at the start of IMDEA where the extracted magnet is analyzed

5.2.3.3 Data and AI Model' Governance

For the data and model governance, we will extend the configuration matrix (*Table 10*), where for each asset and/or network we will define ownership levels and liabilities. The governance configuration matrices are presented in *Annex A*.

From a functional point of view, as the services are not "global" but run at local (asset CDT) level, we can define sharing principles at the shared asset level without a data space implementation. This means that when the asset is shared, an agreement (following the process in *Figure 21*) will be established among the collaborative partners.

6 Discussion

The evolution of value network digitization creates opportunities for new business and operational models. With the adoption of digital twin concepts, value networks can transform from isolated partners into dynamic, living networks sharing information and knowledge with mutual benefits for all involved stakeholders.

The principal idea of our approach is that value networks are **networks of inter-connected digital twins** with different levels of cognition. With this in mind, we are able to design various kinds of networks, such as value networks (consisting of connected DTs with a particular form or relationship) or even clusters of DTs that have no interaction with each other. The latter is also the case for smart cities where in a city context, different entities belong to, without having any formalized collaboration with each other. The core enablers or network CDT modelling are generic, which means that are applicable to any network formation. Of course – depending on the network particularities – in our modelling not all are needed; for instance, in our magnet value network we do not consider the edge/fog/cloud as critical; but there are cases where the value network actors should pay strong attention to. Let us take for example the case of a refrigerator; we might have a model where the smart fridge consists of critical parts and there is a need for each part to have a high enough level of cognition so as to understand the optimal point of withdrawal or maintenance (Kalaboukas et al., 2023). In this scenario, the processing power plays a crucial role in enabling decisions to be made at the individual component level, even when they are situated in distinct locations. In all value network cases, **governance** plays a very important role. But even with the current attempts at digitization the focus is on each individual organization as a separate entity. We proposed a new governance framework that encapsulates all stakeholders, not as isolated entities but rather as a part of a global virtual entity (value network CDT) in which they establish collaborations (stakeholders view) and share materials and information contained therein (material flow). In such a virtual entity and as material and information is shared at different levels/tiers, liability is critical. We have extended the traditional business collaboration with data and model governance. In a material flow (where materials are shared both as physical entities and as Digital Twins) the information of the material CDT is critical and must be shared in the right way with the right actors. Data Governance plays this role, and we have proposed a hybrid approach using widely accepted practices (Data Spaces) and inherited (at the shared asset level) access control policies.

Furthermore, data may come from a specific algorithm. AI model governance is very important, since it contains all aspects of liability, ethics considerations and FAIR principles, ensuring trustworthiness to the end users through explainability and feedback loops. Our approach to AI governance was also generic. We recognize that a value network can utilize different analytics, optimization or any other service that runs using, for example, an ML algorithm. We cannot limit the number of potential AI services applicable to value networks although we can consider some common elements (e.g., planning, forecasting, etc.) Therefore, we preferred to concentrate on the common needs (user centered explainability and trust) and based on these we defined the basic requirements to ensure a minimum level of trust in the data generated by a cognition service. It is up to the AI service provider to choose the appropriate method to ensure explainability and how the model will learn from the user. Our approach addressed the necessity that the end user comprehends and trusts a model (via the AI model certificate), enhancing it through feedback and user engagement loops. Finally, we have defined the **main ICT functional blocks and usage scenarios** to implement the concept of value network CDTs. A plethora of ICT solutions to support digitization already exists in the industry. However, most of them focus on optimizing internal operations and with small glimpse to interoperability and per case. It might be seen that we do not propose a concrete application solution; this is done intentionally because the author believes that this approach should be used by ICT companies to create new functionalities or solutions on top of existing applications. This means that we do not propose a new solution; rather a roadmap and architectural concepts to implement functionalities that can serve value networks operating in different domains with each one having their own characteristics. This roadmap was demonstrated in the magnet value network making use of the deployment approach (section 4.1.4) through the configuration files presented in *Annex A*.

However, the implementation of the proposed framework has some limitations/risks:

From a **business perspective**, the success of such an implementation is highly dependent on the commitment of the value network actors. This is a critical success factor, and all involved stakeholders need to put lot of effort into discussions, business agreements on the collaboration rules (i.e., the business governance) which will then give the principles for deploying the CDT concept in the whole VN-CDT and each separate CDT.

From an **ICT perspective**, there are some technical particularities. First, although it provides a comprehensive approach to information sharing, interoperability among the systems operated by all stakeholders is still an issue. In fact, there is not a unified codification system for materials/ products, which necessitates additional effort to map codes in shared asset CDTs. Many attempts have been made through standardization and other initiatives to develop vocabularies; yet the problem persists.

Further, we have assumed that information is extracted and structured in a way that is easily accessible by the collaborating parties. In practice, this is a more complex process and requires effort for data harmonization. Each organization has different systems that store data that might be needed for information sharing. Wherever data spaces or the shared external asset principle are used, the organization needs to ensure that the commonly agreed information is extracted from the systems and is available for sharing. This is not an easy task, and in some cases (where complex systems operate) it can also be time-consuming.

Lastly, this approach is novel and there are not **many reference implementations/cases** to understand its limitations and areas for improvement in practice. While this is justified by the novelty of the thesis, we still need to apply it to more value network cases, learn from them and improve our approach with new additions.

7 Conclusions – Future Research

Agility and resilience in value networks is becoming a critical factor for sustainability. Through CDTs we can model all entities in the value network and achieve collaborative monitoring, autonomous decision making and improvement through a reference cognition process.

In this thesis we have presented a holistic approach to the configuration and operation of CDTs in agile and resilient value networks. Our proposed model is built on the fundamentals of inter-connectivity, cognition, information sharing and governance of 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 value network context.

Our approach has many implementations; it addresses the need for agility and resilience due to the continuously changing environment that value networks operate within. Also, it is in line with the recent developments and trends in digital transformation and more specifically to circularity (reverse value networks and waste value chains), digital product passport and improved productivity/costs.

Deployment and operation of the model require collaboration at the design phase. All actors in the value network need to work together and agree on a very detailed configuration scheme addressing not only the cognition process, but also all enablers that support 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 crucial aspect is *change management*: the ability to re-engineer both intra- and inter-organization processes involving people, systems, reinforcing collaborative culture, supporting decentralizing decision-making and a mindset towards adaptation and improvement.

Future work on this topic will be on different aspects.

First, we need more implementations and lessons learnt. This will come through measuring the effectiveness of the model deployment in different value network contexts with quantitative KPIs. The evaluation targets need to be set on a per case basis. This means that different value networks 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 value network (early warnings, response times along the value network actors-CDTs), improvements due to the optimization model applied, etc. In addition, we will conduct a qualitative analysis to evaluate intangible factors like satisfaction, growth, and enhanced trust and cooperation among various stakeholders.

Secondly, research is needed on how to create improved mechanisms for data extraction and harmonization from existing systems and make them available through data spaces or shared asset data. Similarly, we need more work on the models' integration. For example, let's consider the scenario of a global network perspective, where decisions need to take into account the results from various services and AI models (e.g., predictive maintenance in one factory producer that affects the production planning in the interactive collaborator). This "global" view requires model alignment looking both at each CDT behavior as well as the aggregate (whole value network).

Lastly, we need research on the mechanisms for liability sharing and reputation schemes in CDT operation. The framework needs to be enriched with such concepts and how they can be materialized into ICT functionalities and usage scenarios.

References

A., S., & R., S. (2023). A systematic review of Explainable Artificial Intelligence models and applications: Recent developments and future trends. *Decision Analytics Journal*, *7*, 100230. https://doi.org/10.1016/j.dajour.2023.100230

Abraham, R., Schneider, J., & vom Brocke, J. (2019). Data governance: A conceptual framework, structured review, and research agenda. *International Journal of Information Management*, *49*, 424–438. https://doi.org/10.1016/j.ijinfomgt.2019.07.008

Agrawal, P., & Narain, R. (2023). Analysis of enablers for the digitalization of value network using an interpretive structural modelling approach. *International Journal of Productivity and Performance Management*, *72*(2), 410–439. https://doi.org/10.1108/IJPPM-09-2020-0481

Alhassan, I., Sammon, D., & Daly, M. (2016). Data governance activities: an analysis of the literature. *Journal of Decision Systems*, *25*(sup1), 64–75. https://doi.org/10.1080/12460125.2016.1187397

Alvarez, G., Pilbeam, C., & Wilding, R. (2010). Nestlé Nespresso AAA sustainable quality program: an investigation into the governance dynamics in a multi-stakeholder value network network. *Value network Management: An International Journal*, *15*(2), 165–182. https://doi.org/10.1108/13598541011028769

APICS. (2017). *Value network Operations Reference Model - SCOR*.

Arnold Steven, Cribb Matthew, French Mathew, Ganguli Jayendra S., Goodman Scott, Hatakeyama Jason, Lorang Melanie K., Matlik John F., Pinon Fischer Olivia J., Schindel William D., Taylor Nigel, & Wang Guijun. (2023). *Digital Thread: Definition, Value and Reference Model*. https://www.aiaa.org/docs/default-source/uploadedfiles/Public-Policy/digital-thread-implementation-paper_june_2023?submissionGuid=2e6c7351-3cb5-4343-b31a-7ae31efefc11

Askew Katy. (2018). *Extended value networks are broken: why Mars thinks the commodities era is over*. https://www.foodnavigator.com/Article/2018/06/06/Why-Mars-thinks-the-commodities-era-is-over?utm_source=copyright&utm_medium=OnSite&utm_campaign=copyright

Bachmann, R., & Zaheer, A. (2008). *Trust in Inter-organizational Relations*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199282944.003.0020

Barbosa, P., Leite, F., Santos, D., Figueiredo, A., & Galdino, K. (2018). Introducing Traceability Information Models in Connected Health Projects. *2018 IEEE 31st International Symposium on Computer-Based Medical Systems (CBMS)*, 18–23. https://doi.org/10.1109/CBMS.2018.00011

Barredo Arrieta, A., Díaz-Rodríguez, N., Del Ser, J., Bennetot, A., Tabik, S., Barbado, A., Garcia, S., Gil-Lopez, S., Molina, D., Benjamins, R., Chatila, R., & Herrera, F. (2020). Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI. *Information Fusion*, *58*, 82–115. https://doi.org/10.1016/j.inffus.2019.12.012

Bashiri, M., Tjahjono, B., Lazell, J., Ferreira, J., & Perdana, T. (2021). The Dynamics of Sustainability Risks in the Global Coffee Value network: A Case of Indonesia–UK. *Sustainability*, *13*(2), 589. https://doi.org/10.3390/su13020589

Batwa, A., & Norrman, A. (2021). Blockchain Technology and Trust in Value network Management: A Literature Review and Research Agenda. *Operations and Value network Management: An International Journal*, 203–220. https://doi.org/10.31387/oscm0450297

Bhagwat, R., & Sharma, M. K. (2007). Performance measurement of value network management: A balanced scorecard approach. *Computers & Industrial Engineering*, *53*(1), 43–62. https://doi.org/10.1016/j.cie.2007.04.001

Bhandal, R., Meriton, R., Kavanagh, R. E., & Brown, A. (2022). The application of digital twin technology in operations and value network management: a bibliometric review. *Value network Management: An International Journal*, *27*(2), 182–206. https://doi.org/10.1108/SCM-01-2021-0053

Bollero A. et al. (n.d.). *Ferrite type materials and process for the production thereof* (Patent PCT/EP2018/063222).

Bollero, A., Rial, J., Villanueva, M., Golasinski, K. M., Seoane, A., Almunia, J., & Altimira, R. (2017). Recycling of Strontium Ferrite Waste in a Permanent Magnet Manufacturing Plant. *ACS Sustainable Chemistry & Engineering*, *5*(4), 3243–3249. https://doi.org/10.1021/acssuschemeng.6b03053

Bonnaud Serge, Didier Christophe, & Kohler Arndt. (2019). *Industry 4.0 and Cognitive Manufacturing, rchitecture Patterns, Use Cases and IBM Solutions*. https://www.ibm.com/downloads/cas/M8J5BA6R

Bove Anne-Titia, & Swartz Steven. (2016). *Starting at the source: Sustainability in value networks*. https://www.mckinsey.com/business-functions/sustainability/our-insights/starting-at-the-source-sustainability-in-supply-chains

Bratianu, C. (2015). *Organizational Knowledge Dynamics*. IGI Global. https://doi.org/10.4018/978-1-4666-8318-1

CGI. (2018). *CGI Client Global Insights 2018 for Manufacturing, Summary*. https://www.cgi.com/en/media/white-paper/manufacturing-client-global-insights-2018

Chen, J.-Y. (2022). Responsible sourcing and value network traceability. *International Journal of Production Economics*, *248*, 108462. https://doi.org/10.1016/j.ijpe.2022.108462

Chen, Y.-H., Lin, T.-P., & Yen, D. C. (2014). How to facilitate inter-organizational knowledge sharing: The impact of trust. *Information & Management*, *51*(5), 568–578. https://doi.org/10.1016/j.im.2014.03.007

Cheng, J., Zhang, H., Tao, F., & Juang, C. F. (2020). DT-II:Digital twin enhanced Industrial Internet reference framework towards smart manufacturing. *Robotics and Computer-Integrated Manufacturing*, *62*. https://doi.org/10.1016/j.rcim.2019.101881

Chiu, M.-C., & Kremer, G. E. O. (2014). An Investigation on Centralized and Decentralized Value network Scenarios at the Product Design Stage to Increase Performance. *IEEE Transactions on Engineering Management*, *61*(1), 114–128. https://doi.org/10.1109/TEM.2013.2246569

CircThread H2020 Project (2023). https://circthread.com/standardization-toolkit/

Cunha Callado, A. A., & Jack, L. (2015). Balanced scorecard metrics and specific value network roles. *International Journal of Productivity and Performance Management*, *64*(2), 288–300. https://doi.org/10.1108/IJPPM-05-2014-0071

D'Amico, R. D., Erkoyuncu, J. A., Addepalli, S., & Penver, S. (2022). Cognitive digital twin: An approach to improve the maintenance management. *CIRP Journal of Manufacturing Science and Technology*, *38*, 613–630. https://doi.org/10.1016/j.cirpj.2022.06.004

De Sousa, T. B., Melo, I. C., Oliveira, P. H. de, Lourenço, C. M., Guerrini, F. M., & Esposto, K. F. (2020). Balanced Scorecard for evaluating the performance of value networks: a bibliometric study. *Journal of Engineering Research*, *8*(1). https://doi.org/10.36909/jer.v8i1.4406

Deloitte. (2017). *Business Ecosystems come of age, 2017*. 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

DIGICOR H2020 Project. Retrieved November 12, 2020, from https://www.digicor-project.eu

Economic and Social Council. (2018). *Principles of effective governance for sustainable development*. https://publicadministration.un.org/Portals/1/Images/CEPA/Principles_of_effective_governance_english.pdf

EFFRA. (2016). *Factories 4.0 and beyond: Recommendations for the work programme 18-19-20 of the FoF PPP under Horizon 2020*. https://www.effra.eu/sites/default/files/factories40_beyond_v31_public.pdf

Ehsan Upol, & Reidl Mark O. (2020). Human-centered Explainable AI: Towards a Reflective Sociotechnical Approach. *HCI International 2020: 22nd International Conference On Human-Computer Interaction*, 449–466. https://arxiv.org/abs/2002.01092

Eirinakis, P., Lounis, S., Plitsos, S., Arampatzis, G., Kalaboukas, K., Kenda, K., Lu, J., Rožanec, J. M., & Stojanovic, N. (2022). Cognitive Digital Twins for Resilience in Production: A Conceptual Framework. *Information*, *13*(1), 33. https://doi.org/10.3390/info13010033

El Saddik, A. (2018). Digital Twins: The Convergence of Multimedia Technologies. *IEEE MultiMedia*, *25*(2), 87–92. https://doi.org/10.1109/MMUL.2018.023121167

Ellen Macarthur Foundation. (n.d.). *Material Circularity Indictor (MCI)*. Retrieved October 26, 2023, from https://www.ellenmacarthurfoundation.org/material-circularity-indicator

Estampe, D., Lamouri, S., Paris, J.-L., & Brahim-Djelloul, S. (2013). A framework for analysing value network performance evaluation models. *International Journal of Production Economics*, *142*(2), 247–258. https://doi.org/10.1016/j.ijpe.2010.11.024

European Commission. (n.d.). *Smart Specialization Platform*. Retrieved March 14, 2021, from http://s3platform.jrc.ec.europa.eu/

European Commission. (2018). *Ehics Guidelines for Trustworthy AI*. https://op.europa.eu/en/publication-detail/-/publication/d3988569-0434-11ea-8c1f-01aa75ed71a1

European Commission. (2022a). *Regulation of the European Parliament and of the Council on harmonised rules for dair access to and use of data (Data Act)*. https://digital-strategy.ec.europa.eu/en/library/data-act-proposal-regulation-harmonised-rules-fair-access-and-use-data

European Commission. (2022b, March 30). *Proposal for a new Ecodesign for Sustainable Products Regulation* .

European Commission. (2023a). *Ecodesign for sustainable Products Regulation*. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en#the-new-digital-product-passport

European Commission. (2023b, November 25). *European Data Government Act*. https://digital-strategy.ec.europa.eu/en/policies/data-governance-act

Feng Tian. (2016). An agri-food value network traceability system for China based on RFID & blockchain technology. *2016 13th International Conference on Service Systems and Service Management (ICSSSM)*, 1–6. https://doi.org/10.1109/ICSSSM.2016.7538424

Force11. (n.d.). *Guiding Principles for Findable, Accessible, Interoperable and Re-usable Data Publishing version b1.0*. The Future of Research Communications and E-Scholarship. Retrieved March 13, 2022, from https://force11.org/info/guiding-principles-for-findable-accessible-interoperable-and-re-usable-data-publishing-version-b1-0/

GAIA-X. (2019). *GAIA-X Initiative on data spaces*. https://gaia-x.eu/what-is-gaia-x/core-elements/data-spaces/

Garay-Rondero, C. L., Martinez-Flores, J. L., Smith, N. R., Caballero Morales, S. O., & Aldrette-Malacara, A. (2019). Digital value network model in Industry 4.0. *Journal of Manufacturing Technology Management*, *31*(5), 887–933. https://doi.org/10.1108/JMTM-08-2018-0280

Garcia-Torres, S., Albareda, L., Rey-Garcia, M., & Seuring, S. (2019). Traceability for sustainability – literature review and conceptual framework. *Value network Management: An International Journal*, *24*(1), 85–106. https://doi.org/10.1108/SCM-04-2018-0152

Gartner. (2018). *Gartner Identifies the Top 10 Strategic Technology Trends for 2019*. : https://www.gartner.com/en/newsroom/press-releases/2018-10-15-gartner-identifies-the-top-10-strategic-technology-trends-for-2019

Gasser, U., & Almeida, V. A. F. (2017). A Layered Model for AI Governance. *IEEE Internet Computing*, *21*(6), 58–62. https://doi.org/10.1109/MIC.2017.4180835

Giannoccaro, I. (2018). Centralized vs. decentralized value networks: The importance of decision maker's cognitive ability and resistance to change. *Industrial Marketing Management*, *73*, 59–69. https://doi.org/10.1016/j.indmarman.2018.01.034

Global Battery Passport Pilot (2023). https://www.globalbattery.org/action-platforms-menu/pilot-test/

Grieves, M., & Vickers, J. (2017). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In *Transdisciplinary Perspectives on Complex Systems* (pp. 85–113). Springer International Publishing. https://doi.org/10.1007/978-3-319-38756-7_4

Grieves Michael. (2015). *Digital twin: Manufacturing excellence through virtual factory replication*.

Gruchmann, T., Elgazzar, S., & Ali, A. H. (2023). Blockchain technology in pharmaceutical value networks: a transaction cost perspective. *Modern Value network Research and Applications*, *5*(2), 115–133. https://doi.org/10.1108/MSCRA-10-2022-0023

GS1 Institute. (2017). *GS1 Global Traceability Standard*. https://www.gs1.org/standards/gs1-global-traceability-standard/current-standard

Gupta Sunil. (2018). *Driving Digital Strategy - A guide to Reimagining Your Business*. Harvard University Press.

Hedberg, T. D., Bajaj, M., & Camelio, J. A. (2020). Using Graphs to Link Data Across the Product Lifecycle for Enabling Smart Manufacturing Digital Threads. *Journal of Computing and Information Science in Engineering*, *20*(1). https://doi.org/10.1115/1.4044921

Hedberg, T., Lubell, J., Fischer, L., Maggiano, L., & Barnard Feeney, A. (2016). Testing the Digital Thread in Support of Model-Based Manufacturing and Inspection. *Journal of Computing and Information Science in Engineering*, *16*(2). https://doi.org/10.1115/1.4032697

Henisz Witold, Koller Tim, & Nuttall Robin. (2019). *Five ways that ESG creates value*. https://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/five-ways-that-esg-creates-value

Heutger Matthias, & Kueckelhaus Markus. (2019). *Digital Twins in Logistics: A DHL Perspective on the Impact of Digital Twins in the Logistics Industry*. https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/glo-core-digital-twins-in-logistics.pdf

IDC. (2014). *IDC Manufacturing Insights*.

IDSA. (2019). *IDS Reference Architecture Model version 3.0*.

In, J., Bradley, R., Bichescu, B. C., & Autry, C. W. (2019). Value network information governance: toward a conceptual framework. *The International Journal of Logistics Management*, *30*(2), 506–526. https://doi.org/10.1108/IJLM-05-2017-0132

Industrial Internet Consortium. (2020). *Digital Twins for Industrial Applications*. https://www.iiconsortium.org/pdf/IIC_Digital_Twins_Industrial_Apps_White_Paper_2020-02-18.pdf

Ivanov, D., & Dolgui, A. (2021). A digital value network twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control*, *32*(9), 775–788. https://doi.org/10.1080/09537287.2020.1768450

Jagusch, K., Sender, J., Jericho, D., & Flügge, W. (2021). Digital thread in shipbuilding as a prerequisite for the digital twin. *Procedia CIRP*, *104*, 318–323. https://doi.org/10.1016/j.procir.2021.11.054

Jinzhi, L., Zhaorui, Y., Xiaochen, Z., Jian, W., & Dimitris, K. (2022). Exploring the concept of Cognitive Digital Twin from model-based systems engineering perspective. *The International Journal of Advanced Manufacturing Technology*, *121*(9–10), 5835–5854. https://doi.org/10.1007/s00170-022-09610-5

Jobin, A., Ienca, M., & Vayena, E. (2019). The global landscape of AI ethics guidelines. *Nature Machine Intelligence*, *1*(9), 389–399. https://doi.org/10.1038/s42256-019-0088-2

Judah Saul. (2019). *7 Must-Have Foundations for Modern Data and Analytics Governance*. https://www.gartner.com/en/documents/3970322/7-must-have-foundations-for-modern-data-and-analytics-go

Kalaboukas, K., Kiritsis, D., & Arampatzis, G. (2023). Governance framework for autonomous and cognitive digital twins in agile value networks. *Computers in Industry*, *146*, 103857. https://doi.org/10.1016/j.compind.2023.103857

Kaplan R.S., & Norton D.P. (1992). The balanced scorecard - measures that drive performance. *Harvard Business Review*, *70*(1), 71–79.

Katiyar, R., Meena, P. L., Barua, M. K., Tibrewala, R., & Kumar, G. (2018). Impact of sustainability and manufacturing practices on value network performance: Findings from an emerging economy. *International Journal of Production Economics*, *197*, 303–316. https://doi.org/10.1016/j.ijpe.2017.12.007

Khanna, T., Nand, P., & Bali, V. (2020). Permissioned Blockchain Model for End-to-End Trackability in Value network Management. *International Journal of E-Collaboration*, *16*(1), 45–58. https://doi.org/10.4018/IJeC.2020010104

Kiritsis, D. (2011). Closed-loop PLM for intelligent products in the era of the Internet of things. *Computer-Aided Design*, *43*(5), 479–501. https://doi.org/10.1016/j.cad.2010.03.002

Kor, M., Yitmen, I., & Alizadehsalehi, S. (2022). An investigation for integration of deep learning and digital twins towards Construction 4.0. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-08-2021-0148

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). *Digital Twin in manufacturing: A categorical literature review and classification*. *51*(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Kung Antonio, Baudoin Claude, & Tobich Karim. (2023). *Landscape of Digital Twin Standards*.

Kwon, S., Monnier, L. V., Barbau, R., & Bernstein, W. Z. (2020). Enriching standards-based digital thread by fusing as-designed and as-inspected data using knowledge graphs. *Advanced Engineering Informatics*, *46*, 101102. https://doi.org/10.1016/j.aei.2020.101102

Li, K., Qin, Y., Zhu, D., & Zhang, S. (2023). Upgrading waste electrical and electronic equipment recycling through extended producer responsibility: A case study. *Circular Economy*, *2*(1), 100025. https://doi.org/10.1016/j.cec.2023.100025

Liao, Q. V., & Varshney, K. R. (2021). *Human-Centered Explainable AI (XAI): From Algorithms to User Experiences*.

Liu, M., Li, X., Li, J., Liu, Y., Zhou, B., & Bao, J. (2022). A knowledge graph-based data representation approach for IIoT-enabled cognitive manufacturing. *Advanced Engineering Informatics*, *51*, 101515. https://doi.org/10.1016/j.aei.2021.101515

Longo, F., Mirabelli, G., Padovano, A., & Solina, V. (2023). The Digital Value network Twin paradigm for enhancing resilience and sustainability against COVID-like crises. *Procedia Computer Science*, *217*, 1940–1947. https://doi.org/10.1016/j.procs.2022.12.394

Lu, J., Chen, D., Wang, G., Kiritsis, D., & Torngren, M. (2022). Model-Based Systems Engineering Tool-Chain for Automated Parameter Value Selection. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *52*(4), 2333–2347. https://doi.org/10.1109/TSMC.2020.3048821

Lu, J., Zheng, X., Gharaei, A., Kalaboukas, K., & Kiritsis, D. (2019). Cognitive twins for supporting decision-makings of internet of things systems. In *arXiv*.

Lu, J., Zheng, X., Gharaei, A., Kalaboukas, K., & Kiritsis, D. (2020). *Cognitive Twins for Supporting Decision-Makings of Internet of Things Systems* (pp. 105–115). https://doi.org/10.1007/978-3-030-46212-3_7

Lu, Y., Liu, C., Wang, K. I.-K., Huang, H., & Xu, X. (2020). Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robotics and Computer-Integrated Manufacturing*, *61*, 101837. https://doi.org/10.1016/j.rcim.2019.101837

Lubell, J., Chen, K. K., Horst, J. A., Frechette, S. P., & Huang, P. J. (2012). *Model Based Enterprise / Technical Data Package Summit Report*. https://doi.org/10.6028/NIST.TN.1753

Maier, P., Sachenbacher, M., Rühr, T., & Kuhn, L. (2010). Automated plan assessment in cognitive manufacturing. *Advanced Engineering Informatics*, *24*(3), 308–319. https://doi.org/10.1016/j.aei.2010.05.015

Maro, S., Steghöfer, J.-P., Knauss, E., Horkoff, J., Kasauli, R., Wohlrab, R., Korsgaard, J. L., Wartenberg, F., Strøm, N. J., & Alexandersson, R. (2021). *Managing Traceability Information Models: Not such a simple task after all?* https://doi.org/10.1109/MS.2020.3020651

Matsokis, A., & Kiritsis, D. (2010). An ontology-based approach for Product Lifecycle Management. *Computers in Industry*, *61*(8), 787–797. https://doi.org/10.1016/j.compind.2010.05.007

McKinsey. (2015). *Industry4.0: How to navigate digitization of the manufacturing sector, McKinsey Digital*. https://www.mckinsey.com/business-functions/operations/our-insights/industry-four-point-o-how-to-navigae-the-digitization-of-the-manufacturing-sector

Meng, X.-L. (2023). Data Science and Engineering With Human in the Loop, Behind the Loop, and Above the Loop. *Harvard Data Science Review*, *5*(2). https://doi.org/10.1162/99608f92.68a012eb

Micheli, M., Ponti, M., Craglia, M., & Berti Suman, A. (2020). Emerging models of data governance in the age of datafication. *Big Data & Society*, *7*(2), 205395172094808. https://doi.org/10.1177/2053951720948087

Miha Cimperman, Angela Dimitriou, Kostas Kalaboukas, Aziz S. Mousas, & Salvatore Quattropani. (2021). SIoT for cognitive logistics: Leveraging the social graph of digital twins for effective operations on real-time events. *ITU Journal on Future and Evolving Technologies*, *2*(5), 69–79. https://doi.org/10.52953/ONRK8179

Minerva, R., Lee, G. M., & Crespi, N. (2020). Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models. *Proceedings of the IEEE*, *108*(10), 1785–1824. https://doi.org/10.1109/JPROC.2020.2998530

Mosqueira-Rey, E., Hernández-Pereira, E., Alonso-Ríos, D., Bobes-Bascarán, J., & Fernández-Leal, Á. (2023). Human-in-the-loop machine learning: a state of the art. *Artificial Intelligence Review*, *56*(4), 3005–3054. https://doi.org/10.1007/s10462-022-10246-w

Moynihan Brian, & Schwab Klaus. (2020). *Measuring Stakeholder Capitalism: Towards Common Metrics and Consistent Reporting on Sustainable Value Creation*. https://www3.weforum.org/docs/WEF_IBC_Measuring_Stakeholder_Capitalism_Report_2020.pdf

Mugurusi, G., & Oluka, P. N. (2021). *Towards Explainable Artificial Intelligence (XAI) in Value network Management: A Typology and Research Agenda* (pp. 32–38). https://doi.org/10.1007/978-3-030-85910-7_4

Nguyen Hoang, & Dsouza Rishad. (2021). *Global: Consumer willingness to pay for environmentally friendly products*. https://yougov.co.uk/topics/food/articles-reports/2021/04/29/global-willingness-pay-for-sustainability

Nochta Timea, Badstuber Nicole, & Wahby Noura. (2019). *On the Governance of City Digital Twins - Insights from the Cambridge Case Study*. https://doi.org/10.17863/CAM.41083

OECD.AI. (2019). *OECD AI Principles overview* .

Otto Boris. (2011). A morphology of the organisation of data governance. *19th European Conference on Information Systems, ECIS 2011*.

Otto Boris, Schleimer Anna Maria, Eitel Andreas, & Lange Christoph. (2021). *GAIA-X and IDS*. https://internationaldataspaces.org/wp-content/uploads/dlm_uploads/IDSA-Position-Paper-GAIA-X-and-IDS.pdf

Palmero, E. M., Rial, J., de Vicente, J., Camarero, J., Skårman, B., Vidarsson, H., Larsson, P.-O., & Bollero, A. (2018). Development of permanent magnet MnAlC/polymer composites and flexible filament for bonding and 3D-printing technologies. *Science and Technology of Advanced Materials*, *19*(1), 465–473. https://doi.org/10.1080/14686996.2018.1471321

Pandey, V., Pant, M., & Snasel, V. (2022). Blockchain technology in food value networks: Review and bibliometric analysis. *Technology in Society*, *69*, 101954. https://doi.org/10.1016/j.techsoc.2022.101954

Patorska Julia, Łaszek Aleksander, Leoniewska-Gogola Joanna, Maciborski Dorian, & Fusiara Aneta. (2022). *Impact of international, open standards on circularity in Europe*. https://www2.deloitte.com/content/dam/Deloitte/pl/Documents/Reports/pl_Deloitte_I_GS1_I_Impact_of_international_open_standards_on_circularity_in_Europe_.pdf

PCDS. (2020). *Product Circularity Data Sheet (PCDS)*.

Pearson Hannah, Noble Glen, & Hawkins Joshua. (2013). *Redistributed Manufacturing Workshop Report*. https://epsrc.ukri.org/newsevents/pubs/re-distributed-manufacturing-workshop-report

Personal Data Protection Commission, S. (2020). *Model Artificial Intelligence Governance Framework*. https://www.pdpc.gov.sg/-/media/files/pdpc/pdf-files/resource-for-organisation/ai/sgmodelaigovframework2.pdf

Petzold Bryan, Roggendorf Matthias, Rowshankish Kayvaun, & Sporleder Christoph. (2020). *Designing data governance that delivers value*.

Plattform Industrie4.0. (2018). *RAMI4.0: A Reference Model for Digitalization*. https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/rami40-an-introduction.html

Qi, Q., & Tao, F. (2018). Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE Access*, *6*, 3585–3593. https://doi.org/10.1109/ACCESS.2018.2793265

Qi, Q., Tao, F., Zuo, Y., & Zhao, D. (2018). Digital Twin Service towards Smart Manufacturing. *Procedia CIRP*, *72*, 237–242. https://doi.org/10.1016/j.procir.2018.03.103

Rahwan, I. (2018). Society-in-the-loop: programming the algorithmic social contract. *Ethics and Information Technology*, *20*(1), 5–14. https://doi.org/10.1007/s10676-017-9430-8

Ramesh, A., Qin, Z., & Lu, Y. (2020, September 3). Digital Thread Enabled Manufacturing Automation Towards Mass Personalization. *Volume 2: Manufacturing Processes; Manufacturing Systems; Nano/Micro/Meso Manufacturing; Quality and Reliability*. https://doi.org/10.1115/MSEC2020-8429

Razak, G. M., Hendry, L. C., & Stevenson, M. (2023). Value network traceability: a review of the benefits and its relationship with value network resilience. *Production Planning & Control*, *34*(11), 1114–1134. https://doi.org/10.1080/09537287.2021.1983661

Reddy. K, J. M., Rao. A, N., & L, Krishnanand. (2019). A review on value network performance measurement systems. *Procedia Manufacturing*, *30*, 40–47. https://doi.org/10.1016/j.promfg.2019.02.007

Rehse, J.-R., Mehdiyev, N., & Fettke, P. (2019). Towards Explainable Process Predictions for Industry 4.0 in the DFKI-Smart-Lego-Factory. *KI - Künstliche Intelligenz*, *33*(2), 181–187. https://doi.org/10.1007/s13218-019-00586-1

Richey, R. G., Roath, A. S., Whipple, J. M., & Fawcett, S. E. (2010). Exploring a Governance Theory of Value network Management: Barriers and Facilitators to Integration. *Journal of Business Logistics*, *31*(1), 237–256. https://doi.org/10.1002/j.2158-1592.2010.tb00137.x

Risso, L. A., Ganga, G. M. D., Godinho Filho, M., Santa-Eulalia, L. A. de, Chikhi, T., & Mosconi, E. (2023). Present and future perspectives of blockchain in value network management: a review of reviews and research agenda. *Computers & Industrial Engineering*, *179*, 109195. https://doi.org/10.1016/j.cie.2023.109195

Roberts, H., Cowls, J., Morley, J., Taddeo, M., Wang, V., & Floridi, L. (2021). The Chinese approach to artificial intelligence: an analysis of policy, ethics, and regulation. *AI & SOCIETY*, *36*(1), 59–77. https://doi.org/10.1007/s00146-020-00992-2

Rocca, R., Rosa, P., Sassanelli, C., Fumagalli, L., & Terzi, S. (2020). Integrating Virtual Reality and Digital Twin in Circular Economy Practices: A Laboratory Application Case. *Sustainability*, *12*(6), 2286. https://doi.org/10.3390/su12062286

Rojas, R. A., & Rauch, E. (2019). From a literature review to a conceptual framework of enablers for smart manufacturing control. *The International Journal of Advanced Manufacturing Technology*, *104*(1–4), 517–533. https://doi.org/10.1007/s00170-019-03854-4

Rožanec Joze, Lu Jinzhi, Kosmerlj Aljaz, Kenda Klemen, Kiritsis Dimitris, Jovanoski Victor, Rupnik Jan, Karlovcec Mario, & Fortuna Blaz. (2020). Towards Actionable Cognitive Digital Twins for Manufacturing. *SeDiT@ESWC* .

Ryciuk, U. (2020). *Value network Governance Mechanisms: A Review and Typology* (pp. 145–159). https://doi.org/10.1007/978-3-030-40160-3_10

S. Teixeira Thales, & Piechota Greg. (2019). *Unlocking the Customer Value Chain: How Decoupling Drives Consumer Disruption*. Crown.

Schmidt, P., Biessmann, F., & Teubner, T. (2020). Transparency and trust in artificial intelligence systems. *Journal of Decision Systems*, *29*(4), 260–278. https://doi.org/10.1080/12460125.2020.1819094

Schuh, G., Rebentisch, E., Dölle, C., Mattern, C., Volevach, G., & Menges, A. (2018). Defining Scaling Strategies for the Improvement of Agility Performance in Product Development Projects. *Procedia CIRP*, *70*, 29–34. https://doi.org/10.1016/j.procir.2018.01.006

Simon Kucher & Partners. (2021). *Global Sustainability Study 2021* . https://www.simon-kucher.com/sites/default/files/studies/Simon-Kucher_Global_Sustainability_Study_2021.pdf

Sohail Omer, Sharma Prakul, & Citic Bojan. (n.d.). *Data Governance for next-generation platforms*. Retrieved March 13, 2022, from https://www2.deloitte.com/content/dam/Deloitte/us/Documents/technology/us-big-data-governance.pdf

Srai Jag, Ettore Settanni, Tsolakis Naoum, & Aulakh Parminder. (2019, September). Value network Digital Twins: Opportunities and Challenges Beyond the Hype. *23rdCambridge International Manufacturing Symposium*.

Suhail, S., Hussain, R., Jurdak, R., & Hong, C. S. (2021). Trustworthy Digital Twins in the Industrial Internet of Things with Blockchain. *IEEE Internet Computing*, 1–1. https://doi.org/10.1109/MIC.2021.3059320

Sun, K. H., Huh, H., Tama, B. A., Lee, S. Y., Jung, J. H., & Lee, S. (2020). Vision-Based Fault Diagnostics Using Explainable Deep Learning With Class Activation Maps. *IEEE Access*, *8*, 129169–129179. https://doi.org/10.1109/ACCESS.2020.3009852

Sustainable Development Goals. (2015). https://www.undp.org/sustainable-development-goals

Taeihagh, A. (2021). Governance of artificial intelligence. *Policy and Society*, *40*(2), 137–157. https://doi.org/10.1080/14494035.2021.1928377

Tao, F., Qi, Q., Wang, L., & Nee, A. Y. C. (2019). Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. *Engineering*, *5*(4), 653–661. https://doi.org/10.1016/j.eng.2019.01.014

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*, *15*(4), 2405–2415. https://doi.org/10.1109/TII.2018.2873186

Terziyan, V., & Vitko, O. (2022). Explainable AI for Industry 4.0: Semantic Representation of Deep Learning Models. *Procedia Computer Science*, *200*, 216–226. https://doi.org/10.1016/j.procs.2022.01.220

Tozanli Özden, & Saénz Maria Jesús. (2023, September 7). Unlocking the Potential of Digital Twins in Value networks. *MITSLoan Management Review*. https://www.mitsloanme.com/article/unlocking-the-potential-of-digital-twins-in-supply-chains/

van der Valk, H., Strobel, G., Winkelmann, S., Hunker, J., & Tomczyk, M. (2022). Value networks in the Era of Digital Twins – A Review. *Procedia Computer Science*, *204*, 156–163. https://doi.org/10.1016/j.procs.2022.08.019

Verzijl Diederik, Rouwmaat Elco, Dervojeda Kristina, Probst Laurent, & Frideres Laurent. (2015). *Traceability across the Value Chain: Standards, Processes and traceability*.

Vickers Peter, & Fojan Claudia. (2023). Digital Twins and the Digital Thread change the game by integrating the physical and digital worlds. In *Deloitte*. https://www2.deloitte.com/ch/en/pages/strategy-operations/articles/digital-twins-and-the-digital-thread-change-the-game.html

Wang, J., & Ran, B. (2018). Sustainable Collaborative Governance in Value network. *Sustainability*, *10*(2), 171. https://doi.org/10.3390/su10010171

Wang, K., Wang, Y., Li, Y., Fan, X., Xiao, S., & Hu, L. (2022). A review of the technology standards for enabling digital twin. *Digital Twin*, *2*, 4. https://doi.org/10.12688/digitaltwin.17549.2

Wang, Y., Wang, X., & Liu, A. (2020). Digital Twin-driven Value network Planning. *Procedia CIRP*, *93*, 198–203. https://doi.org/10.1016/j.procir.2020.04.154

Warlick John, Godziela Richard, & Mitterbuchner Daniela. (2021). *Thread-First Thinking: Staying in front of immense way of product data*. https://www.accenture.com/content/dam/accenture/final/a-com-migration/manual/r3/pdf/pdf-160/Accenture-Thread-First-Thinking.pdf#zoom=40

WBCSD. (2018). *Circular Metrics Landscape Analysis*. https://docs.wbcsd.org/2018/06/Circular_Metrics-Landscape_analysis.pdf

WBCSD. (2019). *Business Climate Resilience: Thriving Through the Transformation*. https://docs.wbcsd.org/2019/09/WBCSD_Business-Climate-Resilience.pdf

WBCSD. (2020). *Circular Transition Indicators 1.0: Metrics for business, by business*.

White Katherine, Hardisty David J., & Habib Rishad. (2019). The Elusive Green Consumer. *Harvard Business Review*, *July-August 2019*. https://hbr.org/2019/07/the-elusive-green-consumer

World Manufacturing Forum. (2020). *WMF. The 2020 World Manufacturing Report: Manufacturing in the Age of Artificial Intelligence*. https://worldmanufacturing.org/wp-content/uploads/WorldManufacturingForum2020_Report.pdf

Xiao, Y., Zheng, S., Shi, J., Du, X., & Hong, J. (2023). Knowledge graph-based manufacturing process planning: A state-of-the-art review. *Journal of Manufacturing Systems*, *70*, 417–435. https://doi.org/10.1016/j.jmsy.2023.08.006

Yin, Z., Shi, L., Yuan, Y., Tan, X., & Xu, S. (2023). A Study on a Knowledge Graph Construction Method of Safety Reports for Process Industries. *Processes*, *11*(1), 146. https://doi.org/10.3390/pr11010146

Zaeh, M. F., Reinhart, G., Ostgathe, M., Geiger, F., & Lau, C. (2010). A holistic approach for the cognitive control of production systems. *Advanced Engineering Informatics*, *24*(3), 300–307. https://doi.org/10.1016/j.aei.2010.05.014

Zheng, X., Lu, J., & Kiritsis, D. (2022). The emergence of cognitive digital twin: vision, challenges and opportunities. *International Journal of Production Research*, *60*(24), 7610–7632. https://doi.org/10.1080/00207543.2021.2014591

Annex A – Magnets Value network Governance tables

The below tables present the data and models' governance for each of the modelled CDT in the magnets value network case.

Table 15 presents the elaborated value network configuration with the following information:

- Decision-making capabilities per CDT
- Applicable AI models/services
- Model ownership
- Identification for an AI passport need
- Ethics or GDPR considerations of the CDT (with regards to the data monitored)

Table 16 and *Table 17*: Data monitoring – IMDEA Magnet Pell present in detail the data to be monitored per asset or network CDT, and different levels of ownership and usage.

Step (operation) name	Network/ Asset	Asset Name	Type (Operation/ Material)	id	Tagging method	Data to be monitored	Decisions taken	Applicable AI services models	Model Ownership	Need for AI model Passport?	Ethics?	GDPR?
FERIMET												
WEEE	Asset	WEEE	Material	WEEE	N/A	N/A					N/A	N/A
Magnet Extraction from WEEE	Network	Magnet Extraction from WEEE	Operation	A								
Classification/ Extraction	Asset (internal)	Classification/ Extraction	Operation								N/A	N/A
Extracted Magnet	Asset	Extracted Magnet	Material	Extr-Magnet	Lot	*Table 16: Data monitoring: FERIMET – Extracted Magnet*					N/A	N/A
IMDEA												
Incoming magnets	Asset	Incoming extracted magnet	Material	Extr-Magnet	Lot						N/A	N/A
Magnet Pellet Production	Network	Magnet Pellet Production	Operation	Mag-Pell								
Demagnitizer	Asset (internal)	Demagnitizer	Operation				Optimal configuration	• Behavioral model • Optimizer	IMDEA	Yes	N/A	N/A
Crushing	Asset (internal)	Crushing	Operation				Optimal configuration	• Behavioral model • Optimizer	IMDEA	Yes	N/A	N/A
Homogenizer	Asset (internal)	Homogenizer	Operation				Optimal configuration	• Behavioral model • Optimizer	IMDEA	Yes	N/A	N/A
Extrusion	Asset (internal)	Extrusion	Operation				Optimal configuration	• Behavioral model • Optimizer	IMDEA	Yes	N/A	N/A
Testing	Asset (internal)	Testing	Operation								N/A	N/A
Magnet Pellet	Asset	Magnet Pellet	Material	Pell	Lot	*Table 17: Data monitoring*					N/A	N/A

Step (operation) name	**Network/ Asset**	**Asset Name**	**Type (Operation/ Material)**	**id**	**Tagging method**	**Data to be monitored**	**Decisions taken**	**Applicable AI services models**	**Model Ownership**	**Need for AI model Passport?**	**Ethics?**	**GDPR?**
						– IMDEA Magnet Pell						
IMA												
Incoming pellet	Asset	Incoming pellet	Material	Pell	Lot						N/A	N/A
Magnet production	Network	Magnet production	Operation	Mag-Production							N/A	N/A
Magnet	Asset	Magnet	Material	Magnet	Lot	*Digital Product Passport*					N/A	N/A

Table 15: Detailed magnets value network modelling and governance

Table: ***Data – Ferimet – Extracted Magnet***

Group of Metris	Metric	Unit	Is metric public (as external)?	who creates/ owns it?	Who process it?	Who has access to it?
Properties	Type (NdFeB/Strontium or Sr-Ferrite)		Yes	FERIMET	FERIMET	IMDEA
Properties	Quantity	Kg	Yes	FERIMET	FERIMET	IMDEA
Properties	Origin (device from which the magnet was extracted (home appliance, washing machine, electronics or other type of WEEE)		Yes	FERIMET	FERIMET	IMDEA

Table 16: Data monitoring: FERIMET – Extracted Magnet

Table: *Data - IMDEA - Magnet Pellet*

Group of Metris	Metric	Unit	Is metric public (as external)?	who creates/ owns it?	Who process it?	Who has access to it?
Type of Material	NdFeB/Strontium or Sr-Ferrite		Yes	FERIMET	IMDEA	IMA
Quantity	Quantity	Kg	Yes	IMDEA	IMDEA	IMA
Pellet Dimension	Shape		Yes	IMDEA	IMDEA	IMA
	Length		Yes	IMDEA	IMDEA	IMA
	Weight	Kg	Yes	IMDEA	IMDEA	IMA
Magnetic properties	Remanent magnetization	emu/g	Yes	IMDEA	IMDEA	IMA
Magnetic properties	Coercivity (kOe),		Yes	IMDEA	IMDEA	IMA
Magnetic properties	Strength of magnet (BH)max,	kJ/m3	Yes	IMDEA	IMDEA	IMA
Chemical properties	Chemical composition of the pellets.		Yes	IMDEA	IMDEA	IMA
Physical properties	Weight	Kg	Yes	IMDEA	IMDEA	IMA
Physical properties	Diameters	mm	Yes	IMDEA	IMDEA	IMA
Physical properties	Thickness	mm	Yes	IMDEA	IMDEA	IMA
Physical properties	Other specs		Yes	IMDEA	IMDEA	IMA
Magnetic properties	Remanent magnetization (emu/g),	emu/g	Yes	IMDEA	IMDEA	IMA
Magnetic properties	Coercivity (kOe),		Yes	IMDEA	IMDEA	IMA
Magnetic properties	strength of magnet (BH)max	kJ/m3	Yes	IMDEA	IMDEA	IMA
Magnetic properties	polarity (isotropic, axial, diametrical, multipolar)		Yes	IMDEA	IMDEA	IMA
Chemical properties	Chemical properties of the final magnets		Yes	IMDEA	IMDEA	IMA

Table 17: Data monitoring – IMDEA Magnet Pell