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Posted Date: 14 November 2025

doi: 10.20944/preprints202511.1049.v1

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Article

Digital Twinning Future Trends Evaluation Framework: A Digital Twins Approach

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Abstract

The contemporary Digital Twinning Paradigm (DTP) emerges from the synergy of conceptual development and experiences gained through the digital transformation of real-world Cyber-Physical and Sociotechnical Systems. Balancing current practices and future trends of Digital Twinning concepts and technologies, framed by maturity and futureness evaluation and assessment, is an invariant. The intended mission of this research article is to: first, establish and collect an open pool of digital twinning future trends, and second, specify the foundations for the development of a Digital Twinning Future Trends Evaluation Digital Twins-based framework. A systematic literature review methodology aided in fulfilling the first part of a mission, while the second one emerged from the characteristics of complementary maturity evaluation frameworks and digital twins referent architectures. The key research hypothesis is that the formation of a future trends persistence database precedes the backward-tracking analysis, enabling the isolation of the persistence rationale. These rationalities then drive the DTP model refinements to foster further prediction accuracy. The research outcomes suggest that, in general, a more rigorous justification of research suitability is necessary, and highlight certain obstacles affecting the representativeness of review-based publishing. Through the continuous improvement of the future trends data layer, coupled with a comprehensive repertoire of cross-related research publications, the proposed framework enables the assessment of future trends in the DTP or other paradigms through Digital Twins.

Keywords: digital twinning paradigm; digital twinning future trends; digital twins; digital twins maturity evaluation; futureness evaluation; engineering complex systems

1. Introduction

The Digital Twinning Paradigm (DTP) timeline spans over more than twenty years, encompassing inherent scientific and industrial frameworks with a variable reporting density and an ever-growing set of announced future trends. It directly correlates with Digital Transformation (DTR) pressures, imposed on organizational systems throughout the entire life cycle, emerging from the synergy of Industry 3.0, 4.0, 5.0, 6.0, 7.0, and beyond drivers [1–3], as well as a growing scope and complexity of real-world systems' structure and behavior affected by engineering or reengineering activities.

To gain the relevant context for the futureness evaluation and assessment methodology, it is necessary to critically analyze the state-of-the-art of general and Digital Twins-related maturity evaluation and assessment domains. Maturity evaluation and assessment paradigm (MEAP) has a much longer timeline spanning from the early human history to the proximal eternity in a constant search for the universal framework with an inclusive metric system and the inherent systematic procedures enabling the effective and efficient management of complex systems with either tangible or intangible nature [4]. A MEAP largely overcomes the simple scoring mechanisms to assess the current compliance level of the assessed system, concept, or phenomenon. It assumes the existence

of an underlying Maturity Model (MM) that specifies the evolutionary process, associated practices, and the all-inclusive upgrade scale.

Throughout the specification and development history of the MMs, a constant struggle between two key principles persists: raising the model's abstraction level towards more general, context and domain-independent applicability, and enabling higher reusability potentials through streaming towards context and domain-specific specializations of key model components.

Within this research, under the dependability of a maturity context (MC), we assume the impacts of real-world systems' influencers that constrain the applicability of a Maturity Model in different human-related fields. Similarly, dependability of a maturity domain (MD) refers to the effects of influencers emerging from the domain-specific characteristics of individually assessed objects. The relevance of a particular Maturity Domain (Systems Thinking in context of Systems Engineering, Technology, Strategy, Skills, Culture, Organization, Process, Data, Leadership, Cyber Security, etc.) in the concrete Maturity Context (Governing, Business, Industry, Environment, Education, Healthcare, etc.), depends on its participation in the metric system used to measure a Maturity Level (ML) of the assessed system or phenomenon, over a selected maturity model (MM), each with a respectable number of research publications and rich individual practices foundation.

The determination and time-stamping of a Maturity Level (ML) within the specified MM represents a universal approach to assessing an arbitrary entity or a concept by the contemporary maturity stage mark-up attachment. Consequently, individual maturity models represent prescribed metric systems that address the related Readiness Level (RL) and the associated Risk Categorization (RC), determining the structural and behavioral compliance of the assessed entity or concept with the mutually accepted scales [5–7]. Besides aiding in the correct identification of the current maturity level, each maturity model proposes a comprehensive roadmap guiding the upgrading path leading from the current to the targeted, usually higher maturity level [6,7].

A traditional MM follows a layered architecture with inclusive completeness, meaning that each higher level demands the persistent satisfaction of all the lower-level embedded features. The generic inclusiveness assumes that a failure to satisfy any lower-level features at the higher maturity level automatically downgrades the current level to the lowest level with the complete set of satisfied ones [8,9].

In [10], after the comprehensive critical analysis of the assessment methods existing in the selected set of popular maturity models, from developers and users perspective, the authors propose a five steps continuous maturity assessment method (CMAM), as promising approach based on Design Science Research (DSR) methodology [11], and inaugurates the continuity as the main characteristic of a sustainable maturity assessment methodology.

The contemporary Sociotechnical Systems paradigm emphasizes the importance of balancing human-centric and organization-centric approaches when engineering or reengineering complex real-world organizational systems [12]. Within a human-centric approach, the Systems Thinking Maturity Models (STMMs), addressing the generic origins of human-related scientific and technical reasoning foundations, including knowledge, skills, behaviors, values, and practices, affect the cognition processes in two distinct ways: understanding how they currently operate, and directing them throughout the transformations leading to upgrading the operations' effectiveness [13].

Within the organization-centric approaches, the specification and development of domain-dependent frameworks is a persistent trend in mitigating the complexity challenges emerging from available technologies and the constant expansion of their applications affecting real-world systems. Enterprise Architecture Frameworks (EAF) traditionally encapsulate the architecting challenges of an engineered/reengineered system through a systematic, controlled, and measurable evolutionary process [14–16]. Although being in the evaluation status at the moment, The Open Group Architecture Framework (TOGAF), within the current Standard Edition 10, declares four standardized Architecture Dimensions: the Business Architecture (strategy, governance, organization, and business processes), the Data Architecture (logical and physical data architecture assets and data management resources), the Application Architecture (individual applications

supporting core business processes according to the specified business architecture), and the Technology Architecture (hardware, software, and communications infrastructure supporting the deployment of business, data and applications services) [17]. Additionally, the TOGAF's Architecture Development Method (ADM) approach supports the iterative and cyclic transformation of the system under consideration with respect to its current maturity status. Within the EAF, the embedded Strategy Management Maturity Models (SMMMs) specify structured evaluation mechanisms for determining how well an organization plans, executes, and adapts its strategies, identifying areas for improvement and guiding growth towards more mature and effective practices [18].

To specify the foundations of the futureness assessment framework, our research efforts focus on an open dimensionality approach adopting TOGAF's four architectural dimensions as the basic cluster defining a coarse-grained boundary of the digital twinning future trends dimensionality. The recursive compositeness of individual dimensions follows our claims, elaborated in [19], that the sustainable maturity assessment framework must adhere to the hyper-framework architecting principles, with the embedded configurability supporting the creation of different paradigms, like contemporary hotspot digital twinning, as coherent collections of individual dimensions constituents (concepts, principles, or technologies).

On the other hand, according to [20–24], the disruptive digital twinning technologies exhibit a high potential for breaking the inherent rigidity of the traditional maturity upgrading process specified within the contemporary EAFs. If armed with a minimal configuration that, on a current maturity level, may trigger transitional shortcuts in the multipath upgrading space, the overall mature model-based gradual transformation principle becomes questionable.

1.1. Research's Intended Mission

The intended mission of this research article is to evaluate the digital twinning concepts when applied to the Digital Twinning Paradigm (DTP), identify the particular DTP trends constantly attributed as future over the relevant historical forward chaining timeline, and relate them to the derived features of the proposed Futureness Assessment Model (FAM). From a methodological perspective, this article explores the structure and evolution of digital twinning future trends across the related DTP development stages, with the common goal of cross-referencing them against conceptual and technology timeline milestones. From an engineering perspective, this article aims to formulate a Digital Twinning Futureness Evaluation Digital Twins architecture as a promising operational framework for mitigating further digital twinning trends.

We claim that the persistence analysis of digital twinning future trends represents a challenging hotspot for backward-tracking analysis and isolating the rationalities for the persistence. Through recursive forward chaining and backward tracking, these persistence rationalities then drive the FAM and DTP model refinements and consequently improve the accuracy of further predictions.

We believe that, throughout the continuous maintenance of the future trends data layer, coupled with the cross-related research publications repertoire, the proposed framework promises long-term sustainability of the digital twinning paradigm's individual future trends evaluation.

1.2. Research Motivations and Relevancy Analysis

In the scientific journal's preparation guidelines and recommendations, the elaboration of related work and future research directions is mandatory. While the related work discusses research on external foundations, future research directions reflect the publication's envisioning potential. They both significantly influence the post-publication referencing rate and directly affect a research article's domain relevance. Further on, a cumulative domain citation index is of crucial importance for institutional and personal academic level assessment and ranking.

Unfortunately, when performing related work analysis and predicting future research directions, it is necessary to search a global publications database. The representativeness and quality of generated results strongly depend on two interdependent features: the quality of search engines'

embedded clustering, classification, and query formulation mechanisms; and the authors' domain expertise level and search engine utilization skills.

If one ignores the obviously disruptive impact of a personal skills level, the engineering rationalities remain. They constantly question the achieved sophistication level of classification and clustering algorithms for context-related referencing, even of the keywords, fostering the development of contemporary search engines. Through the estimated growth of artificial intelligence and natural language processing mechanisms incorporation, the current balance of organic and AI-driven traffic, resulting from global network searching, gradually changes [25–27]. In [28], the Customer-centered search (improving search results relevancy through machine learning and AI-based instead of keyword-based), Personalization (AI-based building of personal search profiles), Recommendations vs. Relevance (shift from questioning to more direct answering), Social Content for Business (the Social Media rankings incorporation), and Leveling-up search (multimedia searching options), have been recognized as the top five trends in search technology.

Currently, the sophisticated post-casting of the gained result set remains crucial in overcoming stated searching obstacles. The need for a digital twins, favoring the reusability of domain-dependent searches of digitally accessible research publications, appears promising.

Our direct motivations emerged from a Google Scholar-based search for scholarly articles that timely correlate digital twinning future trends on a general scale, independent of the underlying real-world system's domain field.

To justify the appropriateness of this research, we first searched Google Scholar online database with the following initial query: "The Comparative analysis of digital twinning future trends", to find previous publications similarly addressing the intended research's topics. The query produced a relatively large result set of 1122 members. After examining, titles, keywords, and available Google Scholar summaries, we have excluded obviously unrelated publications, articles with less than four citations, and articles addressing a domain specific aspects of digital twinning focusing only on general and methodology-related contents, the reduced set with 206 research articles remained. Consequently, the initially estimated time frame of 2000 to 2025 publishing year, reduced to rationally justifiable 2016 to 2025. Finally, focusing only on free-downloadable research articles, the research set has been further restricted by near 25% resulting in the final cardinality of 150 qualified articles. Figure 1 visualize the annual distribution of articles according to the inherent time frames.

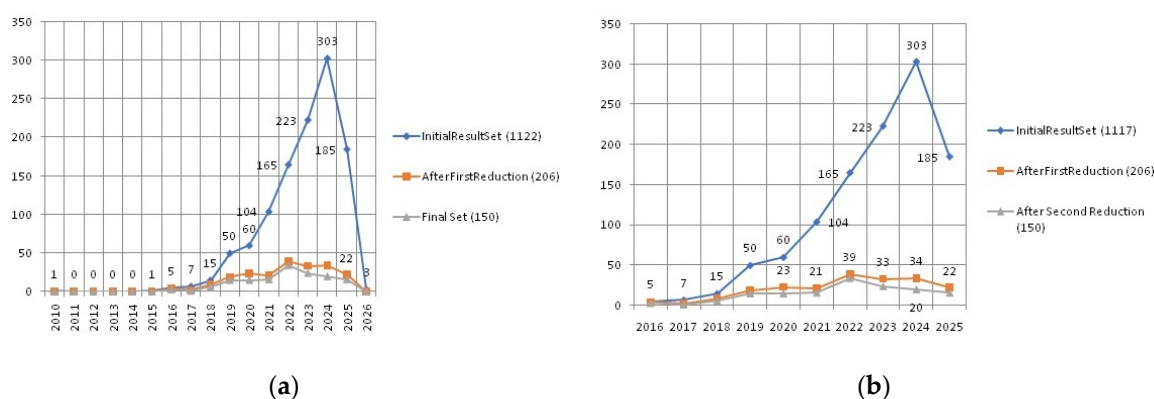


Figure 1. The annual distribution of articles according to the inherent time frames: (a) Represents articles distribution over 2010 to 2026 time frame with the Initial Result Set, Result Set after first reduction, an Final Set; (b) Represents articles distribution over 2016 to 2025 time frame resulting from the elimination of the assumed statistical artifacts (1 article from 2010, 1 article from 2015, and 3 articles from 2026) from the Initial Result Set (a reduction from 1122 to 1117 members).

According to the Publication Categorization of the Final Dataset (Figure 2 (a)), 52.67% of member publications (Others) do not explicitly specify future trends in the publication's metadata (title, keywords, findings, or AI generated summaries), 14.67% are Review only, with insignificant

elaboration on digital twinning future trends, 13.33% Future only, with the less significant elaboration on digital twinning future trends determination sources. Finally, 19.33% exhibits a balanced approach between digital twinning future trends origins and future trends elaboration. Figure 2 (b) systematizes the annual distribution of publication categories over the 2016 - 2025 time frame.

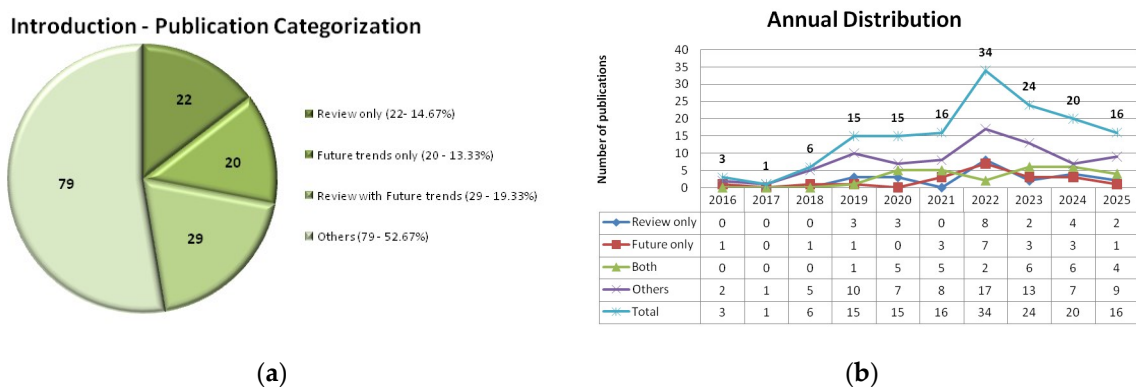


Figure 2. Final Dataset Categorization: (a) Cumulative publication categorization; (b) - Analytical Annual Distribution.

Motivated by the formulated search mission to identify the publications with a highly compliant mission compared to this research article's mission, we have decided to conduct a detailed expert analysis of all individually qualified publications (150). The results showed that among the final dataset, there are no publications explicitly addressing the comparative study of digital twinning future trends maturity assessment in the intended manner.

Based on that conclusion, we believe that it is beneficial to conduct this research according to the methodology principles combining systematic literature review and model-driven engineering approaches to build the article's foundations, formulate a Digital Twins model of the proposed Futureness Assessment Framework (FAF), and specify domain-dependent specializations framing the path towards Digital Twins-Based Digital Twinning Future Trends Evaluation Framework development.

For the eventual independent analysis and previous claim justification, please refer to the Supplementary Resource SR1 (00_01_Supplementary_Resources.zip, Microsoft Excel file named 00_03_Introduction_Systematic_Review_Data.xlsx).

1.3. Research Hypotheses and the Related Research Questions

From the research methodology aspects, this research article focuses on a retrospective analysis of individual digital twinning future trends appearing in a representative set of selected publications spanning the most relevant maturation timeline (2016 to 2025). According to the primary research's motivations, elaborated on in previous subsection (subsection 1.2), we state the key research hypotheses as follows:

- RH1 - The persistence level of digital twinning future trends, expressed on the futureness scale, represents a suitable metrics system and enables recursive forward-chaining and backward-tracking analysis, leading to the continuous evaluation of the persistence reasons and raising the quality of the futureness prediction;
- RH2 - It is possible to specify a digital twinning future trends futureness evaluation framework's Digital Twin Model (DTM) supporting the RH1 claims.

To frame the research methodology and the solution context, we specify a set of research questions (RQ) representing the essential pillars in determining the futureness evaluation framework, with an open set of assessment dimensions, suitable for the assessment of the prospective

future trends announcements rationalities, concerning the futureness level associated with the proposed trend.

RQ1 - Is it possible to establish the foundations for the evaluation of digital twinning future trends, determining the dynamic facts pool suitable for the continuous assessment process?

RQ2 - Is it possible to augment the existing digital twinning maturity modes with the reflexive futureness assessment services and establish the Digital Twinning Futureness Evaluation (DTFE) Digital Twin?

RQ3 - Is it possible to reflexively apply the DTFE mechanisms for its Digital Twin's continuous auto-improvement?

We claim that the affirmative answers to the specified research questions may establish the foundations of an extendible, data-driven, digital twinning futureness assessment framework, which justifies the formulated hypothesis RH1 and aids in the continuous improvement of the futureness evaluation process through the RH2 endeavor.

1.4. Research Article's Organization

With this in mind, the rest of the article is composed of five additional sections. Section 2, Materials and Methods, elaborates on the research methodology and the foundations of the stated hypotheses and related research questions. Section 3, Results, elaborates on the main findings emerging from the conducted comparative analysis and formulates the Digital Twin Model foundations of the open digital twinning futureness evaluation framework. Section 4, Discussion, cross-relates the analyzed references, justifies the appropriateness of the proposed futureness assessment models, and discusses the generic and specific limitations of the proposed solution. Section 5, Conclusions, contains the concluding remarks and future research directions.

2. Materials and Methods

The foundations of this research directly arise from the intended application of the digital twinning paradigm when solving the future trends evaluation problem. A common challenge, significantly affecting the credibility of an arbitrary publication, is the thesis switching risk. In this context, it arises when the digital twinning paradigm, organizational readiness for digital transformation, industry (3.0, 4.0, 5.0, 6.0, and 7.0) conceptual maturity [19], and digital twinning embedded technologies are not well distinguished in the process of maturity evaluation and assessment. This separation is tedious and, if not performed correctly, significantly jeopardizes the credibility of the research results. Throughout the systematic literature review, conducted to justify the need for this research and elaborated on in the Introductory section, we have analyzed several research articles with this fallacy. With that in mind, we did our best to exclude these articles from the representative dataset and strengthen our critical analysis abilities to avoid the same trap. Consequently, the digital twinning future trends evaluation and assessment, as presented in this research context, excludes any aspect related to organizational readiness for Digital Transformation and the conceptual maturity of Industrial Revolutions, Digital Twinning, or Digital Twins, but includes the futureness evaluation and assessment of their embedded technologies, concepts, and paradigms.

With the contemporary digital twins concept [29,30] relating real-world (Physical Twin) with its digital counterpart (Digital Twin) over an integrated database, one of the key questions is how to define a physical twin in this research context.

To answer that question, based on contemporary challenges of digital twinning paradigm [31–33], and model driven digital twins development methodologies [34–37], we believe that it is first necessary to formulate a light-weight extendible Digital Twin Referent Model, and afterwards specify domain-dependent adaptations aligned with this research endeavors leading to the Digital Twinning Futureness Evaluation specializations, compliant with the hypothesis RH2. We claim that the general Digital Twin Model, specified in [30], represents a promising starting point.

According to the stated hypotheses and formulated research questions, in the context of this research article, a physical twin represents an intangible, multilayered, distributed cyberspace library, excluding the underlying information and communication infrastructure.

Additionally, it is necessary to formulate a representative set of reusable enablers addressing the following research methodology foundations:

- challenges for future trends evaluation (Section 2.1);
- systematic reviews foundations building (Section 2.2);
- futureness assessment methodology and mechanisms driving the digital twinning future trends evaluation framework (Section 2.3).

Following these necessities, the Materials and Methods section, besides its initial mission to highlight the research foundations, also serves as a comprehensive analysis of related work, distributed over the announced subsections.

2.1. The Methodology Challenges of Future Trends Evaluation and Assessment

The maturity assessment domain exhibits an inherent duality during the cross-comparison of assessing an object's or phenomenon's maturity level and the futureness level of related future trends. When determining a maturity level over the chronology maturation time scale, the common sense rationality assumes the proportional time dependency of the maturity growth functions (Figure 3).

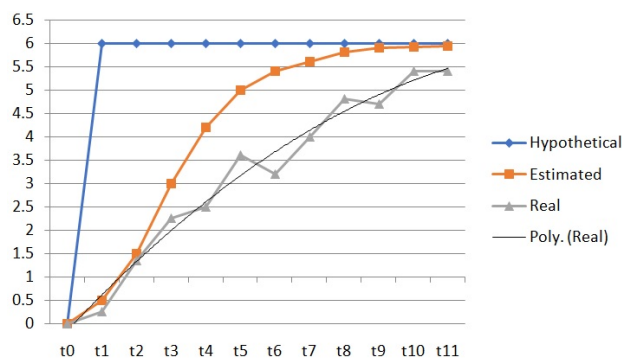


Figure 3. Traditional forms of maturity level growth functions. The estimated maturity scale is divided into six zones (0-1, 1-2, 2-3, 3-4, 4-5, and 5-6) for presentation purposes only. A (0-1) zone may be interpreted as beyond maturation assessment, while the other five zones assume the equivalent maturation level assessment processes.

With traditional maturity level assessment methodologies [38–41], if the assessed object or phenomenon follows the prescribed guidelines, the contemporary maturity level growth function is, at least, monotonically non-decreasing. In a hypothetical situation, an assessed object or phenomenon reaches the maximal maturity level almost instantly and retains it forever (Figure 3 - Hypothetical). Unfortunately, according to the postulates of traditional physics, this demands an unlimited energy source in an extremely short time. Well-balanced maturity assessment frameworks cluster over the expectation that a maturity level growth function is nonlinear and asymptotically approaches the absolute maturity level (Figure 3 - Expected). Unfortunately, in real-world situations, due to stochastic events causing more or less controllable turbulence, oscillations of the assessed maturity level (Figure 3 - Real) values around a polynomial trend distribution function (Figure 3 - Poly(Real)) are more realistic.

On the other hand, when assessing future trends related to an object or phenomenon, the situation radically changes, given that all variables in natural or social sciences follow a normal or near-normal probability distribution, with the mathematical foundations represented in Figure 4 (a), and distribution-related features in Figure 4 (b).

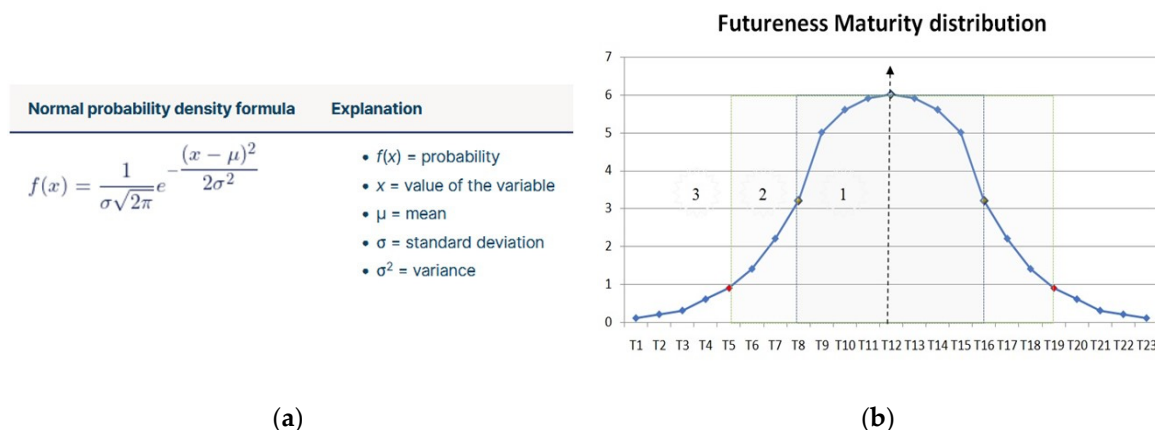


Figure 4. a - The mathematical formulation of the normal probability density function, adopted from [42]; b - Futureness distribution function. The dashed vertical arrow designated the mean value; zone 1 - designates one standard deviation symmetric distance from a mean value (usually 64% (-34% and +34%); zone 2 - designates two standard deviation symmetric distance from a mean value (usually 95% (-47.5% and +47.5%); zone 3 - designates three standard deviation symmetric distance from a mean value (usually 99.7% (-49.85% and +49.85%) [42].

Consequently, we claim that the futureness growth function of the assessed object or phenomenon, if obtained through systematic review clustering mechanisms, follows a near normal probability distribution (Figure 4 (b)), with three areas representing the 1, 2, and 3 standard deviations distances symmetric to the distribution's mean value.

The decreasing zone located right of the mean value of the time-related futureness growth function (Figure 4(b)) suggests that if applied activities lead to the materialization of future trends, they will be achieved and transformed into routine sooner or later.

To guarantee long-term sustainability, the estimated form of a related futureness growth function must reflect the continuous improvements emerging from machine learning algorithms applied to the analytical and aggregated results obtained through data and knowledge mining of the staged database content.

2.2. The Methodology Aspects of Research Foundations Building

To justify research hypotheses and answer related research questions, we have accepted the systematic literature review approach based on the most frequently used PRISMA methodology [43–45], combined with Proknow-C (Knowledge Development Process - Constructivist), and, in certain situations, relying on articles ranking based on Metodi Ordinatio (particularly InOrdinatio method for ranking research articles according to their scientific relevancy - combining citations number, publication year, and Journal's Impact Factor) [46].

For the systematic review of this type it is common to state: goals and the objectives of the survey; first level criteria for literature selection; criteria determining the rationalities in selection of referent databases and resources; literature search and selection mechanisms used in restricting and refining of the initially formed dataset; applied data analysis and classification (with predefined number and type of categories) and clustering (post selecting classification according to the dynamic result set's content) mechanisms; synthesis, visualization, and specific metrics justifying the representativeness level of the formed dataset.

The justified dataset, through subsequent systematic relevance ranking and full-text expert analysis of the qualified articles, aided in isolating, clustering, and time-stamping the extracted set of digital twinning future trends.

2.3. Methodology Foundations of a Futureness Evaluation Framework

According to the specified research hypotheses and related research questions, the methodology foundations of the futureness evaluation frameworks must address the following key problems:

- determining the impacts of general futureness evaluation concepts and principles (2.3.1);
- isolating digital twinning paradigmatic futureness evaluation and assessment mechanisms (2.3.2);
- specifying the sustainable architectural model of the futureness evaluation and assessment framework's Digital Twins (2.3.3).

2.3.1. General Futureness Evaluation Concepts and Principles

While determining the rationalities affecting key research motivations, in the Introductory section, we have analyzed and cross-related the foundational characteristics of the contemporary approaches to the maturity evaluation and assessment methodology, and clarified, without explicit elaboration on the key features of related frameworks emerging from the critical analysis of selected references [4–24], the first of the previously specified problem domains. When transformed into the futureness evaluation domain, the key maturity framework determinants slightly change.

The key determinants of a futureness framework (FF) depend on the general futureness assessment methods, the specific nature of the assessed object or phenomenon, and the evaluation and assessment goals. According to the model-driven systems engineering methodology, these determinants participate in a general futureness model (FM).

Following these determinants, we conclude that the key components of an arbitrary FM are:

- Futureness Context Base (FCB - representing an open set of assessed real-world systems);
- Futureness Domains Base (FDB - representing an open set of assessed concepts or entities being either physically tangible, intangible, or virtual) with composite process areas and key process indicators;
- Futureness Assessment Scale (FAS - representing the FF's value domain, with numerical or fuzzy scaling);
- Futureness Stages (FS - specified milestones fragmenting the FAS);
- Futureness Assessment Logic (FAL - the futureness assessment principles and active services enabling grouping and processing of similar or related FFs) and
- Futureness Presentation Logic (FPL - representing the open set of presentation mechanisms used to communicate the futureness assessment results effectively).

These key components frame the static and dynamic aspects of the proposed futureness evaluation framework.

2.3.2. Digital Twinning Paradigm Frame for the Futureness Evaluation

As stated in the Introductory section, digital twinning represents a contemporary paradigm framing digital transformation activities performed by real-world organizational systems in transition.

A term paradigm first appears in the distinguishable work of American philosopher Thomas Kuhn, generally acknowledged as the originator of a sociology of science, as an "intellectual framework which makes research possible" [47]. Although the paradigm has been used in multiple scientific and technical contexts for a relatively long period and is often classified as a buzzword [48], the originally formulated meaning justifies its association with digital twinning as a composite concept [49,50]. To facilitate further development of digital twins in a paradigm context, the authors in [51] propose building blocks for a related holistic philosophical framework founded on 21 principles.

Based on a methodologically similar approach with different goals than specified in our research, in [52], the authors propose a maturity model with three main dimensions, nine sub-dimensions, and 27 attributes suitable for the domain-specific maturity evaluation and assessment of

digital twins for asset management. The maturity model, specified in [53], supports the classification of Digital Twin's maturity based on seven categories (context, data, computing capabilities, model, integration, control, human-machine interface) with a total of 31 ranking attributes.

From this research context, the maturity assessment of the digital twinning paradigm and its direct reflection on Digital Twins maturity assessment, often intriguing for a proper decoupling, represents a challenge in eliminating direct, indirect, and circular dependences that jeopardize one of the essential characteristics of assessment models and methodologies, the dimensional orthogonality, thereby affecting the statistical independence of the embedded dimensions inducing the untraceable and frustrating impacts on the assessment results.

Automatic verification and validation of the maturity model dimensions orthogonality is a key research direction towards the specification and development of the maturity evaluation framework [54].

In this sense, the maturity evaluation and assessment of digital twinning as a paradigm involve determining its applicability potentials and framing the future assessment mechanisms, according to the principles elaborated on in Section 2.3.1.

2.3.3. Methodology Aspects of the Digital Twins-Based Approach Towards Formulation of the Digital Twinning Future Assessment Framework

Research hypothesis RH2 announces the specification and modeling of the initial framework's prototype, emerging from the systematic literature review findings, cross-related with contemporary Digital Twins (DT) architectural and behavioral models. Among the whole spectrum of methodology influencers, highlighting two key dimensions significantly aids in determining the prototype's boundaries: the DT role evolution timeline and the emerging concept of DT Reference Architecture.

Throughout the digital twinning development timeline [55], the Digital Twin (DT) was first considered a static model of a physical entity serving as a simulation paradigm for Industry 4.0 [56,57]. With further proliferation in systems engineering projects, DT continues to play a crucial role in the simulation-based decision-making process in two key directions: as a surrogate model replacing expensive or risky experimentation with existing mission-critical physical systems [58], and as a tool for estimating structural and behavioral characteristics of a hypothetical asset or phenomenon [59]. Afterwards, DT appears as an executable virtual representation of a physical entity, capable of emulating it (based on real-time data dynamically obtained from a network of interconnected physical entities) [60,61], followed by the evolution towards Industry 5.0 [62] and contemporary Artificial Intelligence (AI) and Natural Language Processing (NLP) foundations [63,64].

According to [65,66], Referent Architecture represents a template or a standardized reusable blueprint, generally heuristically derived from a collection of concrete solutions through an abstracting cognitive process. It embeds the mature practices, standards, and guidelines, enabling fast prototyping of an addressed object or phenomenon.

The simple architecting principles introduced by [67], the development of standardized models of a Digital Twin [68,69], and a general approach to model-driven engineering for digital twins [70] indicate the fundamental directions, methods, and obstacles related to building Digital Twin models. The use of predefined templates represents a challenging approach [71,72], raising the question of building the modeling foundations of an embedded Digital Twin. The most serious impact on specifying our light-weight Digital Twin reference model comes from the Digital Twinning Consortium terminology glossary [73], representing a valuable referent point for comprehending digital twinning fundamentals in a broader sense, through logical decoupling of a Digital Twin System from the traditional concept of Digital Twins incorporating the Real-world Physical System's foundations.

Following the distinguishable principles presented in [71] and the most elaborated approach to Digital Twins architecting similar to one presented in [30], we have adopted a slightly simpler Digital Twin System internal architecture composed of four Digital Twin architectural building blocks:

Separation (encapsulating Physical Twin characteristics and fostering the interoperability), Data (encapsulating the internal repository foundations), Structural and Behavioral Foundations (templates, meta-models, algorithms, and knowledge base supporting dynamic configuring of a Digital Twin System structure and behavior), and Service (internal and external DT services hiding the complexity of other building blocks).

Based on the previously discussed methodology, we claim that the foundations of this research approach are reusable in subsequent research endeavors compliant with the formulated research motivations, hypotheses, and related research questions.

3. Results

Materials and Methods section has established the essential research steps in preparing, forming, presenting and discussing of the obtained results grouped as follows:

- The foundations and results of a systematic review with dataset reliability assessment (3.1.);
- Systematization of digital twinning future trends obtained by clustering-based expert analysis of referent dataset obtained in 3.1 (3.2.)
- Futureness assessment of digital twinning future trends (3.3.);
- Digital Twinning Futureness Evaluation Framework Referent Architecture Model (3.4.);

3.1. Establishing the Foundations - A Systematic Review Process and Results

According to the same systematic review methodology we used to justify the need for this research endeavor, we have decided to relay on Google Scholar search engine, multilevel filtering, and labeling mechanism to enable step-by-step application of a higher fidelity additive filtering towards the formation of final representative dataset, composed of member articles with as high as possible relevance for the detailed expert analysis, based on the clustering mechanisms, leading to the isolation of digital twinning future trends maturity evaluation and assessment dimensions.

Figure 5 presents the overall systematic review process in the form of a UML Sequence diagram.

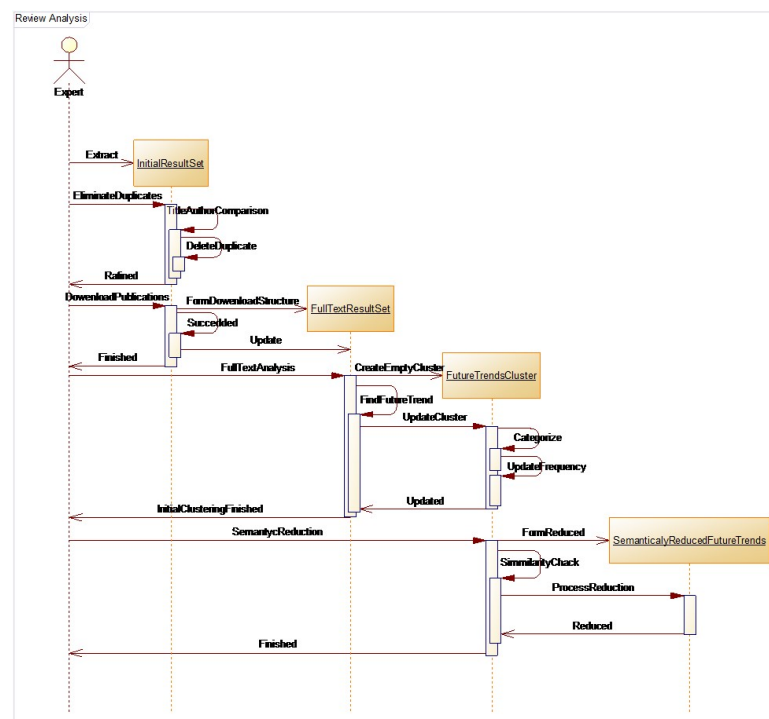


Figure 5. The Overall Analysis Process.

The initial dataset formulated in the Introductory section, with 1122 member articles, is reused as the starting collection. The first applied reduction filter was a simpler one aimed at isolating only

those articles that are classified as either Journal's articles or conference paper, and are accessible for free, either through open publishing libraries or arbitrary research groups with freely downloadable samples. 13 publications have been eliminated due to unclassified type, while, according to the publications metadata, 491 publication was not freely downloadable. The former filtering methodology used the Google Scholar labeling mechanism, resulting in a dedicated library of 618 member publications, consisting of 553 journal's articles and 65 conference papers (Figure 6 (a)).

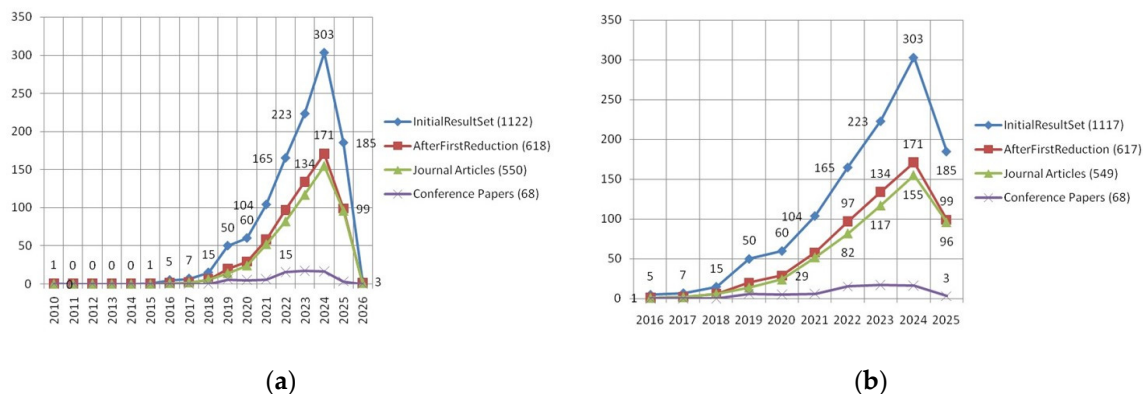


Figure 6. Annual distribution of selected publications: (a) - Annual distribution of publications appearing in the Initial Result Set and After First Reduction result sets. The reduced data set is composed of 550 journal's articles and 68 conference papers; (b) - Annual distributions with final filtering.

A quick analysis of the reduced dataset shows that there are 2 articles distributed over interval from 2010 to 2015 and one article signified as 2026 publication year. These publications may be discarded as statistically irrelevant, leading to the final publications dataset, with time frame from 2016 to 2025 and total number of 617 publications, 549 journal's articles and 65 conference papers (Figure 6 (b)).

The final result set (617) has been further analyzed in order to visualize its overall relevancy. We claim that, concerning digital twinning timeline, the formulated chronological distribution (2016 to 2025) represents relevant time frame for the intended research foundations.

Additionally, the more rigorous peer review process practiced for journal articles acceptance for publication compared with the conference assessment, up to our systematic analysis, is not published yet. Nevertheless, we believe that the ratio of 89 (88.97%) to 11 (11.03%) in favor of journal articles in the final result set is, at the moment, rational, and additionally aids the result set's reliability.

The next step in further assessing the final result set's relevance is to create three additional distributions: over publishers for conference papers and journal articles, over journals for journal articles, and over a real-world field (domain) for both publication categories.

In Figure 7 (a), the distribution of conference papers in the final result set over publisher or conference organizers, while in Figure 7 (b), the distribution of journal's articles over journal publishers.

Figure 8 (a), represents the articles distribution over individual Journals, while Figure 8 (b) represents the articles distribution over clustered fields/domains, formed by the shallow expert analysis of publications metadata and declared Journal's scope.

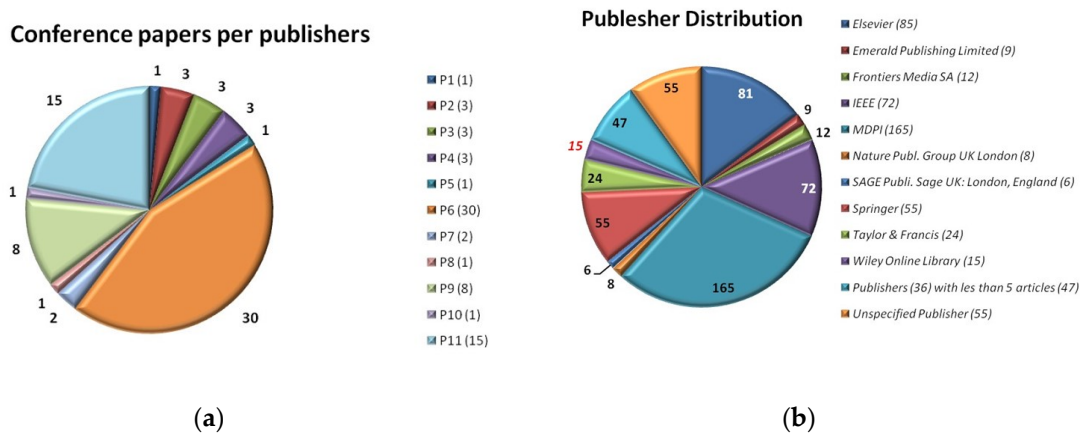


Figure 7. Publication's distribution over publishers: (a) - Conference papers (68) distribution over publishers or organizers. Legend: P1-American Society of Mechanical Engineers (1); P2-Cambridge University Press (3); P3-EDP Sciences (3); P4-Elsevier (3); P5-IAARC Publications (1); P6-IEEE (30); P7-IOP Publishing (2); P8-SPIE (1); P9-Springer (8); P10-Stanford University (1); P11-Unspecified (15). The fairly significant percentage of unspecified publisher/organizers (22.06%) additionally justifies the fundamental importance of the conference papers meta-data completeness; (b) - Journal article's distribution over publishers. To lower the visual density of this distribution chart we have decided to group 36 publishers, each with less than five articles (total of 47), into a single group. Nevertheless, we believe that a publishers distribution of journal articles is sufficiently representative. Although lower compared to the conference papers, the percentage of unspecified publisher (10.02%) additionally highlights the importance of article's meta-data completeness.

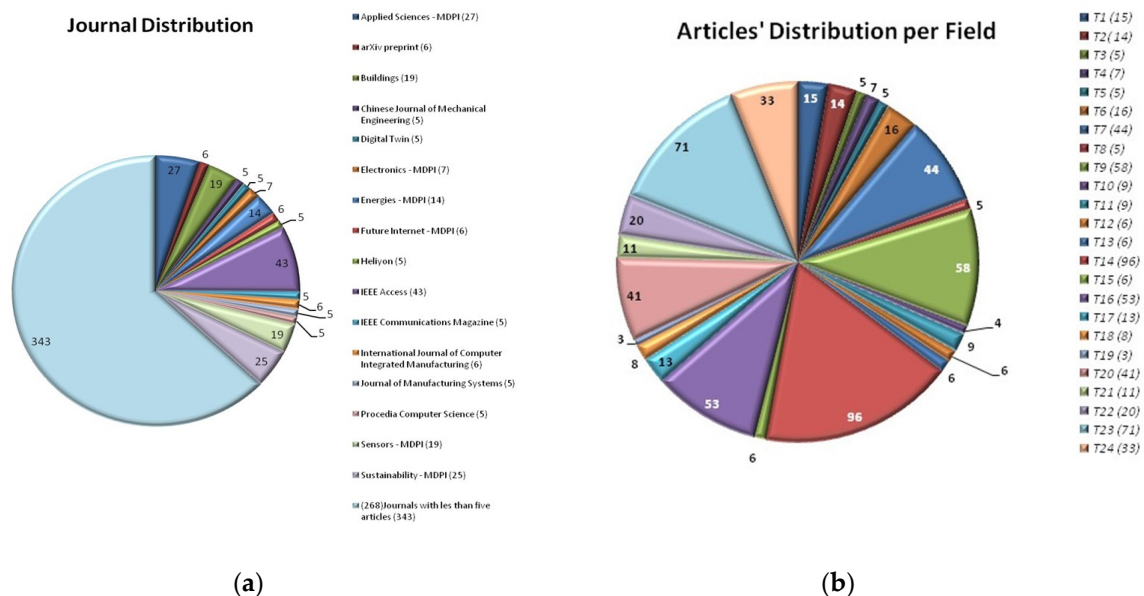


Figure 8. Articles distribution: (a) - Final Set's Articles distribution over Scientific Journals. To lower the visual density of this distribution chart, we have decided to group 268 Journals, each with less than five articles (total of 343), into a single group, which is the largest one, but indicating that a fairly large scope of affected Journals (93,93%) cover 62.48% of articles, while 37.52% is published in 6.07% related Journals. Nevertheless, we believe that a Journal's distribution of the selected articles is sufficiently representative, and fairly well correlates with the addressed Journal's rankings; (b) - Cluster (filed/domain) distribution of selected Data Set (Legend: T1(15)-Agriculture; T2(14)-Artificial Intelligence; T3(5)-Biosciences; T4(7)-Business and Management; T5(5)-Computing; T6(16)-Communications and networking; T7(44)-Construction Engineering; T8(5)-Education; T9(58)-Energy; T10(9)-General Engineering; T11(9)-Environment; T12(6)-Geosciences and mining; T13(6)-Heritage; T14(96)-Industry; T15(6)-Internet of Things; T16(53)-Medicine and healthcare; T17(13)-Modeling and

Simulations; T18(8)-Robotics; T19(3)-Safety; T20(41)-Smart Cities; T21(11)-Social Sciences; T22(20)-Supply Chains; T23(71)-DT Technologies; T24(33)-Transportation.).

Figure 8 (a) sublimates results of rough clustering of the selected publications over real-world domains. Clustering process assumed that each of the analyzed publications (conference paper and journal article) is, based on the authors' expert opinion, clustered in one and only one group, to avoid unnecessary multiplication and simplify the interpretation of the obtained results. This decision was motivated by the final goal of this systematic review, to cluster digital twinning future trends. The clustering process resulted by 24 clusters with publications distribution presented in Figure 8 (b).

A minimal number of articles (3) is clustered in a Safety group (T19) while maximal number of articles (96) is clustered in Industry group (T14). Concerning the Industry group, one of the main challenges in clustering process was a fidelity with which it was possible to separate articles addressing topics with general applicability over different fields (domains), and these that are addressing a field specific contexts. Similarly, although cyber security and safe operations are research hotspots, due to the detailed analysis some of articles are classified in digital twinning technologies cluster (T23) as a more appropriate one.

We believe that the previous elaboration on result set building process and cross-correlation analysis justifies the final result set, with 617 publications (68 conference papers and 549 journal articles), as relevant for further mining and credible isolation of digital twinning future trends, and if further on addressed as referent dataset.

Figure 9, represent annual distribution of publications over fields/domains.

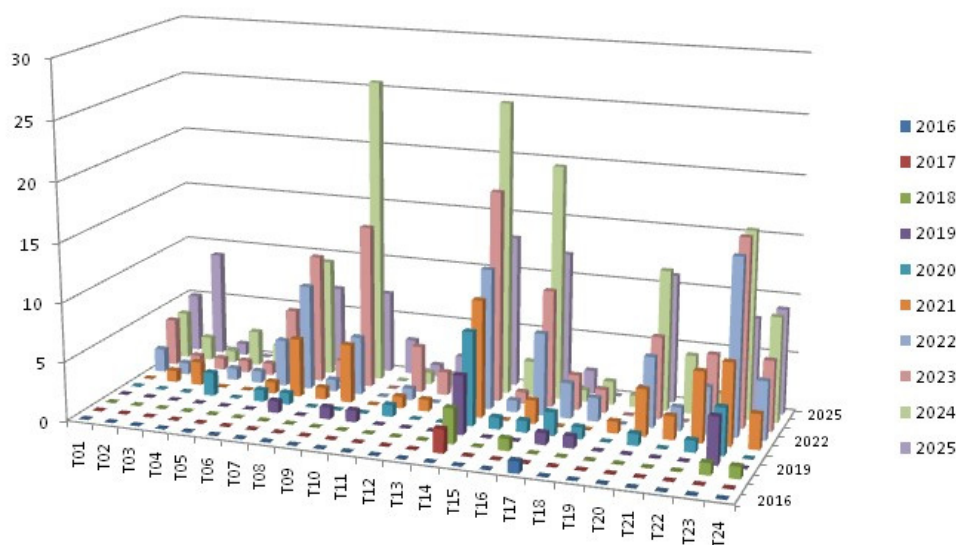


Figure 9. Annual distribution (2016 to 2025) of publications over clusters (T01 to T24) (Legend: T1(15)-Agriculture; T2(14)-Artificial Intelligence; T3(5)-Biosciences; T4(7)-Business and Management; T5(5)-Computing; T6(16)-Communications and networking; T7(44)-Construction Engineering; T8(5)-Education; T9(58)-Energy; T10(9)-General Engineering; T11(9)-Environment; T12(6)-Geosciences and mining; T13(6)-Heritage; T14(96)-Industry; T15(6)-Internet of Things; T16(53)-Medicine and healthcare; T17(13)-Modeling and Simulations; T18(8)-Robotics; T19(3)-Safety; T20(41)-Smart Cities; T21(11)-Social Sciences; T22(20)-Supply Chains; T23(71)-DT Technologies; T24(33)-Transportation.).

Due to the result set building period (September 2025) the number of member publications reflects the appropriate time-scale. It shows that statistically relevant time-frame is from 2020 to 2025, while statistically most relevant groups are T06, T07, T09, T14, T16, T20, T20, T23, and T24.

Concerning our primary goal to cluster digital twinning future trends with respect to the time-scale starting from the first appearance of individual trends, and the fact that the statistical artifacts

may carry a large quantity of information, we have decided to perform detailed expert analysis of the entire referent dataset with integrated conference papers and journal articles.

To support an independent systematic review, in the Supplementary Resources SR1 (00_01_Supplementary_Resources.zip, Microsoft Excel file named 00-04_Results_Clustering_Analysis_Foundation.xlsx) we have included discussed result sets, joined with the authors assessment process illustration, represented in individual tabs.

3.2. Systematization of Digital Twinning Future Trends Obtained by Clustering-Based Expert Analysis of a Referent Dataset

The clustering process has been demanding due to full-text expert analysis of a relatively large number of publications (617) with the unique goal of extracting digital twinning future trends, clustering them accordingly, and determining related appearance frequencies.

During the downloading activities, due to security risk issues related to secondary download sources (4), operational unavailability (14), publishing language issues (5), and duplication (1), we have excluded an additional 24 publications and restricted the referent dataset to a final 593 candidates. After the operational reduction, the analysis time frame changed to 2017-2025, which is compliant with findings reported in [74], which states that from 2011 to 2017 publications almost exclusively elaborate on the Digital Twins concepts.

All downloaded full-text publications are grouped across annual folders with the indicated number of containing publications (Figure 10), and individually marked by a file name addendum PUB<nnn>, where <nnn> represents the ordinal number of a downloaded publication.

During the downloading process, the additional challenge was how to balance effective processing and avoid being blocked by "machine-mining" suspicious categorization while using search engines or dedicated interest groups' network services.

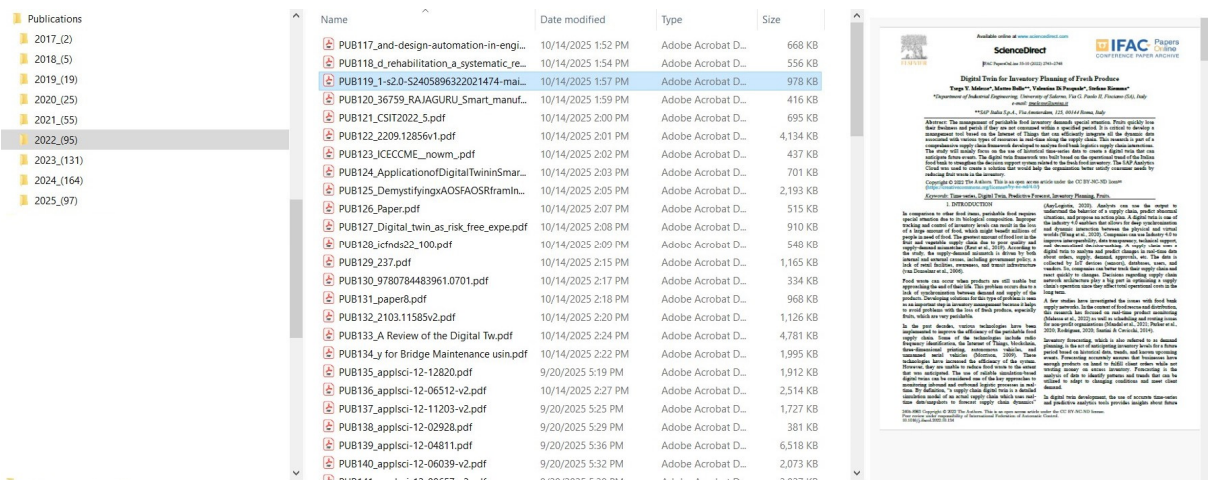


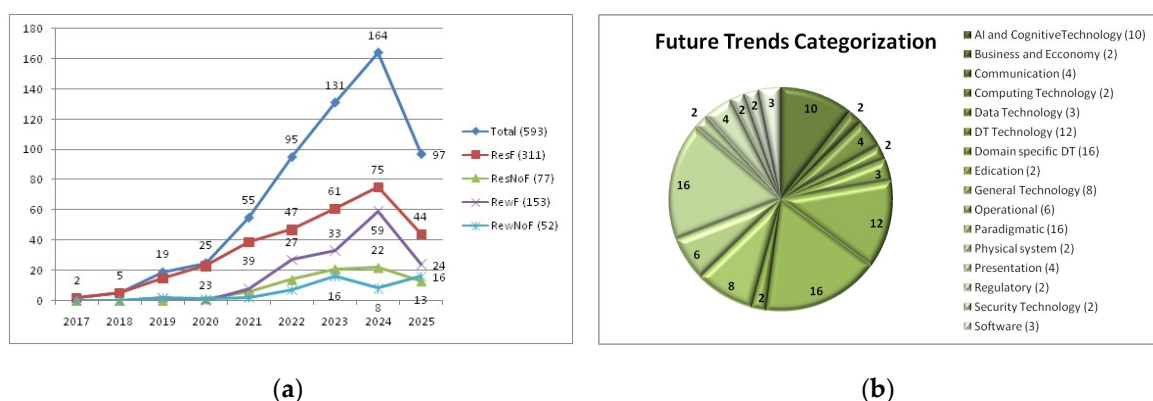
Figure 10. File system repository of full-text downloaded publications (593).

Following the first analysis step, all publications have been full-text analyzed and consequently classified in four major groups: Reviews with explicit future trends elaboration (RewF), Reviews without explicit future trends elaboration (RewNoF), Research publications with explicit future trends specification (ResF), and Research publications without explicit future trends specification (ResNoF) (Table 1 and Figure 11).

Table 1. Annual distribution of four major publication groups, with number of publications and the related percentage.

Total	Total Rew	RewF	RewNoF	Total Res	ResF	ResNoF	Year	(RewF + ResF) Impact
97	40	24	16	57	44	13	2025	68
%	41.24	24.74	16.49	58.76	77.19	22.81		70.10%
164	67	59	8	97	75	22	2024	134
%	40.85	35.98	4.88	59.15	77.32	22.68		81.71%
131	49	33	16	82	61	21	2023	94
%	37.40	25.19	12.21	62.60	74.39	25.61		71.76%
95	34	27	7	61	47	14	2022	74
%	35.79	28.42	7.37	64.21	77.05	22.95		77.89%
55	10	8	2	45	39	6	2021	47
%	18.18	14.55	3.64	81.82	86.67	13.33		85.45%
25	1	0	1	24	23	1	2020	23
%	4.00	0.00	4.00	96.00	95.83	4.17		92.00%
19	4	2	2	15	15	0	2019	17
%	21.05	10.53	10.53	78.95	100.00	0.00		89.47%
5	0	0	0	5	5	0	2018	5
%	0.00	0.00	0.00	100.00	100.00	0.00		100.00%
2	0	0	0	2	2	0	2017	2
%	0.00	0.00	0.00	100.00	100.00	0.00		100.00%

Column Total (Table 1) represents the total number of analyzed publications in the corresponding publishing year. In 2025, 40 (41.24%) review and 57 (58.76%) research publications have been analyzed (total of 97), 24 reviews (24.74%) has been included in the future trends frequency determination while 16 (16.49%) have not, 44 research articles (77.19%) have been included in the future trends frequency determination while 13 (22.81%) have not. Obviously, in 2025, 68 out of 97 publications had an impact on the frequency determination, making a respectable 70.10%.

**Figure 11.** Publications distribution and future trends categorization: (a) - Annual distribution of four major publication groups according to Table 1; (b) - Future Trends Categorization with number of individual future trends according to Table 2.

The significant lack of reviews published from 2017 to 2020 is rational due to the initial digital twinning concepts' maturity and the lack of a critical mass of related publications for credible reviewing.

According to the obtained results, from 2021 to 2025, the percentage of review publications generally increases (2021: 18.18%, 2022: 35.79%, 2023: 37.40%, 2024: 40.85%, and 2025: 41.24%) following the digital twinning publishing trends. We claim that this is also rational and explainable by the overall publishing characteristics of the hotspots in the scientific and engineering domains. We believe that the indicated trend will continue in the future and will impact the futureness evaluation according to the discussed near-normal distribution (Section 2.1).

The clustering process followed three steps. First, following a fast clustering step, 177 future trends have been isolated. In the second step, following a semantic similarity detection process, the initial set is reduced by 46.90 %, resulting in a final set of future trends with 94 cardinality. In the third step, a group categorization, individual future trends are systematized into 16 categories (Table 2), with the relative category's pondered impact calculated according to formula (1).

$$R_i = (FT_i * F_i) / \sum_{i=1}^{16} FT_i \text{ for } \forall i \in [1, \dots, 16] \quad (1)$$

Table 2. Digital Twinning Future Trends main Categories indicators and relative futureness impact.

I (i)	Category	Number of Future trends (FT _i)	Frequency (F _i)	Category Pondered Impact (R _i)
1.	AI and Cognitive Technology	10	200	21.276600
2.	Business and Economy	2	33	0.702128
3.	Communication	4	55	2.340426
4.	<i>Computing Technology</i>	2	80	1.702128
5.	Data Technology	3	153	4.882979
6.	Digital Twinning Technology	12	267	34.085110
7.	Domain Specific Digital Twins	16	138	23.489360
8.	Education	2	30	0.638298
9.	General Technology	8	148	12.595740
10.	Operational Technology	6	130	8.297872
11.	Paradigmatic Concepts	16	195	33.191490
12.	Physical System Technology	2	103	2.191489
13.	Presentation Technology	4	108	4.595745
14.	Regulatory Principles	2	93	1.978723
15.	Security Technology	2	101	2.148936
16.	<i>Software Technology</i>	3	10	0.319149
		94	1844	

In Figure 12, the distribution of relative futureness impacts over identified categories, defined in Table 2, is presented.

Table 3 contains complete analytical data obtained through clustering analysis of Digital Twinning Future Trends. Category ID corresponds to Table 2, while Trend ID is the absolute number of specified Future Trend. A Digital Twinning Future Trend Description Column and Trend Frequency results from an expert-based naming and summarizing performed through the semantic similarity reduction step. The rest of the columns result from the futureness impact calculation formulas: Category Pondered Impact according to the formula (1), Category Relative Impact according to the formula (2), and the Absolute Impact according to the formula (3).

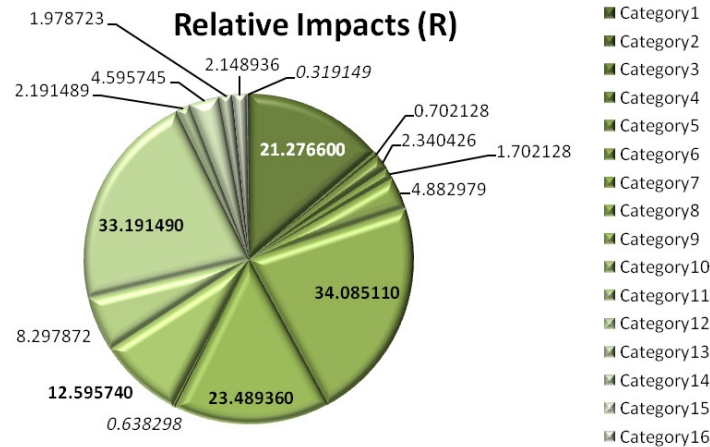


Figure 12. Digital Twinning Future Trends Categories Pondered Impacts Distribution. Maximal relative impact (34.08511) is associated with Category6 (Digital Twinning Technology), followed by Category10 (Paradigmatic Concepts) (33.191490), and Category7 (Domain Specific Digital Twins) (23.489360). Minimal relative impact (0.319149) is associated with Category 16 (Software Technology), followed by Category 8 (Education) (0.638298), and Category 2 (Business and Economy) (0.702128).

$$CRI = (TFi) / \sum_{j=1}^n TFi \text{ for } \forall i \in [1, \dots, 94] \text{ where } (n) \text{ is cardinality of category } (i) \quad (2)$$

$$AI_i = (TFi) / \sum_{i=1}^{94} TFi \text{ for } \forall i \in [1, \dots, 94] \quad (3)$$

Table 3. Digital Twinning Future Trends obtained through clustering process over referent dataset.

Cat. ID.	Trend ID	Digital Twinning Future Trend Description	Trend Frequency (TFi)	Formula (1)	Formula (2)	Formula (3)
				Category Pondered Impact (CRi)	Category Relative Impact (AIi)	Absolute Impact
1.		Artificial intelligence (Perceive (data collection and storage), Understanding (machine learning, deep learning, Knowledge representation) and Decide (Reinforcement Learning, Operational Research))	91	9.869848	0.455000	0.049349
		Machine learning	48	5.206074	0.240000	0.026030
		Knowledge based, semantic technologies, ontologies, cognitive systems, web mining	15	1.626898	0.075000	0.008134
		Operation and evaluation (iterative optimization, self learning, self-organization, self-adaptation, self-maintenance)	13	1.409978	0.065000	0.007050
		Decision making, support (real time)	10	1.084599	0.050000	0.005423
		Neural networks, deep neural networks	6	0.650759	0.030000	0.003254
		Natural Language Processing	5	0.542299	0.025000	0.002711
		Federated Learning Platforms (Federated Scope, OpenFL, Nvidia's Clara, Substra, IBMFL, TensorFlowFL, PaddleFL)	5	0.542299	0.025000	0.002711
		Cognitive systems Cognitive Operator 4.0, Cognitive DT	4	0.433839	0.020000	0.002169
		Large language Models (LLM) enhanced Digital Twins	3	0.325380	0.015000	0.001627
2.		Economic challenges in implementing DT, time and cost	21	0.375813	0.636364	0.011388
		Business , Financial technologies, logistics, supply chains	12	0.214751	0.363636	0.006508
3.		5G networks/6G networks, added value for network operators	31	0.924620	0.563636	0.016811
		Interconnection and interaction in PS: perception and access, communication protocols, data encapsulation,	10	0.298265	0.181818	0.005423

	Mobile technologies, mobile systems, autonomous mobility, space technology	8	0.238612	0.145455	0.004338
	Multi agent technology	6	0.003254	0.178959	0.109091
4.	Cloud technologies, edge, fog	49	2.125813	0.612500	0.026573
	Computational infrastructure, Virtual machines, computational efficiency, fuzzy and granular computing. Quantum computing)	31	1.344902	0.387500	0.016811
5.	Information and Data fusion, data cleaning, data integration, data fusion, two-way mirrors between physical and virtual data and time sensitive data	103	8.546095	0.673203	0.055857
	Big data, and data analytics	45	3.733731	0.294118	0.024403
	Heterogeneous datasets, Semantic database	5	0.414859	0.032680	0.002711
6.	Multidimensional modeling, model integration and model verification in Virtual space, modeling platforms	88	12.741866	0.329588	0.047722
	DT operational mechanisms, Interoperability and integration with existing systems	53	7.674078	0.198502	0.028742
	Real-time interaction PS-VS (data transmission latency)	43	6.226139	0.161049	0.023319
	Managing and orchestration of multiple instances of DT DT network paradigm, network digital twins. Internet of Digital Twins, (DT ecosystems)	27	3.909436	0.101124	0.014642
	Human-in-the-loop expert participation, Human robot interaction, Human DT interaction	22	3.185466	0.082397	0.011931
	Referent model - DT	11	1.592733	0.041199	0.005965
	Digital Twins Platforms and software solutions (AWS IoT Twin Maker, Azure Digital Twins, Google Supply Chain Twin, NVIDIA Omni verse Enterprise,..)	5	0.723970	0.018727	0.002711
	Virtual Twin as replacement for prototyping, Behavioral modeling, rule modeling	4	0.579176	0.014981	0.002169
	Performance indicators prediction, parameters optimization, DT components	4	0.579176	0.014981	0.002169
	DT Maturity evaluation and assessment	4	0.579176	0.014981	0.002169
	Drone-based Digital Twins	4	0.579176	0.014981	0.002169
	Digital Twin System, System of Digital Twin Systems	2	0.289588	0.007491	0.001085
7.	Smart cities, buildings management. City DT sociotechnical aspects	38	2.843818	0.275362	0.020607
	Smart manufacturing/production	32	2.394794	0.231884	0.017354
	Personalized medicine, Data driven health care, Model driven health care	20	1.496746	0.144928	0.010846
	Precision medicine and medical DT (Nanobot surgery, Virtual Biopsy, Virtual experiments, Virtual Consulting, Vital monitoring and alert response)	16	1.197397	0.115942	0.008677
	Agricultural and forestry DT	11	0.823210	0.079710	0.005965
	Heritage Digital Twins	3	0.224512	0.021739	0.001627
	Traffic Flow Digital Twins, Railway Digital Twins, Transportation System Digital Twin	3	0.224512	0.021739	0.001627
	Holistic Health Ecosystem DT, Hospital Digital Twin	3	0.224512	0.021739	0.001627
	Common Information Model (CIM), micro-grid digital twin	3	0.224512	0.021739	0.001627
	Carbon emission monitoring	3	0.224512	0.021739	0.001627
	Smart Pandemic City	1	0.074837	0.007246	0.000542
	Sports Digital Twins	1	0.074837	0.007246	0.000542
	TV Digital Twin and media metaverse	1	0.074837	0.007246	0.000542
	Water system management DT	1	0.074837	0.007246	0.000542
	Earth Digital Twin	1	0.074837	0.007246	0.000542
	Landscape and urban DT	1	0.074837	0.007246	0.000542
8.	Education-expertise knowledge, skill and cultural gap	27	0.439262	0.900000	0.014642
	DT as a new profession	3	0.048807	0.100000	0.001627
9.	Interoperability and integration with existing systems	52	4.173536	0.351351	0.028200

	Building Information Modeling BIM, and GIS integration	30	2.407809	0.202703	0.016269
	Scalability and performance	29	2.327549	0.195946	0.015727
	Service encapsulation, composition and publication, demand decomposition, cooperation, micro-services	13	1.043384	0.087838	0.007050
	Real-time location system (indoor and outdoor)	10	0.802603	0.067568	0.005423
	Multi robot cooperation, IoRT (Internet of Robotic Things), Elastic robot control	6	0.481562	0.040541	0.003254
	3D/4D Printing connected with DT	5	0.401302	0.033784	0.002711
	Control systems (fuzzy, neural networks) and monitoring	3	0.240781	0.020270	0.001627
10.	Simulations	72	5.075922	0.553846	0.039046
	Sustainability	18	1.268980	0.138462	0.009761
	Algorithms, low latency algorithms, mathematical models	14	0.986985	0.107692	0.007592
	Complexity reduction and management	14	0.986985	0.107692	0.007592
	Verification and Validation, test suits	6	0.422993	0.046154	0.003254
	Safety	6	0.422993	0.046154	0.003254
11.	Digital twin frameworks, platforms, and Quantum DT	82	8.671367	0.420513	0.044469
	Personal / human digital twin/ behavior modeling/ virtual patient	24	2.537961	0.123077	0.013015
	Virtual worlds, Metaverse, Integration of data, Models, Analytics, and Human on world-level	23	2.432213	0.117949	0.012473
	Sociotechnical systems (STS), social DT, digitalization, Cyber-Physical Systems	20	2.114967	0.102564	0.010846
	Smart technologies and systems, Emergent dynamical systems concepts, emergency management	15	1.586226	0.076923	0.008134
	Asset related Digital Twins (component DT), product twinning, process twinning, tools twinning, virtual sensors	8	0.845987	0.041026	0.004338
	Infrastructural systems (mission critical)	6	0.634490	0.030769	0.003254
	Integration of DT across domains (DT ecosystems)	4	0.422993	0.020513	0.002169
	Multilayer Intelligent Digital Twin	3	0.317245	0.015385	0.001627
	Spatial Digital Twins	2	0.211497	0.010256	0.001085
	Maturity models, maturity levels	2	0.211497	0.010256	0.001085
	Existing challenges (future trends), required strategies	2	0.211497	0.010256	0.001085
	Organizational Digital Twin	1	0.105748	0.005128	0.000542
	Communication Networks Digital Twin	1	0.105748	0.005128	0.000542
	Democracy Deliberation DT	1	0.105748	0.005128	0.000542
	Virtual City , transition from Smart City to Virtual City_	1	0.105748	0.005128	0.000542
12.	IoT and Industrial IoT, IoE (Internet of Everything)	63	3.518980	0.611650	0.034165
	Sensors, sensing, and compressed sensing and RFID, PLC, microwave sensors, sensor networks	40	2.234273	0.388350	0.021692
13.	Augmented reality, mixed reality, extended reality	36	2.108460	0.333333	0.019523
	Human-Machine Interface, integration, collaboration, UI UX	32	1.874187	0.296296	0.017354
	Virtual reality	24	1.405640	0.222222	0.013015
	Visualization and image processing	16	0.937093	0.148148	0.008677
14.	Standardization	55	2.773861	0.591398	0.029826
	Regulatory and ethical considerations	38	1.916486	0.408602	0.020607
15.	Security and cyber security and privacy. And data ownership	71	3.888829	0.702970	0.038503
	Blockchain technology, BlockNet	30	1.643167	0.297030	0.016269
16.	DT Software development, software architecture, Softbot integration	8	0.043384	0.800000	0.004338
	Health Based DT Platforms (Siemens, Philips, IBM, GE, Dessault, Amsys, Medtronic, Oracle)	1	0.005423	0.100000	0.000542
	Open source solutions	1	0.005423	0.100000	0.000542
		1844			

Table 3 data collection represents a challenging pool with great potential for the post-festival analysis, discussion, recommendation deriving, and cross-relation visualization. The elaboration on

the entire potential is apparently far beyond the rational scope of a single article. Consequently, we believe that it opens the space for research endeavors for the overall digital twinning community. To illustrate some of the possibilities we have derived an additional table data, systematized in Appendix A. Table 5, and used it create Figures 13–16 as the representative visualization samples.

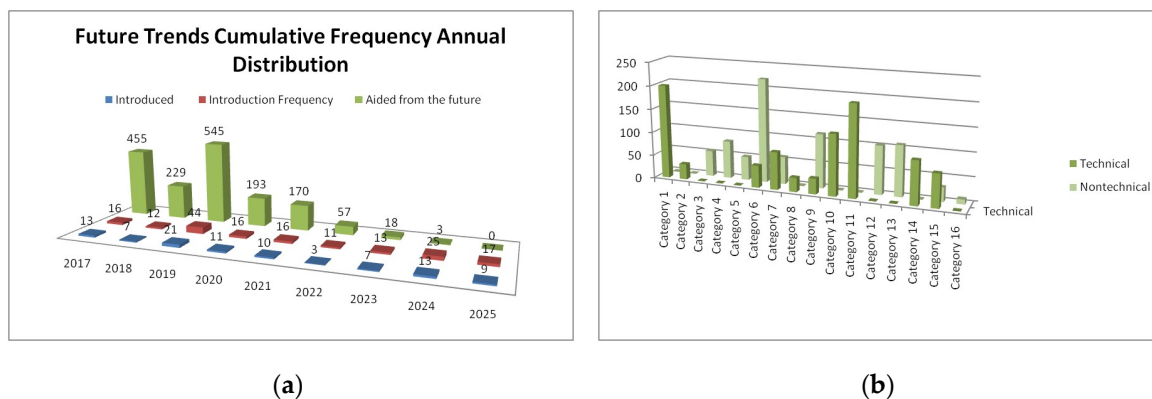


Figure 13. Future trends distribution: (a) - Future trends cumulative frequency distribution. Introduced represents a number of added novel trends in the specified year (13, 7, 21, 11, 10, 3, 7, 13, 9) respectively. Introduction frequency sublimates the appeared trend annual frequency (16, 12, 44, 16, 16, 11, 13, 25, 17) respectively. Aided from future cubes represent cumulative frequency contribution to introduced trends from future years, indicating the future trends annual persistency; (b) - Future trends categories distribution over technical and nontechnical categories may serve for further refining of the isolated categories.

Figure 14 visualizes the annual cross-distribution of future trends frequencies on a yearly and category basis.

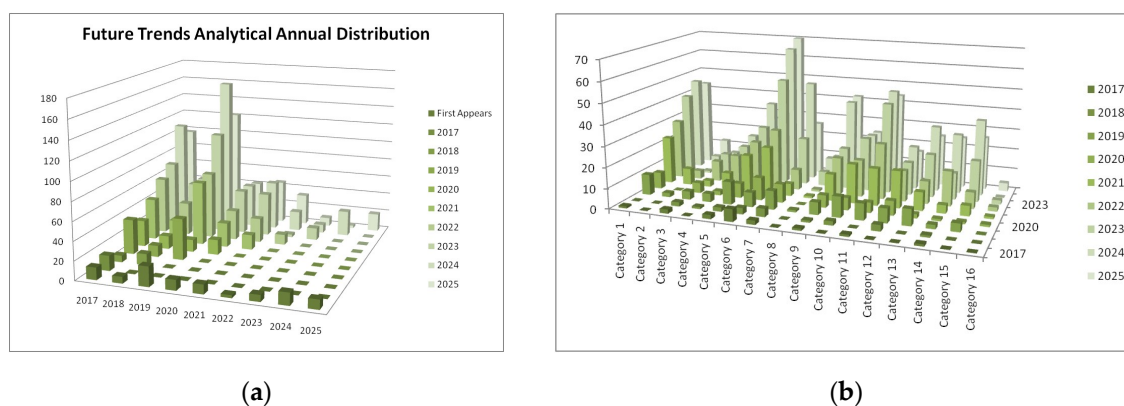


Figure 14. Future trends cross-distribution: (a) - Analytical cross-annual cumulative frequency distribution with separated first appearance; (b) - Cross-category annual frequency distribution.

Figure 15 and Figure 16 represent individual future trends (Future Trend (i) - specified in Table 3) annual frequency distribution for the selected future trends categories defined in Table 2, derived from Appendix A. Table 5.

The AI and Cognitive Technology category (Category 1), with future trends frequency distribution presented in Figure 15 (a), with 10 individual future trends, shows strong clustering towards general Artificial Intelligence (Future Trend 1) and Machine Learning (Future Trend 2), indicating a possible fidelity problem because machine learning is currently perceived as embedded in general AI technology. However, the majority of reviewed articles separate them, which may be intriguing and deserves further elaboration to justify the rationality of their simultaneous appearances in the same context.

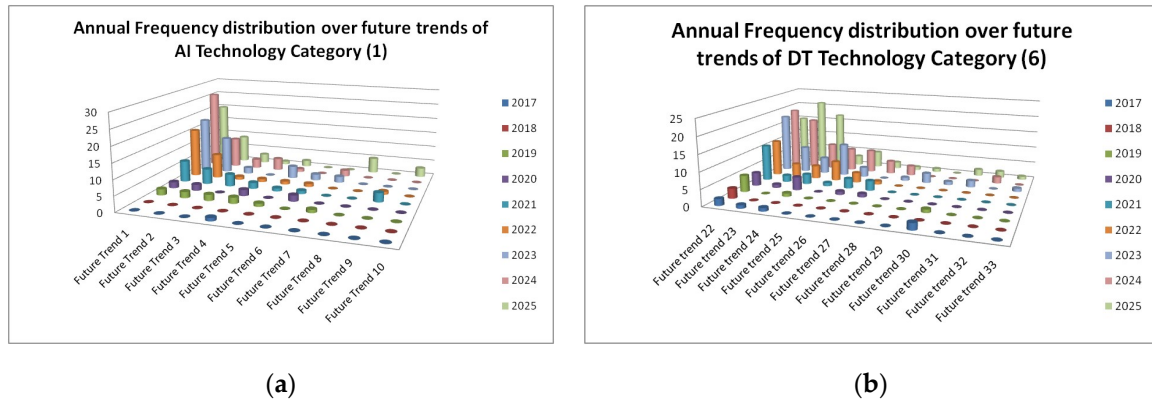


Figure 15. Category-based future trends frequency distribution: (a) AI and Cognitive Technology Category (1); (b) Digital Twins Technology Category (6).

Similarly, DT technology category (Category 6) with futureness frequency distribution presented in Figure 15 (b), with 12 individual future trends, shows strong clustering towards three future trends: Multidimensional modeling, model integration and model verification in Virtual space, modeling platforms (Future Trend 22), DT operational mechanisms, Interoperability and integration with existing systems (Future Trend 23), and Real-time interaction of Physical and Virtual Systems (PS-VS) (data transmission latency) (Future Trend 24).

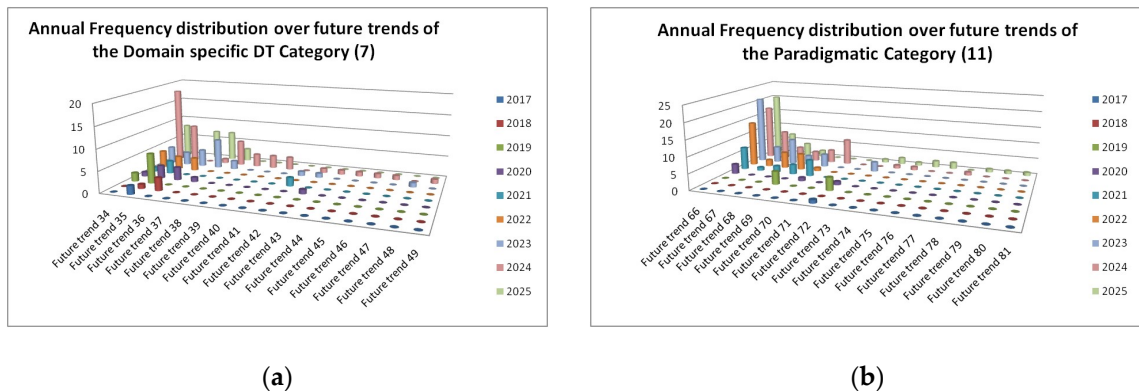


Figure 16. Category-based future trends frequency distribution: a) Domain specific DT category (7); (b) Pragmatic Category (11).

The Domain-specific DT category (Category 7) with futureness frequency distribution presented in Figure 16 (a), with 16 individual future trends, shows strong clustering towards three future trends: Smart cities, buildings management (Future Trend 34), City DT sociotechnical aspects (Future Trend 35), Smart manufacturing/production (Future Trend 36), and Personalized medicine, Data driven health care, Model driven health care (Future Trend 37). Within this category, the fidelity issues are more evident, indicating a need for further refining activities.

The Pragmatic category (Category 11), with 16 individual future trends, is characterized by Digital Twins abstraction-level-raising initiatives. Appearing in domain-independent and domain-dependent digital twinning, predominantly within 2024 and 2025, and promoting the more generalized Digital Twins. Consequently, the majority of individual future trends, currently with low frequency (Future Trends: 74 - 81), will improve the futureness score on a timely basis.

On the other hand, Digital twin frameworks, platforms, and Quantum DT (Future Trend 66), Personal/human digital twin/behavior modeling/virtual patient (Future Trend 67), Virtual worlds, Metaverse, Integration of data, Models, Analytics, and Human on world-level (Future Trend 68), Sociotechnical systems (STS), social DT, digitalization, Cyber-Physical Systems (Future Trend 69),

and Smart technologies and systems, Emergent dynamical systems concepts, emergency management (Future Trend 70) are highly challenging for the future research endeavors.

All of the distributions (Figures 14–16, and Appendix A Table 5) indicate the existing time persistency of clustered, categorized, and analytical digital twinning future trends resulting from this research endeavor, and suggest that digital twinning futureness frequencies are distributed on the left side of the normal distribution function, indicating that in the digital twinning context, they exhibit low maturity but high futureness.

Additionally, the gained experience with the clustering process helped us in specifying the foundations of the digital twinning futureness evaluation framework, as a collateral goal.

3.3. Futureness Evaluation Framework Foundations

According to [30], the most elaborated approach to Digital Twin modeling decouples its internal architecture into Physical Twin, Digital Twin, Data Layer, and the Digital Twin's structural and behavioral foundations.

The reusability potential of the specified DT referent model is directly proportional to the isolation level of domain-dependent and domain-independent aspects of Digital Twins architecture layers. The Information Harvesting Layer, throughout the decoupling and openness features of a bridge pattern architecture, represents a focal area for leveraging domain-dependent and domain-independent moderation actions (Figure 17).

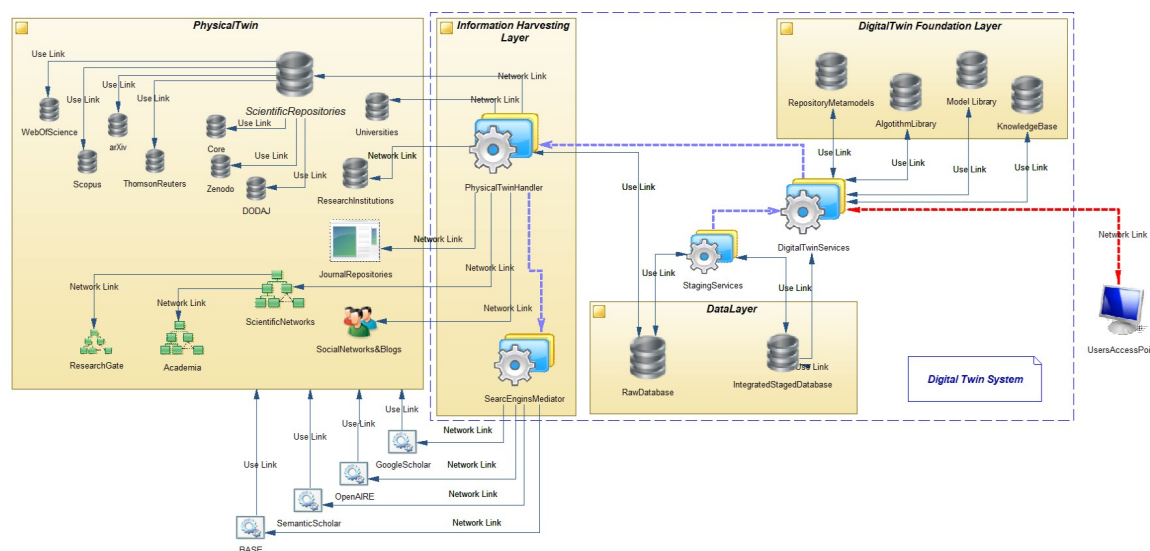


Figure 17. Digital Twins Referent Model, EA Infrastructure Diagram (Adapted from [30]). In this research context PhysicalTwin is recognized as an opened collection of research publications residing in different Scientific Repositories (Elsevier Scopus - scientific abstracts and citations database, Clarivate Web of Science - payed access platform, ThomsonReuters - world largest news information-based tools, archivX - the largest pre-prints repository, Core - the Open University Connecting REpositories, DODAJ - Directory of Open Access Journals, Zenodo - general purpose open access repository hosting dominantly research data sets and publications), belonging to the Universities and Research institutions publications repositories, scientific Journals Repositories, Scientific Networks (Research Gate, Accademia, etc.), and extremely challenging repositories build in the context of Social Networks and Blogs. The Information Harvesting Layer, Data Layer, Digital Twin Foundation Layer, and related Services, form a Digital Twin System[65]. The Information Harvesting Layer moderates direct access to the Physical Twin (PhysicalTwinHandler Services), and indirect access over SearchEngineMediator wrapping the open set of search engines (Google Scholar, Semantic Scholar, OpenAIRE, and BASE). Data Layer encapsulates two DT-related multi-model repositories: RawDatabase (storing the extracted article candidates) and IntegratedStagedDatabase (storing post-processed, classified, and indexed articles). The Digital Twin Foundation Layer integrates Repository Metamodels, Algorithms Library, Models Library, and a Knowledge Base, and supports an open set of Digital Twin Services, accessible over an

expandible set of specific User Access Point interface implementations. (Legend: **data flow** - black arrow; **control flow** - dashed blue arrow; **hybrid flow** - dashed red arrow).

Similarly, the Digital Twin Foundation Layer represents a focal area for Model-based and metadata-based static structure adaptability, while Knowledge-driven and a strategy pattern alignment support behavioral adaptability of individual Digital Twin configurations. The architectural flexibility of the Data Layer stems from the separation of raw and staged databases, as well as the data-driven behavior of Digital Twin services.

To mitigate the inherent complexity and improve consistency and accessibility, the multi-model database, with an open set of mechanisms supporting structured, semi-structured, and unstructured data, aligns well with the characteristics of Digital Twin's Data Layer and Digital Twin's Foundation Layer individual repositories, according to the selected set of configuration instances dynamically built from the Repository.

Metamodel database (Figure 17) compliant with the recommendations on metamodel-based configurability role in digital twins modeling, simulation, and operation, elaborated in our previous publications [54,74,75].

Consequently, we claim that the formulated DT model (Figure 17) aligns well with other methodological aspects that frame this research foundation.

4. Discussion

Within this research endeavor, several valuable approaches emerge. First, due to the systematic review methodology, this research highlights the importance of an explicit evaluation of the foundational dataset's relevance with respect to the intended goals. In the Introductory section (1.2. *Research motivations and relevancy analysis*), which, to our knowledge, is highly unusual, the initial systematic review serves to justify the rationality of this research initiation, and related mission and motivations declarations. We believe that this approach is of significant importance not only for digital twinning but equally for other research communities. Practicing this will help researchers to avoid repeating endeavors with questionable positive impacts, particularly through systematic and bibliographic reviews.

Second, during the selected publications deep analysis the importance of trustworthy publications metadata is exercised without the reliance on AI-based publications analysis tools, primarily due to the Google Scholar-based systematic review conduction. This approach helped us in highlighting certain obstacles related to the publication's metadata quality and contemporary search engine mechanisms access policy preventing the near-automated access to publications metadata, and consequently raised the consciousness level concerning the quality of the systematic and bibliography-based review articles' foundations. Our analysis shows that one of the most promising feature in publication analysis is a use of more sophisticated Explainable Artificial Intelligence (XAI) mechanisms than currently is the case [76].

Third, the highlighting of the intriguing relations between the maturity and futureness of arbitrary concepts or phenomenon and their appropriate argumentation, elaborated on in the Introductory and Materials and Methods sections, is another valuable result presented in this research article. Focusing on the futureness evaluation, it is possible to cross-relate the futureness and maturity aspects of the evaluated concept or phenomenon, representing hot spots in related research domains, for example, Digital Twinning and Artificial Intelligence.

Fourth, a multiphase systematic review, documented with supplementary resources, encourages other researchers to apply their expertise to the same dataset, supporting further research activities related not only to the authors of this research article, but also to arbitrary interested stakeholders.

Fifth, the proposed Digital Twinning Futureness Evaluation Digital Twins Framework, although conceptually not novel, exhibits novelty in the addressed domain, the reusability of knowledge extracted from systematic reviews. The proposed framework suggests knowledge harvesting not

only from the pool of peer-reviewed publications, but also from alternative sources, with preservation and reuse through Digital Twins. As mentioned earlier, contemporary scientific research and publishing are motivated by two main goals: a proper evaluation of research's mainstream novelty leading to the rational framing of research efforts, and comprehensive related work positioning in the overall research community. With the proliferation of Information and communication technologies, globally adopted scientific maturity evaluation and assessment principles, mechanisms, and frameworks, the overall number of scientific publications has exploded. On the other hand, individual scientific dignity and ethical aspects in research and publishing endeavors are under persistent pressure from the ongoing AI-based automation through software platforms and methodologies that use statistical and quantitative techniques to analyze academic literature, assess research performance, and identify trends. Some of them have evolved into stand alone commercial operational frameworks, often integrated with the popular scientific databases [77]. Orchestrating them through an interoperable platform, as suggested in the proposed framework's Information Harvesting Layer (Figure 17), would be at least beneficial for the overall research community. The evident grow of systematic bibliometric reviews after addressed concept or phenomenon has reached stable initial maturity level is rationally expected, but intriguing when related to the availability of the enhanced versions of supportive software platforms.

Additionally, during the systematic review of selected research articles, three additional article groups were isolated and are presented in Table 4.

Table 4. Notations on the special groups of analyzed publications.

Group	No.	Ref.	Focused on
Mission Related	1	[78]	The review of DT in the manufacturing industry aims to identify the contribution of machine learning (ML), current methods, and future research directions.
	2	[79]	The systematic examination of the science mapping of building information modeling and digital twins technologies in the digitalization of transportation.
	3	[80]	Bibliometric and patent analysis for the comprehensive and in-depth research on digital twins by reviewing the current status of academic research and technological development, distribution of countries and institutions, and technological competition situations.
	4	[81]	The analysis and identification of research trends in the past and present, isolating the essential functions of DT (prototyping, pilot testing, monitoring, improvement, and control).
	5	[82]	The functional aspects, appeal, and innovative use of DT in smart industries by systematically reviewing and reflecting on recent research trends in next-generation (NextG) wireless technologies (5G-and-Beyond networks) and design tools, and current computational intelligence paradigms (edge and cloud computing-enabled data analytics, federated learning).
Review Related	1	[83]	A bibliometric survey of the digital twin concept based on the Scopus database to present a global view of scholars' contributions in the manufacturing area.
	2	[84]	The development of the Digital Twins (DT) concept, its maturity, and its vital role in the Industry 4.0 context. Identifying DT's potential functionalities for the digitalization of the manufacturing industry, the digital twin concept, its origin, and perspectives from the academic and industrial sectors.
	3	[85]	This study aims to analyze existing fields of applications of DTs for supporting safety management processes to evaluate the current state of the art. A bibliometric VOSviewer-based review helped in determining DTs' use in the engineering and computer science areas and to identify research clusters and future trends. The successive bibliometric and systematic reviews deepen the relationship between the DT approach and safety issues.
	4	[86]	Gaining a better understanding of Digital Twin technology in Smart City development through a comprehensive and bibliometric review approach, on more than 4,220 articles.

		Differentiation of DT from other advanced 3D modeling technologies, such as BIM, examining the present applications of DT and BIM in the construction industry, emphasizing the similarities and differences between them, and developing solutions and design methods for the integration of BIM and DT in building construction.
5	[87]	
6	[88]	A comprehensive review of DTs applications in building energy efficiency analyzes research trends and identifies research gaps and potential future research directions.
7	[89]	The development of a proper methodology for visualizing the digital-twin science landscape using modern bibliometric tools, text-mining, and topic-modeling, based on machine learning models—Latent Dirichlet Allocation (LDA) and BERTopic (Bidirectional Encoder Representations from Transformers).
8	[90]	Creating insights into approaches used to create digital twins of human–robot collaboration and the challenges in developing these digital twins.
1	[91]	The T-Cell framework container for models, data, and simulations that interact dynamically in a smart city context.
2	[92]	The semi-heuristics framework for robust scheduling. Composed of genetic algorithms for schedule optimization and discrete event simulation, synchronized with the field through a Digital Twin (DT) that employs an Equipment Prognostics and Health Management (EPHM) module.
3	[93]	A digital twin framework for structural engineering.
4	[94]	The characteristics and applications of three disruptive concepts that are generating transformative change in the management of supply chains and business operations: Cloud-based systems.
5	[95]	The development of Digital Twin (DT) technology and its adoption within the maritime domain.
6	[96]	The DT state-of-the-art case studies with focus on concept
7	[97]	The innovative approach to addressing the challenges of smart mobility within the METACITIES initiative. Due to the increasing complexity of urban transportation systems
Framework Related		The AI-driven digital twin framework for real-time tool life prediction management. Addressing these limitations by integrating multiple modules, including an on-machine direct inspection system, a seamless connectivity integration module for real-time data management, and a deep learning module for tool wear prediction
8	[98]	
9	[99]	The definition of the DT-based smart factory and its components, the methodology of the DT-CFE-based smart factory, and the network topology and operation mechanism. The framework aids in testing the transmission and response performance of data interactions during job scheduling.

Consequently, we believe that the Materials and Methods and Results sections have justified the validity of the stated research hypotheses and have positively answered all the formulated research questions, thereby approving the research efforts.

4.1. Research Limitations

Although challenging, this research has common limitations inherent to all systematic reviews, first, the stratum selection. We have harvested publications from a single available database accessed by Google Scholar, assuming that with a representative dataset and an assumed near-natural distribution of future trends, it is more likely that with larger datasets, the overall tendency would not change significantly to jeopardize the obtained results. However, it would be beneficial to expand and diversify publication sources and step beyond the traditional systematic review context, to datasets containing not only peer-reviewed publications but also the holistic cyberspace. Nevertheless, the proposed Digital Twinning Futureness Evaluation Framework proposes such an holistic approach.

Second, despite the expertise level, the expert-based analysis suffers from the potential scientific and engineering autism emerging from the individual experience and knowledge profiles. Hypothetically, to overcome such an obstacle, it would be beneficial to rely on the three-cycled Modified Delphi method with a large enough expert pool, with intermediate plenary refinements, followed by final statistical decision-making. If one ignores the likelihood of organizing a large group of domain experts, the time needed to process our reduced dataset of 593 publications in the same manner will probably be a mission impossible. On the other hand, the involvement of the Large Language Models, Natural Language Processing, and Machine Learning mechanisms would speed up the process, assuming the existence of reliable and trustworthy AI mechanisms with a large enough training pool, which, to our knowledge, is not currently available. Nevertheless, the proposed Digital Twinning Futureness Evaluation Framework may serve as a promising initial step towards a fully operational, cloud-based, service-oriented Digital Twins-based framework.

To encourage other interested researchers from the digital twinning community to undertake similar endeavors, we have attached a complete working set used during the systematic review phases as Supplementary Resources associated with this research article (Article_Resources.zip).

5. Conclusions

Digital twinning future trends analysis motivations, research activities, systematic review conduction, the multiphase expert analysis, methodology principles and introduced methods, research findings and presentation mechanisms, joined by the discussion section, and highlighted research limitations, assure us that the obtained results and the proposed Futureness Evaluation Framework may be a challenging place to start further research activities and specify the future research directions for the authors team, but we believe, equally well for the much broader research community.

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Future research directions are multifold and are not limited by the following:

- Further enrichment of the referent dataset, based on the same review methodology;
- Further enhancements of clustering and classifying mechanisms, and more sophisticated semantic analysis to gain better fidelity while deriving individual future trends and more coherent categories;
- Launch a set of systematic review initiatives directed to evaluate the futureness and maturity of non-digital twinning originated trends related to concepts, paradigms, and technologies, and cross-correlate them with the results obtained in this research article. Apparently, a variety of combinations exists. We believe that an interesting one would be to, at first, use three non-digital twinning originated trends with the highest individual trend frequency (Table 3, Column 4):
 - Information and Data fusion, data cleaning, data integration, data fusion, two-way mirrors between physical and virtual data, and time-sensitive data (103);
 - Artificial intelligence (Perceive (data collection and storage), Understanding (machine learning, deep learning, Knowledge representation), and Decide (Reinforcement Learning, Operational Research)) (91);
 - Multidimensional modeling, model integration, and model verification in Virtual space, and modeling platforms (88).
- Specify and develop the operational Digital Twins supporting the specified Digital Twinning Futureness Evaluation Framework;

- Generalize it to support an arbitrary concept, technology, or paradigm as a futureness evaluation domain;
- Extend it by the maturity evaluation mechanisms and upgrade to Futureness and Maturity Evaluation Framework;

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: "All authors have equally contributed the article's structure and content."

Funding: "This research received no external funding."

Data Availability Statement: "The data used to support the findings of this study are included in the article."

Conflicts of Interest: "The authors declare no conflicts of interest."

Appendix A: The Visualization Foundations (Figures 13 to 16) - Table 5

Table 5. Future Trend Analytical Data and Annual Futureness frequency distribution.

Future Trend Data				Annual futureness frequencies								
Trend ID	Tech. (1/0)	Trend Freq.	Initial year	2017	2018	2019	2020	2021	2022	2023	2024	2025
	1	91	2019	2	3	5	4	11	11	18	19	15
	0	48	2019	0	0	2	2	7	16	18	26	20
	0	15	2019	0	0	0	3	7	14	21	17	20
	1	13	2017	1	2	6	5	9	13	13	33	21
	1	10	2019	1	0	0	1	2	4	8	16	21
	1	6	2020	1	0	1	4	3	4	5	8	17
	0	5	2019	0	0	2	2	5	8	12	10	9
	0	5	2025	0	1	5	6	11	8	19	12	10
	1	4	2021	0	0	0	0	2	4	8	16	22
	1	3	2025	0	0	0	0	1	6	10	7	3
	0	21	2022	0	0	3	0	2	4	12	31	19
	1	12	2019	1	0	4	2	8	9	13	4	4
	1	31	2021	0	0	5	3	13	11	11	11	9
	0	10	2017	0	0	0	1	3	3	3	7	5
	1	8	2018	0	0	2	1	1	4	4	18	8
	0	6	2017	1	0	2	1	2	11	8	14	16
	0	49	2018	0	0	0	0	1	2	5	9	7
	0	31	2019	0	0	0	0	2	5	8	4	4
	0	103	2017	0	0	0	1	6	6	5	8	4
	0	45	2017	2	1	7	3	3	3	3	9	1
	1	5	2019	0	0	0	0	0	3	3	9	14
	1	88	2017	0	3	2	4	5	4	5	10	7
	1	53	2017	0	1	2	0	2	10	14	10	10
	0	43	2017	0	0	4	0	3	5	3	3	2
	1	27	2021	0	0	3	0	2	4	9	9	9
	0	22	2020	0	1	0	0	2	6	5	15	9
	1	11	2020	0	0	1	1	3	2	4	13	8
	1	5	2023	0	0	1	1	3	4	8	6	7
	0	4	2023	0	0	2	0	4	1	2	3	3
	0	4	2017	0	0	0	1	3	1	0	4	2
	0	4	2023	0	0	0	1	5	1	4	4	0
	1	4	2024	0	3	0	3	0	3	4	0	7
	0	2	2023	1	0	2	2	2	1	0	4	1

1	38	2019	0	0	2	1	1	3	6	6	5
1	32	2017	0	0	2	2	6	4	2	9	6
0	20	2018	0	0	0	0	0	5	0	6	7
0	16	2020	0	0	0	1	0	0	7	1	7
0	11	2023	0	0	1	0	1	1	4	1	2
1	3	2024	1	1	3	1	4	1	0	2	0
0	3	2024	0	1	1	0	2	4	3	1	2
0	3	2024	0	0	0	0	1	1	2	6	4
1	3	2021	0	0	2	0	3	2	2	4	3
1	3	2020	0	0	0	0	2	7	9	7	6
0	1	2024	0	0	0	0	0	0	0	8	0
0	1	2024	0	0	0	0	0	0	2	6	3
1	1	2024	0	0	0	3	0	2	1	2	2
1	1	2024	0	0	0	0	0	0	1	3	1
0	1	2023	0	0	0	2	1	1	2	0	0
0	1	2024	1	0	4	1	0	0	0	0	0
0	27	2019	0	0	0	0	0	0	3	0	1
0	3	2021	2	0	1	0	0	0	1	0	0
0	52	2021	0	0	0	0	0	0	2	0	2
1	30	2020	0	0	0	0	0	0	0	2	2
0	29	2022	0	0	1	0	0	0	2	2	0
0	13	2017	0	0	0	0	0	0	0	0	5
1	10	2020	0	0	0	1	0	2	1	2	0
0	6	2020	0	0	1	0	0	1	6	10	9
0	5	2021	0	0	0	0	3	1	0	0	0
0	3	2019	0	0	3	0	2	0	1	0	0
0	72	2018	0	0	1	0	3	0	1	0	1
0	18	2022	0	0	0	0	0	0	3	0	1
1	14	2018	0	0	1	0	1	0	1	0	2
1	14	2021	0	0	0	0	1	0	2	2	0
0	6	2019	0	0	0	0	0	3	0	6	12
0	6	2019	0	0	0	0	0	0	0	0	3
0	82	2020	0	0	0	0	0	0	0	1	2
1	24	2021	1	0	2	4	0	1	2	0	0
0	23	2021	0	0	0	0	0	0	1	0	1
0	20	2019	0	0	3	0	0	0	0	0	0
1	15	2020	0	2	2	1	1	0	0	1	1
0	8	2024	0	0	0	0	0	0	0	3	0
0	6	2017	0	0	0	0	0	0	0	3	0
0	4	2023	0	0	0	0	0	0	0	3	0
0	3	2024	0	0	0	0	2	0	1	0	0
0	2	2024	0	0	0	1	0	0	1	1	0
0	2	2025	0	0	2	0	8	1	1	0	0
0	2	2025	0	0	0	0	0	0	0	1	1
0	1	2024	0	0	0	0	0	0	0	0	2
0	1	2025	0	0	0	0	0	0	0	0	2
1	1	2025	1	0	0	0	0	2	0	1	2
0	1	2025	0	0	0	0	0	0	0	1	0
0	63	2019	0	0	0	0	0	0	0	0	1
0	40	2018	0	0	0	0	0	0	0	0	1
0	36	2019	0	0	0	0	0	0	0	0	1
0	32	2019	0	0	0	0	0	0	0	1	0
0	24	2019	0	0	0	0	0	0	0	1	0
0	16	2019	0	0	0	0	0	0	0	1	0
0	55	2017	0	0	0	0	0	0	0	1	0

0	38	2018	0	0	0	0	0	0	1	0	0
0	71	2019	0	0	0	0	0	0	0	1	0
0	30	2019	0	0	0	0	1	0	1	1	0
1	8	2020	0	0	0	1	1	2	2	0	2
1	1	2025	0	0	0	0	0	0	0	0	1
1	1	2025	0	0	0	0	0	0	0	0	1
	1844		16	19	93	71	177	235	339	476	418

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