

CHAPTER 4. DIGITAL RESILIENCE AND POST-WAR RECOVERY OF UKRAINE: THE ROLE OF INFORMATION TECHNOLOGIES AND CYBERSECURITY

4.1. DIGITAL TWIN Technologies in the Digital Transformation of the European Union Economy: Experience for Ukraine and the Concept of a Projective Digital Twin

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Digital twins have developed from an engineering modelling tool into one of the core technologies of Europe’s green and digital transition. They are used in industry, energy, climate modelling, ocean management, cities, transport, buildings, and complex infrastructure systems (European Commission. Destination Earth (DestinE); European Commission. European Digital Twin Ocean; European Commission. Digital Europe Programme; European Commission, Directorate-General for Research and Innovation. Industry 5.0).

The European Commission considers Destination Earth a flagship initiative for creating a highly accurate digital model of the Earth that can monitor, model, and predict the interaction between natural phenomena and human activity. The European Digital Twin Ocean develops a similar approach for ocean systems by combining heterogeneous data, models, and decision-support tools (European Commission. Destination Earth (DestinE)).

In manufacturing, Horizon Europe and Digital Europe support the transition from isolated digital models to interoperable twins, industrial data spaces, and distributed intelligence systems. The Change2Twin, MODAPTO, CONVERGING, and TwinEU projects show that a Digital Twin is becoming not a separate software product but an element of a digital ecosystem (European Commission. Destination Earth (DestinE); European Commission. European Digital Twin Ocean; European

Commission. Digital Europe Programme; European Commission, Directorate-General for Research and Innovation. Industry 5.0).

At the same time, most modern digital twins start with a physical object that already exists and aim to represent its current state, predict its behaviour, or optimise its operating mode. The opposite direction is much less formalised: first creating a digital model of the desired physical result, then building the process for achieving it, generating control instructions, receiving actual feedback, and adaptively changing the uncompleted part of the process.

The purpose of this study is to systematise current European approaches to Digital Twin and to justify the concept of a projective digital twin as a new functional class of digital models focused on forming a future physical state.

The relevance of the topic is strengthened by the fact that in the EU Digital Twin technology is increasingly viewed not as a separate visualisation tool but as infrastructure for testing policies, engineering solutions, and scenarios before they are implemented in the physical world. This change of scale creates new requirements: a digital twin must work with heterogeneous data, explain assumptions, support several time horizons, be compatible with other models, and preserve the possibility of human control.

The object of the study is the development and application of digital twins in European digital and manufacturing ecosystems. The subject of the study includes the conceptual, architectural, and organisational foundations of Digital Twin, as well as the possibility of extending them to form and manage the achievement of a future physical state.

In the broadest sense, a Digital Twin is a digital representation of a defined physical entity, process, or system, supported by data and used for analysis, modelling, forecasting, or control. However, there is still no universal definition. Different disciplines define the sufficient level of connection between the physical and digital worlds, the role of bidirectional exchange, and the boundaries of the life cycle in different ways (Nativi S. et al., 2020; Kritzinger W. et al., 2018; Fuller A. et al., 2020; Rasheed A. et al., 2020).

The classical distinction between a digital model, a digital shadow, and a digital twin is based on the nature of data exchange. A digital model may exist without an automatic connection to a physical object. In a digital shadow, data transfer is mainly directed from the physical object to the model. A fully functional digital twin involves bidirectional interaction: a change in the physical state updates the model, while the results of digital analysis may influence the physical process (Kritzinger W. et al., 2018).

This classification remains useful, but it no longer covers all modern cases. For example, a climate twin does not “control” the Earth in the usual technical sense, but it provides high-accuracy scenario modelling for policy and management decisions. At the same time, a manufacturing twin may generate equipment operating parameters in a closed loop. Therefore, digital twins should be compared not by the presence of one formal attribute but by a set of functions: representation, synchronisation, diagnostics, forecasting, optimisation, scenario modelling, decision support, and control.

It is important to distinguish forecasting from design. Forecasting answers the question of what is likely to happen under given conditions. Design determines which state is desirable and which sequence of actions can achieve it. In many digital twins, both functions are partly present, but the model for moving from a target state to specific physical operations usually remains an external planning module.

From a life-cycle perspective, a digital twin can support the concept, design, manufacturing, operation, maintenance, and decommissioning of an object. At the early stages, the physical object may not yet exist; therefore, the digital entity acts as a specification of the future object. After the object is created, the focus shifts to synchronisation and observation. During operation, diagnostics, failure prediction, and optimisation become central, while at the end of the life cycle the focus is on reuse, recycling, and environmental impact.

The Digital Twin technology stack includes IoT and sensor networks, computer vision, cyber-physical systems, cloud and edge computing, semantic models, artificial intelligence, simulation, high-performance computing, and visualisation tools. Practical maturity is determined by integration rather than by the presence of any single component.

Standardisation has a dual role. It establishes common terminology and architectural roles, but it should not prematurely limit new functional classes. ISO 23247 provides a digital twin framework for manufacturing, IEC 63278 links the digital representation of industrial assets with the Asset Administration Shell, and European data spaces develop organisational mechanisms for sovereign and controlled exchange (ISO 23247-1:2021; IEC 63278-1:2023; European Commission. Common European data spaces).

From the perspective of economic theory, a digital twin can be considered a mechanism for reducing information asymmetry between the state of a physical asset and the decision-maker. The more completely the model represents relevant parameters, the lower the costs of information search, diagnostics, coordination of actions, and performance control. At the same time, creating and maintaining a twin generates its own transaction costs: data verification, system integration, maintenance of semantic interoperability, and access-right management. Thus, the economic effect does not arise from digitalisation itself, but when the reduction of costs and risks in the physical process exceeds the total cost of the digital infrastructure.

An important methodological distinction is the difference between a digital twin and a conventional simulation model. A simulation model may be accurate but have no systematic connection with a specific physical object. A digital twin maintains the identity of the relevant asset or process, is updated with life-cycle data, and makes it possible to compare a forecast with the actual result. This capability turns modelling into an organisational learning tool: a forecasting error is not only recorded but is also used to improve subsequent decisions.

The maturity level of a Digital Twin should be determined not by the volume of accumulated data or the complexity of three-dimensional visualisation, but by the depth of its integration into the management cycle. At the initial level, the model performs a descriptive function; at subsequent levels, it provides diagnostics, forecasting, optimisation, and adaptive control. Such a gradation allows an organisation to relate the expected result to investment and avoid a situation in which a technologically complex system does not improve the quality of decisions.

Table 4.1

Digital Twin maturity levels

Level	Twin function	Management result	Key maturity condition
1	Description and visualisation	Transparency of the asset state	Identified data and objects
2	Diagnostics	Identification of causes of deviations	Data quality and traceability
3	Forecasting	Assessment of future states and risks	Validated model and uncertainty
4	Optimisation	Comparison of alternative decisions	Formalised criteria and constraints
5	Adaptive control	Adjustment of the physical process	Feedback, safety, and human oversight

Source: developed by the author.

The European approach to Digital Twin is developing at the intersection of digital and green transformations. It differs from the narrow implementation of individual corporate platforms because it combines technological, legal, ethical, and social requirements. The main focus is on scalability, open interfaces, model reuse, control of data access, and algorithmic accountability.

In the digital economy of the European Union, Digital Twin technologies are gradually changing from a local engineering tool into an infrastructure mechanism for coordinating data, models, and decisions. Their economic value lies in the ability to move part of experimentation from the physical environment to the digital one, test scenarios in advance, reduce the cost of error, and shorten the period between making a management decision and implementing it in practice.

For industrial enterprises, a digital twin supports coordination between design, manufacturing, operation, and asset maintenance. In logistics, it makes it possible to model material flows, warehouse operations, transport loading, and supply-chain resilience. In energy, digital twins are used to coordinate distributed sources, forecast loads, and assess emergency scenarios. In construction and urban management, they

combine data on facilities, infrastructure, resources, and user behaviour in a single decision-support environment.

The macroeconomic effect of Digital Twin is associated with higher capital productivity, reduced downtime, resource savings, and faster innovation. The possibility of comparing alternative scenarios before physical investment reduces uncertainty and supports better allocation of resources. However, value is created only when the digital model is included in the real decision-making cycle and when its accuracy, costs, and risks are aligned with a specific economic task.

The European model of Digital Twin development is based on a combination of market incentives, research funding, standards, and legal regulation. The Digital Decade programme sets digital transformation targets up to 2030, while Digital Europe and Horizon Europe provide financial and research support for supercomputing, artificial intelligence, cybersecurity, data spaces, and digital skills.

There is no single EU law specifically on digital twins. Their use is regulated by a set of legal acts depending on the data, algorithms, sector, and level of risk. The Data Governance Act creates mechanisms for trusted data reuse and voluntary data sharing, while the Data Act, applicable from 12 September 2025, establishes rules for access to data from connected products and related services (European Commission. Data Governance Act; European Commission. Data Act). For digital twins, this defines the legal conditions for obtaining machine and sensor data without which models cannot be kept up to date.

If a digital twin uses artificial intelligence for forecasting, risk assessment, or the generation of control decisions, the requirements of the AI Act apply. The Regulation establishes a risk-based approach and requirements for data quality, documentation, transparency, and human oversight. For the concept of a projective digital twin, this means that automatic generation of a target state and transition trajectory must be accompanied by safety checks, explainable criteria, and the possibility of operator intervention (European Commission. AI Act: Regulatory framework for artificial intelligence).

The cybersecurity environment is shaped by NIS2 and the Cyber Resilience Act. NIS2 establishes a common cyber-risk management framework for critical sectors,

including energy, transport, healthcare, and digital infrastructure. The Cyber Resilience Act introduces mandatory requirements for products with digital elements throughout their life cycle (European Commission. NIS2; European Commission. Cyber Resilience Act). Therefore, protection of a digital twin must cover not only the central model but also sensors, communication channels, storage systems, interfaces, and actuators.

The EU legal framework effectively turns digital twin quality from a purely technical category into a socio-economic one. A model must be not only accurate but also lawful, safe, accountable, and auditable. This corresponds to the European focus on digital sovereignty, trust in data, and human-centred transformation.

For Ukraine, European experience is important in two areas. First, alignment with EU rules creates conditions for Ukrainian enterprises to participate in common data spaces, research programmes, and cross-border production chains. Second, digital twins can become a recovery tool by modelling infrastructure, energy networks, construction projects, logistics routes, and the use of scarce resources before capital-intensive physical actions are undertaken.

The Industry 5.0 concept complements the Industry 4.0 focus on automation and productivity with three interconnected principles: human-centricity, sustainability, and resilience. The European Commission emphasises that technological progress should create value for a wider range of stakeholders, respect planetary boundaries, and place worker well-being at the centre of the production process (European Commission, Directorate-General for Research and Innovation. Industry 5.0).

For Digital Twin, human-centricity means transparent presentation of recommendations, the possibility of human intervention, and consideration of ergonomics, safety, skills, and the distribution of responsibility. Sustainability requires assessment of energy consumption, material flows, emissions, repairability, and circularity. Resilience involves modelling disruptions, resource shortages, cyberattacks, supplier failures, and rapid replanning.

Therefore, the optimal solution cannot be determined only by minimum cost or duration. It should result from multi-criteria assessment in which productivity is

balanced with safety and with social and environmental consequences. This requirement directly affects the concept of the projective digital twin proposed below.

Destination Earth (DestinE) is a flagship European Commission initiative to create a highly accurate digital model of the Earth. Its first operational release was launched on 10 June 2024, and the system is planned to develop in stages until 2030. The architecture includes the Core Service Platform under ESA responsibility, the Data Lake under EUMETSAT responsibility, and thematic digital twins developed by ECMWF (European Commission. Destination Earth (DestinE)).

The first thematic components were twins for climate-change adaptation and extreme weather events. They combine real-time observations with high-resolution predictive modelling. The user receives not only a dataset but an environment in which scenarios can be created, consequences analysed, and applied services developed. This demonstrates a key change: the digital twin becomes a platform for producing verifiable knowledge.

DestinE shows that a large-scale twin requires a clear distribution of roles. The platform provides access and service orchestration; the data lake provides storage, data-proximate processing, and scalability; thematic twins provide domain models and simulations. This division reduces dependence on a single provider and makes it possible to gradually connect new domains, including the ocean, biodiversity, and geophysical risks.

The European Digital Twin Ocean develops a virtual representation of the ocean by integrating satellite observations, marine sensor data, historical datasets, and numerical models. The scientific value of the initiative lies in combining observation with scenario analysis: users can explore the impact of climate, environmental, and economic decisions without directly experimenting on the natural system (European Commission. European Digital Twin Ocean).

The ocean twin also shows the limits of a literal interpretation of bidirectionality. Modelling results do not create an automatic control signal for the ocean, but they can change policies, regulation, spatial planning, and user behaviour. Thus, physical impact may be mediated by an institutional decision. For Digital Twin theory, this means that

the feedback channel should be described not only through technical commands but also through decisions made by people and organisations.

The Digital Europe Programme is mainly focused on deploying digital capabilities: supercomputing, artificial intelligence, cybersecurity, digital skills, and broad technology adoption. Horizon Europe funds research novelty, demonstration, and validation of new architectures. Together, they create a pathway from research to operational infrastructure (European Commission. Digital Europe Programme; European Commission. Horizon Europe — Cluster 4).

Change2Twin supported manufacturing small and medium-sized enterprises for which the barriers include not only software costs but also the lack of adequate-quality data, competencies, and a clearly defined business case. The project experience highlighted the need to diagnose digital maturity, introduce technology in stages, and demonstrate measurable value (CORDIS).

MODAPTO creates flexible manufacturing systems in which modules are enhanced by distributed intelligence through interoperable digital twins. Module interfaces are standardised using the Asset Administration Shell, while collective intelligence supports production design and reconfiguration. The project is important because it moves from one monolithic twin to a coordinated set of local twins (CORDIS. MODAPTO).

TwinEU is creating a federated ecosystem of digital twins for the European electricity system. It covers transmission, distribution, and market operations and combines physical and AI models, standard interfaces, data spaces, and high-performance computing. As of 2026, a reference architecture is being developed and validated in eight large demonstration environments (CORDIS. TwinEU).

A common result of these projects is a change in the unit of analysis. The object is no longer a single machine or line, but a federation of twins that exchange data, models, and assessment results. This requires semantic interoperability, coordination of time scales, model version management, and trust mechanisms.

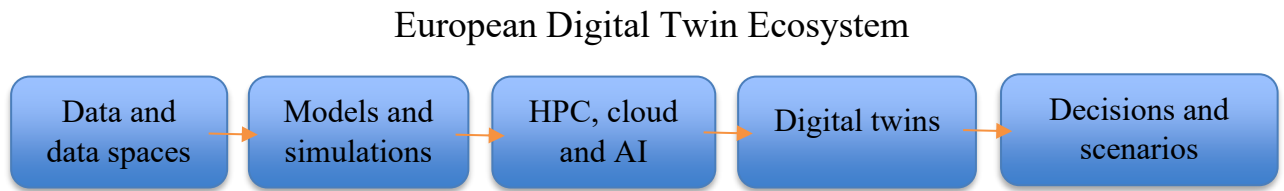


Fig. 4.1. Generalised logic of the European Digital Twin ecosystem
Source: developed by the author.

Table 4.2

Levels of digital twin implementation

Level	European example	Dominant function	Key requirement
Planetary	Destination Earth	Scenario modelling of climate and extremes	HPC, data, scientific verification
Natural system	Digital Twin Ocean	Integration of observations and models	Openness and interdisciplinarity
Infrastructure	TwinEU	Federation of power-system twins	Interoperability and cybersecurity
Manufacturing	MODAPTO	Reconfiguration of modular systems	AAS and distributed intelligence
Enterprise	Change2Twin	Practical implementation in SMEs	Maturity, competencies, business value

Source: developed by the author.

The standardisation basis of European digital twins is formed at several levels. ISO/IEC 30173:2023 establishes basic concepts, the context of a digital twin system, the life cycle, functional views, and the range of stakeholders (ISO/IEC 30173:2023). The ISO 23247 series specifies the framework for manufacturing: it defines general principles, a reference architecture, digital representations of manufacturing elements, and information-exchange requirements. IEC 63278-1:2023, in turn, formalises the

Asset Administration Shell as a standardised digital representation of an asset that provides unified access to information and services throughout the life cycle.

The combined use of these standards creates an important methodological hierarchy. ISO/IEC 30173 provides common terminology; ISO 23247 describes functional roles and interaction in a manufacturing context; AAS creates a machine-readable container for the data and services of a specific asset. However, the standards do not define a single optimisation method or mandatory decision-making algorithm. Therefore, applied systems should combine standardised exchange with domain models while preserving the ability to verify the origin of each parameter and the version of the algorithm.

Legal regulation of data influences architecture no less than technical standards. The Data Act differentiates access to data from connected products and related services but does not remove requirements concerning trade secrets, personal data, and security. Therefore, a federated digital twin should support differentiated rights: one participant may see raw measurements, another an aggregated indicator, and a third only the result of a constraint check. Such an access model reduces the risk of unjustified data distribution while preserving inter-organisational interaction.

If artificial intelligence is used within the digital twin loop, legal assessment should be based on the function and consequences of the specific application rather than on the name of the technology. For systems whose decisions may affect safety, human rights, or critical infrastructure, risk management, data quality, technical documentation, logging, human oversight, and the ability to reproduce decision logic are especially important. In a projective digital twin, these requirements should be built in at the stage of generating alternative target states rather than added after the algorithm has been developed.

Despite significant progress, the spread of Digital Twin is limited by a combination of technical, organisational, and methodological problems. The first is fragmentation of definitions. The same term may refer to a static 3D model, an asset information model, a simulator, a monitoring dashboard, or an adaptive cyber-physical system. This makes results difficult to compare and creates a risk of inflated expectations.

The second problem is interoperability. The formal availability of an API does not guarantee that two systems interpret an object, event, measurement quality, or acceptable delay in the same way. Common information models, semantics, identifiers, version policies, and machine-readable access rules are needed. This is why data spaces and AAS play an increasing role in European projects.

The third problem concerns data quality and provenance. A digital twin may produce convincing visualisation even when the data are incomplete or biased. Responsible use requires tracing the source, time, accuracy, preprocessing method, and limits of data applicability. The model should communicate not only the result but also uncertainty.

The fourth problem is model validation in a changing environment. Initial correspondence with the physical object does not guarantee continued accuracy because of wear, reconfiguration, changes in operating modes, or user behaviour. Continuous calibration, drift detection, and rules for safe transition to a fallback mode are required.

The fifth problem is cybersecurity. The more closely a digital twin is connected with control, the greater the potential impact of data, model, or command substitution. Protection must cover the entire chain: sensor, transmission channel, storage, model, decision interface, and actuator. A federated ecosystem additionally requires a clear distribution of responsibility among participants.

The sixth problem is economic feasibility. High detail increases the cost of sensors, computing, and maintenance but does not always increase decision value. Therefore, the level of accuracy should correspond to the specific task. A practically useful twin is not the largest model but the minimum sufficient model with a proven impact on decisions.

The seventh problem is the human in the loop. An automated recommendation may conflict with a worker's non-formalised experience. Completely ignoring such experience reduces system acceptance, while uncontrolled manual intervention destroys reproducibility. An interface is needed that allows a person to confirm, reject, or modify a plan while recording the reason.

The eighth problem is the environmental cost of digital technologies themselves. Complex models, large datasets, and HPC consume energy. The positive effect of optimising the physical system should be compared with the digital footprint. The European logic of the twin transition directly requires digital and green transitions to reinforce each other rather than merely being declared (Muench S. et al., 2022).

A critical review reveals a separate functional gap. Most systems answer the questions “what is happening?”, “why did it happen?”, “what will happen?”, and “which operating mode is better?” quite well. The full cycle is less formalised: “what physical result should be created?”, “what alternatives are feasible?”, “what sequence of actions will move the system to the selected state?”, and “how should the uncompleted part of the plan be changed after an actual deviation?”

Table 4.3

Classes of twins

Twin class	Main question	Typical output	Limitation
Descriptive	What exists and what is happening?	Current digital state	Does not create a future result
Diagnostic	Why did a deviation occur?	Cause or component state	Reacts after the event
Predictive	What is likely to happen?	Forecast and risk	Does not necessarily contain an action plan
Optimisation	Which operating mode is better?	Recommended parameters	The target is often set externally
Projective	What state should be created and how can it be achieved?	Target state, trajectory, instructions	Requires feasibility control

Source: developed by the author.

A separate limitation is computational complexity. As the number of objects, permitted orientations, resources, and time dependencies increases, the space of possible configurations grows combinatorially. In spatial placement or scheduling

tasks, exhaustive search quickly becomes unacceptable. Practical implementation therefore requires a combination of exact methods for small subtasks, heuristics and metaheuristics for finding acceptable solutions, and early elimination of options that violate hard constraints. The quality criterion is not a mathematically absolute optimum but the best proven feasible solution obtained within the time available for control.

The risk of false synchronisation arises when the digital model has formally been updated but the actual data arrived late, were incomplete, or belonged to another state of the physical system. To reduce this risk, each observation should include a timestamp, source identifier, accuracy estimate, and validation status. In critical operations, a confidence threshold should be established: if total uncertainty exceeds the acceptable value, automatic control is suspended or requires operator confirmation.

Organisational barriers are often more significant than technological ones. Data may belong to different departments, use incompatible reference systems, or be used without a clearly defined quality owner. Overcoming this barrier requires a data-governance model: roles of owner, steward, and user; rules for changing reference data; quality indicators; and incident-review procedures. Without this, a digital twin automates the contradictions of the existing organisation instead of improving controllability.

A scenario approach is appropriate for risk assessment. For each critical function, the hazardous event, its cause, probability, scale of consequences, detectability, and compensating mechanism are identified. Examples include sensor failure, RFID-tag substitution, drift of a computer-vision model, loss of communication, conflict between local and central twins, or incorrect learning from an unsuccessful scenario. Such analysis links cybersecurity, functional safety, and model quality into one management system.

To address the identified gap, the concept of a projective digital twin is proposed. It is a single structured digital model of one possible future state of a physical system and the predicted method of transition from the current state to that state. It includes not only an image of the result but also a model of the process for creating it, resources, constraints, risks, criteria, and expected indicators.

The term “projective” has two interconnected meanings. In the temporal sense, it refers to projecting a physical system into a possible future state. In the spatial-interface sense, the result or the next action may be visually projected onto a work surface, container, or other physical space. The second meaning is a possible implementation method but is not a mandatory feature of the concept.

The fundamental difference lies in the direction of causality. A traditional twin mainly moves from the physical state to its digital representation and then to a forecast. A projective twin starts with a set of feasible future states, selects or agrees on one of them, transforms it into a trajectory and control actions, and then verifies actual achievement.

A projective digital twin should be represented as a composition of interconnected models: the physical system; initial state; target state; transition; resources; constraints; risks; assessment criteria; observation mechanism; and adaptation rules.

The system may generate one twin if the decision is unambiguous, or a set of alternative twins. In the second case, each alternative describes not simply another result but another “result–method of achievement” pair. This is important because the same final state may require different resources, time, and levels of risk.

The initial stage is to obtain data on the actual system. Sources may include sensors, machine-vision cameras, information systems, digital catalogues, and user input. The data are transformed into a consistent state description that records not only values but also their accuracy and relevance.

Next, goals and constraints are formalised. A goal should not be reduced to one number. For example, packaging requires simultaneous consideration of capacity, compatibility, fragility, retrieval order, weight, material costs, and ease of execution. In the Industry 5.0 context, worker safety, environmental impact, and resilience to disruptions are added.

On this basis, a space of feasible future states is formed. The algorithm eliminates physically impossible or legally unacceptable solutions, evaluates the remaining ones using a vector of criteria, and presents one or more options. Selection may be automatic, human, or mixed.

The selected state is transformed into a transition model. For each operation, prerequisites, the expected intermediate state, resource, acceptable deviation, and verification method are defined. The link between the future configuration and the physical sequence of actions creates the management value of the model.

During execution, the system receives actual feedback. If a deviation is within acceptable limits, the already achieved part of the state is accepted and the uncompleted part may be rebuilt. If a deviation violates safety or makes the target unreachable, the system stops the process, changes the target, or returns to an alternative twin.

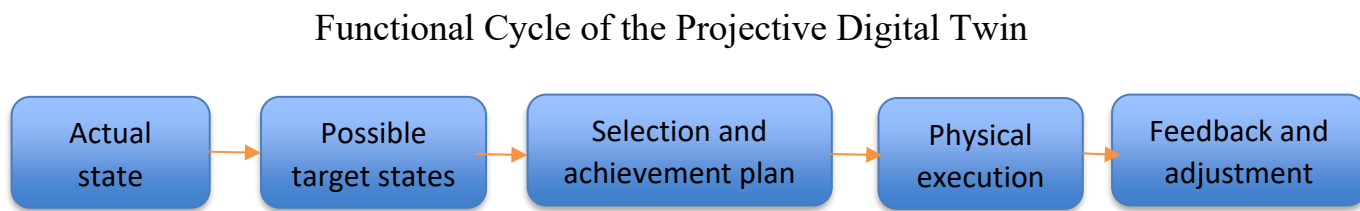


Fig. 4.2. Functional cycle of the projective digital twin

Source: developed by the author.

In formalised form, the projective digital twin can be represented as the structure $D^p = \langle x_0, G, P, U, R, C, Q, F \rangle$, where x_0 is the estimated initial state; G is the set of feasible target states; P is the predicted transition trajectory; U is the sequence of control actions; R represents resources; C is the system of constraints; Q represents assessment criteria; and F is the feedback mechanism. This notation emphasises that the model of the future result is only one component: without a trajectory, resources, and verification of the actual state, it remains a digital design rather than a twin of a controlled physical process.

The choice of an alternative can be described as a multi-criteria assessment problem $D^* = \arg \min J(D_k), D_k \in \Omega$, where Ω is the set of physically feasible projective twins. Function J aggregates normalised indicators of time, cost, energy, risk, ergonomics, and resilience. Since reducing criteria to one number may hide conflicts between priorities, responsible decisions should additionally form a Pareto set and show the user which indicator makes one alternative preferable to another.

The architecture of a projective twin has at least four logical levels. The data level identifies physical objects, the environment, and events; the model level

maintains the current state and generates possible target states; the decision level checks constraints, compares alternatives, and performs planning; the execution level transfers instructions to a person or machine and receives confirmation. Formalised data contracts should exist between the levels so that replacing a sensor, optimisation algorithm, or interface does not damage system integrity.

Validation of the concept should be performed separately for the state model, the transition model, and the adaptation mechanism. For the state model, the accuracy of reconstructing the physical configuration is assessed; for the transition model, the share of executable instructions, duration, and resource costs are evaluated; for adaptation, the ability to preserve target achievability after a deviation is assessed. Comparison should be made with baseline modes: manual execution, a static digital instruction, and a traditional twin without automatic replanning.

A representative area of application is order picking, packaging, palletising, and internal logistics. Here the future physical result has a clear spatial structure, while errors arise from incomplete data, the human factor, changes in order composition, unsuitable packaging, or actual displacement of objects.

The system creates a digital model of each material object involved in picking, placement, or packaging processes. The digital model contains a set of parameters describing the physical, geometric, and operational properties of the object that are required for automated analysis and modelling of its placement in physical space.

To support automated generation of a digital twin for picking, placement, and packaging processes, the system creates a digital model of the available physical space intended for placing material objects. The digital model of physical space is a structured set of parameters describing geometric characteristics, constraints, and environmental features within which operations with material objects are performed.

Physical space may include packaging, transport containers, boxes, bags, pallets, racks, work surfaces, production zones, vehicle cargo compartments, warehouse cells, or other objects intended for the placement of material objects.

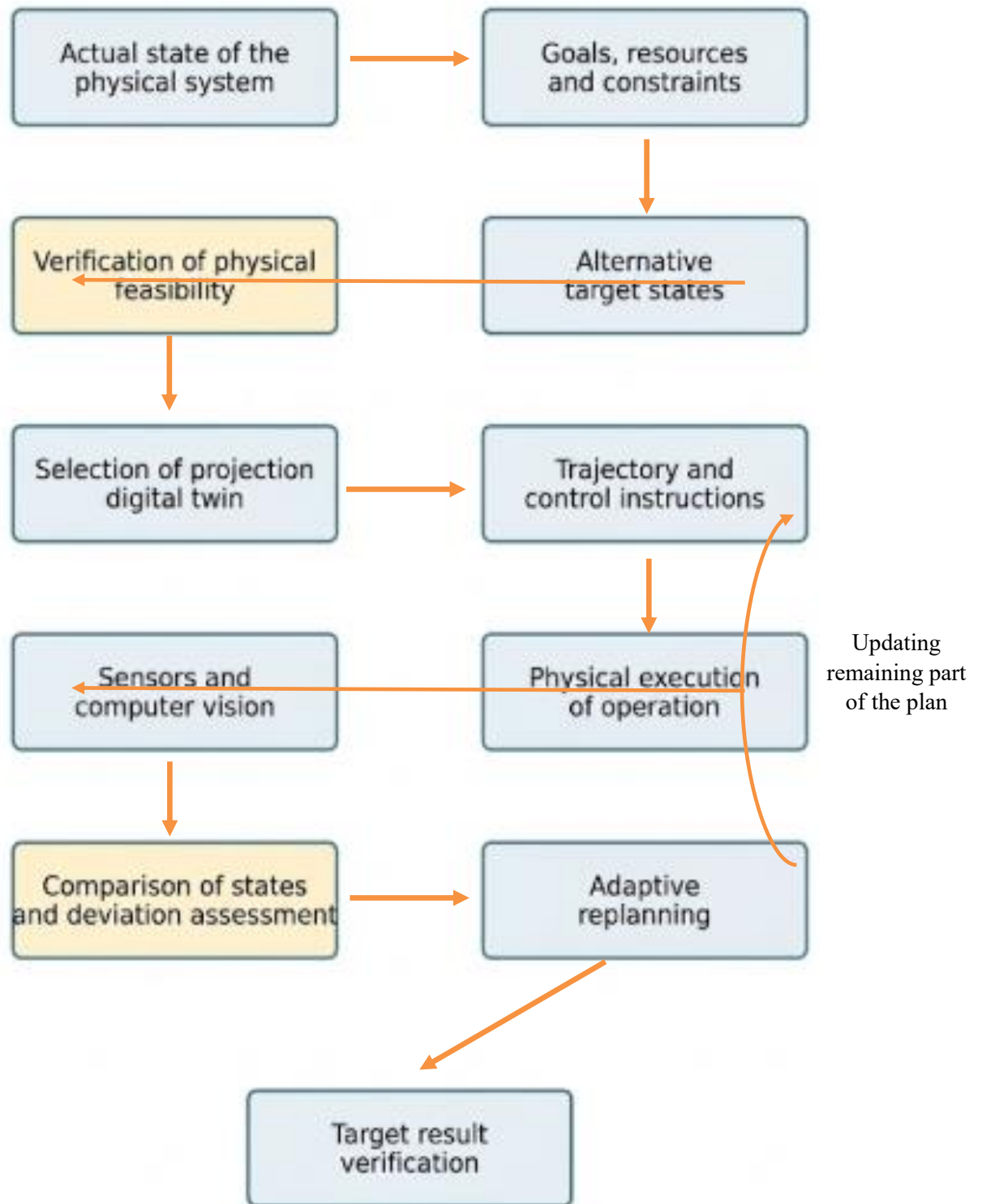


Fig. 4.3. Projective digital twin operation algorithm
Source: developed by the author.

The system performs automated analysis of digital models of material objects and digital models of the available physical space in order to determine one or more possible options for their spatial placement. During the analysis, the system considers the geometric parameters of material objects, their quantity, weight, permitted orientations, compatibility characteristics, placement constraints, and the parameters of the physical space in which the operation is planned.

Based on these data, the system automatically generates a set of possible placement options for material objects in the available physical space and evaluates them according to specified criteria. After a set of feasible spatial-placement options has been generated, the system evaluates them according to defined criteria and automatically determines an optimal option.

The optimal option may be the one that provides the most efficient use of available physical space, minimises the consumption of packaging materials, reduces the number of packaging units used, meets transport-safety requirements, or satisfies other criteria established by the system rules.

After determining the optimal option, the system allows the user to review one or more alternative placement options that also meet the established constraints and can be implemented in the physical environment.

The system controls the feasibility of the user's choice by automatically checking whether the selected option complies with the geometric parameters of material objects, the parameters of physical space, and other constraints used in modelling. If the user selects an option that does not allow complete or correct placement of material objects, the system automatically blocks the choice or offers the closest feasible alternatives.

In particular, the system may allow the selection of larger packaging, another geometric form, several packaging units, or other feasible placement options provided that all material objects can be physically placed according to the established rules.

The system automatically updates the digital placement model when the composition of objects, the parameters of physical space, or user actions change. When material objects are added, removed, or replaced, the system re-analyses the available

physical space and automatically generates an updated spatial-placement option based on the new input data.

The system enables interactive user interaction with the digital twin by changing the position of individual objects, selecting alternative stacking options, or changing the type of packaging used. When the user makes changes, the system automatically checks whether the proposed option can be implemented, taking into account object geometry, available space, and established constraints.

If the proposed changes are feasible, the digital twin is updated and used for further generation of instructions and execution of operations. If the proposed option cannot be physically implemented, the system automatically rejects it or offers the closest feasible alternatives.

Based on digital models of material objects, digital models of available physical space, and the results of automated analysis of placement options, the system forms a digital twin of the picking, placement, or packaging process.

The digital twin is a digital model of the future physical result of an operation. It contains information about the set of material objects, their spatial positions, orientation, placement sequence, packaging used, and other parameters required to implement the process. The digital twin may be formed before physical operations begin and used to analyse, visualise, verify, approve, or optimise modelling results.

The system can generate one or more digital twins for different placement options, followed by comparison and selection of the most suitable option. Based on the generated digital twin, the system automatically creates control instructions for picking, placement, packaging, transport, or other processing of material objects.

Control instructions are generated according to the spatial model of object placement, the sequence of operations defined by the system, and established technological or logistics rules. The system automatically determines the order of operations and forms the sequence of actions required to achieve the result represented by the process digital twin.

To keep the digital twin up to date, the system receives and processes feedback from the physical execution of operations with material objects. Feedback may come

from users, enterprise employees, automated identification tools, sensor systems, scanning devices, measuring equipment, robotic systems, transport systems, or other data sources that monitor operations in the physical environment.

The system provides automatic dynamic adjustment of the digital twin based on data received during physical operations, changes in the parameters of material objects, characteristics of physical space, or other factors affecting process implementation. After new data are received, the system analyses their impact on the current state of the digital twin and determines whether it must be updated.

If deviations between the planned and actual process states are detected, the system automatically changes the digital model to keep it consistent with the current state of material objects and the physical environment. After the digital twin has been generated or adjusted, the system automatically transfers current control instructions to the performer involved in the relevant physical process.

Instructions may be transferred directly to enterprise employees, end users, automated control systems, robotic systems, transport systems, or other technical means that perform operations with material objects.

For example, the system receives the geometric characteristics of three objects and a container. The algorithm forms a feasible target configuration, determines the placement order, and visually indicates the position of the first object. If the worker places it with a displacement, but the object remains within the container and does not violate constraints, there is no need to require an exact return to the planned position. The system records the actually occupied area and rebuilds the positions of the next two objects.

This mechanism is fundamentally different from a static projection prompt. A static system repeats the initial template and treats any displacement as an error. A projective digital twin evaluates the meaning of the deviation: whether the target remains achievable, whether constraints remain satisfied, and whether a feasible residual plan exists.

Practical performance indicators may include operation duration, error rate, number of repacking operations, volume utilisation ratio, packaging-material

consumption, number of damaged items, ergonomic load, and training time for a new worker. Scientific validation of the concept requires comparison of at least three modes: work without prompts, a static digital instruction, and an adaptive projective twin.

Practical implementation of the concept requires compliance with a number of principles. Based on the analysis of European programmes, research projects, and modern approaches to Digital Twin development, a set of strategic, technical, and organisational recommendations can be formulated. Their implementation should support the transition from isolated digital models to interoperable, adaptive, and human-centred systems that can not only represent and predict the state of physical objects but also form and manage the achievement of a future physical result.

A primary condition for scalable use of digital twins is interoperability. Monolithic and isolated solutions limit model reuse, complicate data exchange, and create dependence on a specific technology provider. Therefore, Digital Twin architecture should include standardised interfaces, unified asset descriptions, including the Asset Administration Shell, open APIs, and mechanisms for interaction with European data spaces. This creates the basis for integrating local digital twins into federated manufacturing, energy, and infrastructure ecosystems.

The level of detail of a digital model should be defined according to the specific management task. Excessive accuracy does not always increase the practical value of a Digital Twin, but it requires additional sensors, computing resources, data-transfer channels, and maintenance costs. Therefore, the principle of minimum sufficient accuracy is proposed: the model should contain only the volume and level of data detail necessary for informed decision-making and safe control of the physical process.

When evaluating Digital Twin efficiency, it is necessary to consider not only the optimisation results of the physical system but also the digital environmental footprint of the technology itself. Energy costs of high-performance computing, artificial-intelligence algorithms, cloud infrastructure, and storage of large datasets should be compared with the resource, economic, and environmental effects achieved in the

physical environment. This approach corresponds to the European concept of interconnected digital and green transitions — the Twin Transition.

Data provenance traceability should be a mandatory component of a digital twin. Together with a modelling result or recommended decision, the system should provide information about the data source, time of receipt, accuracy, preprocessing method, degree of uncertainty, and limits of applicability of the relevant model. This improves the justification of decisions and reduces the risk of using digital-modelling results outside the conditions for which the model was developed and validated.

Cybersecurity should be ensured throughout the information and control loop: from the sensor, transmission channel, and data storage to the mathematical model, user interface, and actuator. The history of model versions, input data, automatically generated recommendations, operator decisions, and actually performed actions should also be retained. Such logging ensures system accountability and creates a basis for allocating responsibility among the developer, data provider, operator, and organisation that operates the digital twin.

In processes focused on creating a specific material result, it is appropriate to move from reactive to projective Digital Twin logic. Traditional logic mainly moves from the physical object to its digital representation and then to forecasting its behaviour. Projective logic begins with the formation of a digital model of a feasible target state, after which the method of achievement, control actions, sequence of physical operations, and mechanism for verifying the actual result are determined.

One of the central principles of a projective digital twin should be adaptive replanning. A minor deviation made by a worker, robot, or other actuator should not automatically require the system to return to the initial state. If the actual deviation does not violate safety, spatial, technological, or resource constraints and does not make the target impossible to achieve, the system should accept the current actual state as a new starting point. Only the uncompleted part of the trajectory is then rebuilt, while the already created feasible part of the physical result is preserved.

It is appropriate to provide one or more alternative projective digital twins. Each alternative should describe an interconnected “future physical result — method of

achievement” pair. Alternatives may be compared using a multi-criteria function that considers execution time, cost, energy consumption, material use, ergonomic load, safety, risks, and resilience to possible disruptions. If the criteria conflict, a set of Pareto-optimal solutions should be generated and the final choice should remain with an authorised user.

Feedback between the digital model and the physical process should be formalised using sensors, machine-vision cameras, RFID tools, weight sensors, or other available information sources. The data obtained should be used to determine the actual position of objects, verify completion of individual operations, detect deviations, and automatically update the uncompleted part of the projective digital twin.

In accordance with the human-centred Industry 5.0 approach, a digital twin should not remove people from the decision-making process but expand their capabilities. The system should propose recommended scenarios and explain the criteria for their selection while allowing the worker or operator to choose another feasible option, change priorities, or adjust the sequence of operations.

Changes proposed by the user should be automatically checked for physical feasibility. If a worker chooses a personal option for spatial placement, packaging, or execution of an operation, the system should verify geometric parameters, object compatibility, resource constraints, stability, safety, and achievability of the final result. Physically impossible or unsafe decisions should be blocked, with the reason explained and the closest feasible alternative generated at the same time.

An important development direction is controlled self-learning of the projective digital twin. This requires accumulating data on generated scenarios, user choices, actual trajectories, deviations, replanning cases, and final performance indicators. If a particular alternative scenario regularly provides a better result under comparable conditions, the system may gradually increase its priority. At the same time, changes in algorithmic priorities should be transparent and verifiable and should not automatically reinforce incorrect or unsafe actions.

Thus, practical implementation of a projective digital twin requires a combination of three interconnected components: technological interoperability,

adaptive control of the physical process, and preservation of meaningful human control. This combination makes it possible to align the proposed concept with Industry 5.0 principles and transform the digital twin from a tool for observation and forecasting into an instrument for forming, implementing, and verifying a future physical result.

A step-by-step picking scenario begins with identification of the order, packaging, and available work area. After geometric and technological characteristics are obtained, the system eliminates incompatible objects and prohibited orientations, generates several feasible configurations, evaluates them, and selects a placement sequence. The worker is not shown the entire model at once but receives a contextual instruction for the next action. After each step, a camera or another sensor confirms the identity and position of the object and compliance with constraints, reducing the accumulation of unnoticed errors.

If the first object is placed with a displacement, the algorithm first classifies the deviation. A geometrically acceptable displacement is accepted as a new condition; the occupied area is recorded, and the residual problem is solved for the objects not yet placed. A deviation that creates instability, blocks access, or violates compatibility is not accepted: the system explains the reason and proposes a corrective action. Thus, adaptability does not mean weaker control but a differentiated response to acceptable and dangerous changes.

Another scenario concerns a change in order composition during execution. After an object is added, the system should not automatically cancel all completed work. It first checks whether the new object can be included in the remaining space without violating constraints. If this is impossible, options for local repacking, changing packaging, or splitting the order are compared. Each option is assessed by additional time, material costs, risk of damage, and convenience for further logistics.

For palletising, the criteria are supplemented by stack stability, permitted load, unloading sequence, and centre of mass. A projective twin can model not only the final configuration but also intermediate states, because a physically stable final result does not guarantee a safe trajectory for creating it. This illustrates a general principle: feasibility of the target state and feasibility of the transition process are different conditions that should be checked simultaneously.

The effectiveness of the adaptive loop should be assessed using a system of indicators: the share of operations without repeated execution, average time from detecting a deviation to updating the plan, percentage of successfully accepted feasible deviations, number of unsafe decisions blocked before execution, and relative change in resource costs. Cognitive load and user trust should also be measured, because a complex but unclear recommendation may be systematically ignored.

For Ukraine, the introduction of digital twins should be linked not to mechanical copying of individual European platforms but to the formation of a compatible institutional and information base. Priorities should include standardised asset models, access to high-quality data, staff training, cybersecurity, and the ability to connect to European federated ecosystems.

The greatest short-term effect is possible in the recovery of critical infrastructure, energy, construction, transport, and logistics. Projective digital twins make it possible to compare alternative future states of an object, assess resources and risks, and form a sequence of physical actions before work begins. This is especially important when financing, materials, and time are limited.

Ukraine's participation in Digital Europe and Horizon Europe creates an opportunity not only to receive funding but also to include Ukrainian organisations in common standards, research networks, and demonstration projects. At the same time, practical implementation should be accompanied by assessment of economic feasibility, the digital footprint, data availability, and the organisation's readiness to change its own processes.

The first perspective is the integration of projective twins into federated ecosystems. A local twin of a work operation can use asset models provided through AAS, receive data from a corporate data space, and transfer aggregated results to a production-line twin. This makes it possible to combine detailed physical execution with system-level planning.

The second perspective is the use of generative and causal artificial intelligence. Generative models can propose alternative configurations, but their results must be checked against physical and regulatory constraints. Causal models can explain why a particular action leads to a result, which is especially important for safe control.

The third perspective is integration with augmented reality and spatial interfaces. Visual projection or AR overlay reduces the gap between the digital model and the work area. However, the interface should be an implementation tool rather than a substitute for the model: without a target state, feasibility rules, and adaptation, visualisation remains an electronic instruction.

The fourth perspective is learning from execution history. A database can accumulate generated twins, actual trajectories, causes of deviations, worker decisions, and final performance indicators. This creates a basis for refining criteria, forecasting complexity, personalising instructions, and identifying systemic constraints.

The fifth perspective is expansion from local operations to construction, maintenance services, medical logistics, emergency response, and urban infrastructure. Common features are the existence of a material result, a set of feasible scenarios, physical constraints, and the need to adapt the plan using execution data.

In the European context, the concept is consistent with Industry 5.0 if automation does not remove the worker from the loop but strengthens the ability to make safe decisions. The system should explain the reason for replanning, show uncertainty, allow recommendations to be rejected, and learn only from verified results.

Legal responsibility requires separate research. If a target state is generated by an algorithm, a worker follows a visual instruction, and the result causes harm, responsibility must be allocated among the model developer, data provider, operator, and organisation. Therefore, logging versions, decisions, and interventions is part of a scientifically grounded architecture rather than merely a technical function.

Further empirical validation should cover the accuracy of physical-state reconstruction, speed of alternative generation, frequency and effectiveness of replanning, worker cognitive load, resilience to incomplete data, and the digital energy footprint. Such experiments will make it possible to identify the conditions under which a projective twin has advantages over a conventional decision-support system.

For practical implementation in Ukraine, a phased model is appropriate. The first stage is an audit of the process, data, and economic problem; the second is a pilot in a limited area with measurable indicators; the third is model standardisation and integration with corporate systems; and the fourth is scaling and connection of external

participants. Transition between stages should depend on achieving criteria rather than on the formal completion of equipment procurement.

A policy of technological neutrality is especially important. Public and corporate customers should define requirements for interoperability, security, data portability, and model verification but avoid unjustified commitment to one format or provider. This reduces long-term dependence and facilitates integration of Ukrainian solutions with European data spaces.

Investment assessment should combine financial and non-financial indicators. Financial indicators include reductions in downtime, defects, material costs, and cycle time; non-financial indicators include improved safety, resilience, decision transparency, and the ability to train personnel. The costs of digital infrastructure, cyber protection, data maintenance, and revalidation after changes in the physical system should be considered separately.

A pilot implementation of a projective digital twin should be organised as a controlled quasi-experiment. First, baseline process indicators are recorded over a representative period without digital support: operation duration, error frequency, non-productive losses, number of repeated actions, and worker load. After implementation, the same indicators are measured for a static digital instruction and an adaptive projective twin. Operations of comparable complexity should be compared, because a simple comparison of averages without considering task composition may create a false impression of technology effectiveness.

The evaluation methodology should consider not only the average result but also the variation of indicators and the stability of the effect. If time reduction is achieved only by experienced operators or under ideal data quality, the solution cannot be considered ready for scaling. Therefore, results should be grouped by operation complexity, worker experience, frequency of deviations, and completeness of sensor data. Cases in which the system could not form a feasible plan or transferred the decision to a person should be analysed separately. This makes it possible to identify the actual limits of model applicability.

Economic justification should be based on total cost of ownership rather than only on the price of the initial software. Costs include sensors, computing

infrastructure, integration, preparation of digital models, cybersecurity, staff training, maintenance of reference data, and revalidation after changes in the physical process. Benefits include reductions in defects, downtime, material consumption, and time, as well as lower damage risk and lower costs of training new workers. A scaling decision should be based on the total discounted effect and sensitivity analysis of key assumptions.

Criteria for pilot readiness for industrial use should include confirmed state-reconstruction accuracy, stable economic effect, acceptable replanning time, absence of critical safety violations, manageable model versions, and positive user evaluation. If at least one critical criterion is not met, scaling should be postponed and the root cause removed. Such a staged approach reduces the risk of turning the digital twin into a formally implemented but practically unused information system.

After the pilot is completed, the external validity of the results should also be checked — the possibility of transferring them to other sites, enterprises, or types of operations. The conditions under which the effect was achieved should be recorded: object characteristics, data quality, staff qualifications, technical environment, and accepted constraints. Scaling without such a description creates a risk that a successful local model will be used outside its area of applicability. Therefore, the pilot result should include not only the value of an economic indicator but also a formalised profile of the conditions under which the solution can be reproduced.

The study has shown that Digital Twin in the European Union is moving from local digital replicas to federated, cross-sectoral, and socially significant ecosystems. Destination Earth and the European Digital Twin Ocean demonstrate scenario modelling of natural systems; TwinEU demonstrates interoperability of infrastructure twins; MODAPTO demonstrates distributed intelligence in manufacturing; and Change2Twin demonstrates mechanisms for spreading the technology among SMEs.

The European approach is defined not only by technological scale but also by the Industry 5.0 regulatory framework. Human-centricity, sustainability, and resilience become criteria for architecture and evaluation. At the same time, problems of semantic interoperability, data quality, model validation, cybersecurity, economic feasibility, and responsibility remain.

A scientific gap has been identified between representing or forecasting a state and the integrated formation of a future physical result together with the method for achieving it. To address this gap, the concept of a projective digital twin is proposed — a model of the target state, transition trajectory, resources, constraints, risks, criteria, control actions, and adaptive feedback.

The scientific novelty lies in functionally identifying a class of digital twins focused not only on representation and forecasting but on the controlled creation of a physical result. The key property is the ability to accept an admissible actual deviation, record the part of the state already created, and rebuild the uncompleted part of the trajectory.

Practical feasibility is demonstrated using the example of spatial placement of material objects with visual guidance and adaptive replanning. Further research should focus on experimental validation, development of metrics, integration with standard information models, and identification of conditions for safe use in human-centred manufacturing systems.

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4.2. Unified Digital Platform for Suburban and Intercity Bus Transport Based on the PSO Model with Integrated Anti-Corruption Mechanisms

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The current state of Ukraine's suburban and intercity passenger bus transport