Lecture Notes in Networks and Systems 1716

Alvaro Rocha
Francisco García Peñalvo
Carlos J. Costa
Ramiro Gonçalves *Editors*

Proceedings of 20th Iberian Conference on Information Systems and Technologies (CISTI 2025)

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Alvaro Rocha · Francisco García Peñalvo ·
Carlos J. Costa · Ramiro Gonçalves
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Introduction

This book compiles selected papers presented at CISTI'2025 – the 20th Iberian Conference on Information Systems and Technologies, held from June 16 to 19, 2025, at ISEG – Lisbon School of Economics and Management, University of Lisbon, Portugal.

Organized jointly by ISEG and the Information and Technology Management Association (ITMA), CISTI'2025 provided an international platform for researchers and industry practitioners to share and discuss recent advancements, emerging trends, experiences, and future concerns across the diverse domain of Information Systems and Technologies.

The Scientific Committee comprised 273 international experts from multiple disciplines within Information Systems and Technologies, who rigorously evaluated submissions using a double-blind peer-review process. This meticulous procedure ensured the high quality and relevance of contributions selected for presentation in the conference's key thematic areas:

A) Organizational Models and Information Systems
B) Knowledge Management and Decision Support Systems
C) Software Systems, Architectures, Applications, and Tools
D) Computer Networks, Mobility, and Pervasive Systems
E) Human-Centered Computing
F) Health Informatics
G) Information Technologies in Education
H) Architecture and Engineering of Construction

CISTI'2025 attracted nearly 500 paper submissions from 43 countries worldwide, demonstrating the conference's global reach and academic significance. Accepted papers presented at the conference are published by Springer in this book, as well as by ITMA, and will be submitted for potential indexing in renowned databases such as Scopus, Web of Science (WoS), EI-Compendex, DBLP, and Google Scholar.

We extend our sincere gratitude to all contributors whose dedication and effort made CISTI'2025 possible, including authors, committee members, workshop organizers, and sponsors. Their valuable support has significantly contributed to the continued success and prestige of the conference.

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Improving the Design and Implementation of Digital Twins with Model-Driven Software Development

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Abstract. Digital twins are virtual replicas of physical systems that are used to optimize performance, improve decision-making, and drive innovation in a variety of sectors. However, many existing digital twin solutions are highly specialized and designed to address industry-specific needs or use cases, and there is a lack of domain-independent development frameworks. As a result, developers often have to design and build each system from scratch, leading to long development cycles and high costs. To overcome these challenges, this ongoing doctoral research aims to propose a Model-Driven Software Development (MDSD) approach to simplify the design and implementation of digital twin systems. This approach will allow digital twin designers and developers to focus on system design from an abstract, high-level perspective. Model-to-Text (M2T) transformations will then automate the generation of system code from these models. Ultimately, this doctoral thesis aims to make digital twin development more accessible, structured, and cost-effective.

Keywords: Digital Twins · Model-Driven Software Development · Model-to-Text Transformations · Software Engineering

1 Introduction

The digital twin concept has gained significant attention across various industries due to its potential to enhance operational efficiency, optimize decision-making, and drive technological innovation [22,26,27]. A digital twin is a virtual representation of a physical entity or system that mirrors its behavior, conditions, and processes in real-time [22,28]. By leveraging digital twins, organizations can simulate "what-if" scenarios, proactively detect failures or undesirable outcomes before they occur, and optimize overall system performance in a variety of domains such as manufacturing [14], healthcare [8], and agriculture [25].

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However, despite their benefits, most existing digital twin solutions are highly specialized and tailored to specific industry needs or use cases [20,21], and there is a lack of domain-independent development frameworks [15,20,21]. As a result, developers frequently need to design and implement each digital twin from scratch, leading to extended development cycles, increased costs, and a lack of scalability [19,30].

To overcome these challenges, this ongoing doctoral research aims to propose a Model-Driven Software Development (MDSD) approach, specifically through the creation of a Domain-Specific Language (DSL) and Model-to-Text (M2T) transformations for digital twin development. This DSL will allow developers to focus on the abstract, high-level design of digital twin systems rather than dealing with tedious low-level implementation complexities [5,16,29]. Then, automatic code generation capabilities will create the system code from these high-level models, reducing manual coding efforts, minimizing human-induced errors, and ensuring consistency throughout the development process [5,16,29]. In addition, this approach also aims to make digital twin development more accessible to a broader audience, including those with limited expertise in low-level coding or specific technologies [5,29].

Therefore, the objective of this ongoing research is to make digital twin development more accessible, structured, and cost-effective across various industries. By streamlining the implementation process, the proposed MDSD approach seeks to enable faster prototyping, reduce development overhead, and improve the scalability of solutions.

This communication is part of the Doctoral Symposium of the Congress. The project began 15 months ago and is expected to be completed by October 2026. The research aligns with the “SSAAT – Software Systems, Architectures, Applications, and Tool,” Congress theme, as it focuses on leveraging MDSD for the development of digital twins.

The remainder of this manuscript is structured as follows. Section 2 defines the research questions and objectives guiding this study. Section 3 reviews related work, while identifying gaps that this research aims to address. Section 4 describes the proposed methodology. Section 5 discusses the expected results. Finally, Sect. 6 concludes the manuscript.

2 Research Questions and Objectives

This ongoing doctoral research aims to develop an MDSD approach for digital twin development. The following Research Questions (RQ) and objectives guide the research.

2.1 Research Questions (RQ)

– **RQ1:** How can a conceptual model of digital twins be defined to effectively capture their essential components, features, and functionalities in a domain-independent manner?

This question is formulated to establish a foundational understanding of digital twins, ensuring that the proposed approach is applicable across multiple domains. It will serve as the foundation for further metamodeling steps.

- **RQ2:** How can MDSD be applied to the definition, validation, generation, and deployment of digital twins across industries?
  This question investigates how MDSD principles and techniques can be leveraged to automate and optimize the design, validation, and implementation processes for digital twins.
- **RQ3:** What are the challenges of applying MDSD to digital twin development, and how can they be addressed?
  This question seeks to examine the challenges encountered when applying MDSD to digital twin development, identifying potential obstacles and proposing solutions to ensure the effectiveness of the methodology.
- **RQ4:** How can the proposed MDSD approach be validated to assess its applicability and effectiveness in real-world digital twin implementations?
  This question focuses on the validation of the proposed methodology through practical case studies, particularly assessing its real-world applicability in diverse industries and identifying any limitations or areas for improvement.

2.2 Research Objectives

- **Objective 1:** Define a domain-independent conceptual model for digital twins.
  The first objective is to establish a flexible, domain-independent model that captures the core components, features, and functionalities of digital twins. This model will serve as the foundation for the proposed approach.
- **Objective 2:** Develop and implement an MDSD approach for digital twin development.
  The second objective is to create a domain-agnostic development framework for digital twins. This approach will integrate key MDSD principles to automate the design, validation, and generation of digital twin solutions.
- **Objective 3:** Validate the approach in real-world case studies.
  The third objective is to test the applicability and effectiveness of the proposed MDSD approach in real-world contexts, with particular emphasis on the agricultural sector.
- **Objective 4:** Disseminate research findings and results.
  The final objective is to disseminate the research outcomes to the academic and industrial communities. This will involve presenting findings at relevant conferences, submitting research papers to high-impact journals. With the dissemination of the results, this research aims to promote the widespread adoption of digital twins, offering valuable insights that encourage the integration of model-driven methodologies in their development across both academic and industrial communities.

The following section reviews related work that has explored similar approaches in the realm of digital twin development, identifying their limitations and gaps.

3 Related Work

MDSD has been traditionally applied to software systems closely related to digital twins, such as Internet of Things (IoT) systems. This section explores the intersection of MDSD with IoT systems and digital twins, highlighting key advancements, ongoing challenges, and gaps that remain in the field.

3.1 MDSD and the Internet of Things

MDSD has proven its effectiveness in the development of IoT systems. For instance, Fortino et al. [13] provide a review of 70 different IoT platforms, identifying several that incorporate MDSD principles to facilitate IoT system design and development. Similarly, Ihirwe et al. [17] discuss 16 low-code IoT development platforms, many of which integrate MDSD principles. These reviews highlight the growing role of MDSD in improving efficiency and reducing complexity in IoT development.

In this context, Ciccozzi and Spalazzese [6] introduce MDE4IoT, a model-driven approach that allows modeling the different components of an IoT system. MDE4IoT also enables the automatic generation of executable code based on the modeled system.

Similarly, Moin et al. [23] present ThingML+, an extension of ThingML [24], a model-driven tool for developing IoT and cyber-physical systems with a focus on machine learning needs. The tool also supports automatic code generation.

Another notable application of MDSD in the IoT is SimulateIoT, proposed by Barriga et al. [3]. SimulateIoT is a model-driven tool that enables the design, code generation, and execution of IoT system simulations. In addition, this tool has been extended in subsequent studies to tackle specific IoT challenges, like supporting IoT systems with mobile nodes [7] and testing and optimizing task scheduling strategies [2].

3.2 MDSD and Digital Twins

With the rise of digital twin technology, researchers have begun exploring MDSD as a means to streamline the development of digital twin systems.

One of the early MDSD-based approaches for digital twins is proposed by Bibow et al. [4], which focuses on modeling reactive digital twins using event-driven rules. This work was then extended by Dalibor et al. [9], introducing a graphical monitoring interface for enhanced user interaction. However, while these approaches enable real-time response mechanisms, they primarily rely on predefined rule-based behaviors and lack the integration of advanced virtual models, such as machine learning models.

Similarly, Vale et al. [30] present an MDSD framework tailored for industrial digital twins and validate their approach through an iron ore sintering plant case study. While effective for industrial applications, this solution is domain-specific and could not generalize well to other fields. Moreover, it remains unclear whether the framework supports full automation, including automatic code generation and deployment.

Therefore, despite these advancements, several challenges remain in applying MDSD to digital twin development. Existing solutions tend to be industry-specific, limiting their adaptability across different domains. Additionally, many frameworks lack comprehensive automation, requiring significant manual effort in model transformation and system deployment. Moreover, digital twin service modeling remains incomplete, with limited support for key functionalities such as predictive analytics and "what-if" scenario testing.

To address these gaps, this research aims to propose a domain-independent MDSD framework for digital twin development. The following sections will outline the proposed methodology and expected contributions.

4 Methodology

This section outlines the methodology that will be employed. First, the layers of metamodeling [5] are introduced. Then, the research methodology is presented. Finally, the tools and technologies involved are stated.

4.1 Layers of Metamodeling

In MDSD, metamodeling is organized into four hierarchical layers: M0, M1, M2, and M3, each serving a distinct purpose (see Fig. 1). A clear understanding of these layers provides the foundation for the approach followed in this research. Therefore, before delving into the specific research methodology, each of these layers is described below.

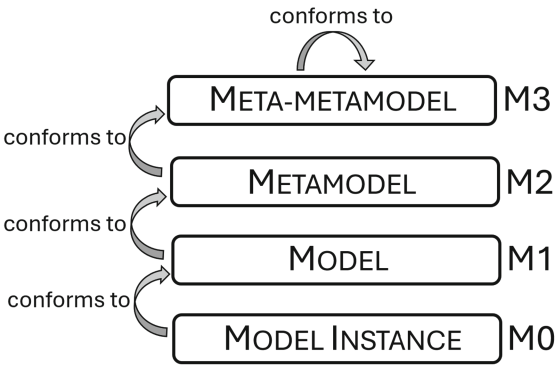

Fig. 1. Layers of metamodeling. Adapted from Brambilla et al. [5].

– **M0 Layer (Real world objects)**: This layer represents actual instances of the system, such as code or data.

- **M1 Layer (Model)**: The M1 layer contains abstract representations of real-world systems or processes. These models describe the structure and behavior of the M0 instances.
- **M2 Layer (Metamodel)**: The M2 layer defines the language, rules, and semantics for constructing M1 models. It provides a standardized framework for ensuring consistency and correctness in the creation of models.
- **M3 Layer (Meta-metamodel)**: Finally, the M3 layer governs the creation of M2 metamodels. It provides the foundational rules and principles that define how metamodels should be structured and constructed. This layer is reflexive, i.e., the meta-metamodel conforms to itself.

Therefore, to develop an MDSD approach for the definition, validation, generation, and deployment of digital twins, it is crucial to focus on these metamodeling layers. With this foundation in mind, the research methodology is outlined below.

4.2 Research Methodology

The research methodology follows a systematic approach, consisting of the following stages:

- **Literature Review**: A comprehensive review of existing literature is being conducted to assess current trends and challenges in digital twin modeling.
- **Conceptual Model Identification**: Based on the findings from the literature, the key characteristics, behaviors, and relationships of digital twins will be identified. This conceptual model will serve as the foundation for further metamodeling steps.
- **Metamodel Design and Formulation**: A formal metamodel (M2) will be defined to formalize the structure and semantics of digital twin systems.
- **Graphical Syntax Development**: A graphical modeling tool will be developed, providing an intuitive interface for users to create and visualize digital twin models (M1) without the need for extensive technical knowledge.
- **Automatic Code Generation Capabilities Implementation**: To achieve automation in digital twin deployment, M2T transformations will be implemented. This will allow digital twin models (M1) to be automatically converted into executable code (M0).
- **Use Case Validation**: The proposed tool will be validated through real-world use cases.
- **Iterative Refinement**: The methodology adopts an iterative approach, with continuous refinement of the proposed approach based on feedback from the use case validation phase.
- **Dissemination of Results**: Research findings, methodologies, and tools developed throughout the project will be disseminated through academic publications, conference presentations, and collaborations with the research community and industry stakeholders.

4.3 Tools and Techniques

Several tools and techniques will be employed throughout the research:

- **Eclipse Modeling Tools**: For the creation of the metamodel (M2), Eclipse Modeling Tools [11] will provide the necessary infrastructure.
- **Sirius and Eugenia**: The Sirius [12] and Eugenia [18] tools will be used to develop the graphical syntax for model representation (M1).
- **Acceleo**: The Acceleo tool [10] will be employed to implement the M2T transformations.

5 Expected Results

The primary goal of this research is to develop a domain-agnostic DSL together with M2T transformations for digital twin development, leveraging MDSD principles. The expected outcome is a flexible, scalable, and consistent development framework that can be applied across various sectors. In addition, by utilizing tools such as Sirius and Eugenia, the MDSD approach will provide an intuitive, visual interface for system design, making digital twin development more accessible to non-expert users.

To date, an article has been published in a high-impact journal in this line of research [1], where an MDSD approach for distributed intelligent systems is introduced. The proposal's applicability is demonstrated through an agricultural digital twin integrating intelligent capabilities. Additionally, the author participated in the 2024 *Sociedad de Ingeniería de Software y Tecnologías de Desarrollo de Software* (SISTEDES) Congress, presenting in the Software Engineering for Digital Twins (ISGD) track.

6 Conclusion

This research aims to develop a domain-independent Domain-Specific Language (DSL) together with Model-to-Text (M2T) transformations for the streamlined development of digital twin systems, addressing the limitations of current industry-specific solutions. By utilizing Model-Driven Software Development (MDSD) principles, the proposed tool will enable the efficient design, code generation, and deployment of digital twins across diverse industries. The focus on abstraction and automation through M2T transformations will simplify the development process, reducing costs, minimizing errors, and enhancing scalability.

The proposed MDSD approach will be validated through real-world case studies, ensuring its practical applicability. The research also aims to contribute to the broader adoption of digital twin technology by providing a flexible and accessible framework that reduces the technical barrier for developers.

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