Annales Mathematicae et Informaticae
61 (2025) pp. 215–228
DOI: 10.33039/ami.2025.10.023
URL: https://ami.uni-eszterhazy.hu

cRAMI 4.0 an Improved Reference Architectural Model for Industrie 4.0 (RAMI 4.0) based on a three-dimensional cubic lattice model

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Abstract. In the context of Industry 4.0, the increasing complexity of 5G-enabled Internet of Things (IoT) systems demands efficient and scalable methods for optimizing information flow across distributed architectures. This paper presents a novel approach to optimizing information flows in IoT systems by leveraging a three-dimensional cubic lattice model aligned with a customized Reference Architectural Model for Industry 4.0 (cRAMI 4.0). The novelty and improvement consist in the use of a three-dimensional lattice structure that maps three critical axes, detection level functions (X-axis), analysis and maintenance processes (Y-axis), and access control levels (Z-axis), onto a unified spatial model for representing and optimizing in-

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Accepted: October 28, 2025
Published online: October 28, 2025

formation flows in IoT systems. Each node within the lattice represents a combination of these dimensions, enabling a comprehensive representation of functional, procedural, and security aspects in IoT environments. This spatial model facilitates the visualization, analysis, and optimization of data flows and access control mechanisms, enhancing system efficiency, security, and maintainability. The approach offers practical benefits for designing scalable and secure IoT architectures compliant with the main RAMI 4.0 principles. We formalise the proposed system using Petri net based modelling to simulate process transitions across Cloud-IoT-Lattice domains. Each IoT layer (perception, network, application) is treated as a distinct computational zone, and transitions between zones are defined across lattice-encoded relations. This interdisciplinary approach bridges informatics and industrial informatics, offering a new paradigm for adaptive, low-latency IoT systems in smart manufacturing, healthcare, and logistics.

Keywords: Internet of Things, RAMI 4.0, cRAMI 4.0, cubic lattice model, Petri nets

1. Introduction

The concept of the *Internet of Things* (IoT) describes a highly interconnected world, in which various objects are integrated with sensors and other digital devices, enabling their networking for the collection and exchange of data [19]. These devices, often referred to as *connected objects* or *IoT devices*, range from household appliances to industrial machines, and are equipped with sensors and actuators to gather and transmit data [8].

In the context of manufacturing, IoT enables real-time data collection and sharing among various production resources, such as machines, workers, materials, and tasks. Furthermore, IoT can provide enhanced connectivity across objects, systems, and services, allowing data exchange [19].

In the future, a convergence of IoT-related technologies is anticipated, including ubiquitous wireless standards, Data Analytics, and Machine Learning (ML) [19]. Industrial IoT (IIoT) is considered a key driving force for increasing productivity and efficiency in industrial landscapes. IoT is one of the core technologies underpinning Industry 4.0 [8].

The *Reference Architectural Model Industrie 4.0* (RAMI 4.0) is widely regarded as the preferred framework for implementing Industry 4.0 architectures [9, 15, 18]. It is represented as a three-dimensional cube encompassing the most important business elements and technological innovations of Industry 4.0. RAMI 4.0 aims to guide the implementation of compatible system architectures and to provide a shared framework for stakeholders to understand and communicate effectively. The model facilitates the classification of objects such as machines, and the description and implementation of complex Industry 4.0 (I4.0) concepts.

Regarding the *integration* of IoT within the RAMI 4.0 structure, the RAMI provides a framework for incorporating information technology/operational technology (IT/OT) systems (in which IoT plays a crucial role) into industrial ecosystems.

Those three axes of RAMI 4.0 (hierarchical levels, life cycle stages, and architecture layers) allow mapping and analysis of how IT/OT microsystems interact and contribute to value creation. The 3D visualisation of microsystems within RAMI 4.0 cubes demonstrates how legacy IoT systems can be integrated with newer I4.0 technologies by treating legacy systems as *closed systems*. Mapping administrative shells and technical assets to appropriate layers ensures the functional and communication properties are correctly assigned [13].

Petri nets [1] have long been employed as a formal modeling tool for the analysis of discrete event systems, particularly in the context of concurrency, synchronization, and resource sharing [4, 16, 21]. Due to their graphical nature and rigorous semantics, Petri nets are especially suited for representing the behavior of distributed systems, making them a natural fit for modeling Internet of Things (IoT) environments. In recent years, their use has expanded into Industry 4.0 contexts, where complex device interactions and process flows require formal verification and simulation tools.

Lattice structures are widely used in computer science and engineering to represent discrete, multi-dimensional spaces in which elements are organized based on defined rules of adjacency and interaction. In the context of system modeling, a lattice provides a structured way to map complex relationships across multiple dimensions, enabling clear visualization and analysis of interdependencies. Particularly in domains where hierarchical, procedural, and control aspects intersect - such as in industrial IoT systems - a lattice can serve as an effective abstraction for organizing system components and their interactions. By defining nodes at the intersection of key dimensions, lattice-based models allow for both conceptual clarity and computational tractability in modeling, simulation, and optimization tasks.

The innovative contribution of this work lies in the integration of a three-dimensional cubic lattice model with a customized RAMI 4.0 (cRAMI 4.0) framework, where the axes correspond to detection level functions, analysis and maintenance processes, and access control levels. This structural approach enables a new perspective on modeling and optimizing information flows in IoT systems. Based on this architectural model can be described agent-based systems in Industry 4.0 developments [10, 11].

To capture the dynamic and often unpredictable nature of IoT environments, we extend our modeling approach to include both deterministic and stochastic Petri net simulations. While deterministic models provide a baseline for system behavior under ideal conditions, stochastic modeling allows us to incorporate variability in transition delays, fault occurrences, and data flow rates. This dual perspective enables a more realistic evaluation of system responsiveness, fault tolerance, and access control enforcement, especially in scenarios involving fluctuating sensor inputs, network latency, or probabilistic failures.

The following sections detail the theoretical foundation of the model, its mapping to the custom RAMI axes, and the simulations with experimental evaluation purposes using Petri Nets.

2. Reference Architectural Model Industry 4.0

Internet of Things (IoT) refers to the network of interconnected physical devices that can collect, transmit and process data from the real world (sensors, actuators, smart devices, etc.) [17]. In the following, we will highlight several aspects concerning data analysis in IoT systems and their architectures [8].

Data Analysis Challenges in IoT. These include the vast volume and variety of data, the need for real-time processing and long-term maintenance.

IoT Data Processing Techniques. Techniques such as data denoising, outlier detection, missing data imputation, and data aggregation are frequently employed.

Integration with Emerging Technologies. Data analysis in IoT is increasingly integrated with cloud computing, fog computing, and edge computing to address specific challenges in sensor networks and data analytics.

Typical IoT Architectures. These include multiple layers: the Perception Layer (sensors and actuators), the Network Layer (routers and gateways, connectivity and protocols), the Application Layer (cloud/servers, industrial applications), and occasionally a middleware or support layer for intelligent data processing and decision-making [8].

The RAMI 4.0, proposed for understanding and implementing Industry 4.0, highlights the importance of security as a fundamental condition.

RAMI 4.0 plays a central role in structuring and providing a common understanding of the complex systems specific to Industry 4.0 [22]. Its main roles include the following:

- **Developing a shared understanding:** The main goal of RAMI 4.0 was to guarantee that all parties involved understood Industry 4.0.
- **Structuring complexity:** RAMI 4.0 is a three-dimensional model that helps to address the problem of Industry 4.0 in a structured manner.
- **Integrating components:** Combines the IT elements and components into a layered model of the lifecycle. This includes aspects such as data privacy and IT security.

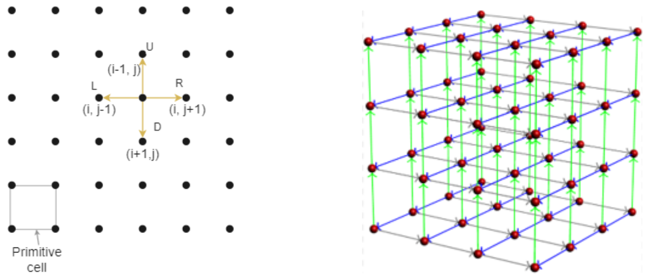
RAMI 4.0 as an Architectural Model. Previously discussed as a three-dimensional reference framework for Industry 4.0. Its dimensions include Architecture Layers, the Life Cycle / Value Stream, and Hierarchy Levels. RAMI 4.0 helps to structure and understand the complexity of Industry 4.0 systems and facilitates the integration of components and data [22].

3. Lattice definition in the context of our research

Algebraically, a lattice is an abelian group that spans a vector space; geometrically, it forms a grid. The space exists only at the lattice nodes, meaning that entities (components, objects, amino acids, molecules, particles) are constrained to these fixed positions [6, 14].

A Walk on a lattice is defined as a sequence of adjacent nodes and serves as a way to encode spatial configurations. In a two-dimensional (2D) square lattice, each node has four nearest neighbors, corresponding to the four cardinal directions: right (R), up (U), left (L), and down (D). In absolute encoding, each step of the walk is represented by one of these direction symbols.

In a three-dimensional (3D) cubic lattice, each node has six nearest neighbors, aligned with the three spatial axes. The absolute directions are: right (R), left (L), up (U), down (D), forward (F), and backward (B). Thus, in 3D, each step in the walk is encoded using one of these six direction symbols. Figure 1a and 1b show the representation of a 2D square lattice and 3D cubic lattice, respectively [20].



(a) 2D square lattice. **(b)** 3D cubic lattice.

Figure 1. Lattices visual overview.

4. A novel customised architecture of RAMI 4.0

An innovative approach is introduced in this paper, specifically for analysing and interpreting information within IoT environments. This approach utilises a three-dimensional cubic lattice model.

While existing sources address IoT data analysis, varied architectures (including the 3D RAMI 4.0 model), and advanced communication technologies like 5G, this paper introduces a novel, innovative methodology: a three-dimensional cubic lattice model for the analysis and interpretation of data in 5G-based IoT environments.

IoT offers the connectivity and data necessary for operational execution, while RAMI 4.0 provides the architectural framework to organise and contextualise these capabilities by linking physical assets to the digital IoT ecosystem.

4.1. Formal mapping of cRAMI 4.0 from a cubic lattice structure to Petri nets

The RAMI 4.0 provides a multidimensional framework for modeling industrial systems, typically structured along three conceptual axes: hierarchy levels, product life cycle, and IT/OT layers. In this work, we propose a customized interpretation of these axes of the RAMI 4.0, that we called cRAMI 4.0, more directly aligned with practical aspects of IoT system design and management. Specifically, we define the following mapping:

- **X-axis (horizontal axis to the left) – Detection Level Functions:** This axis represents the range of sensing and detection functionalities in the IoT system, from basic physical sensors to higher-level data acquisition and pre-processing modules. Each step along this axis corresponds to increasing levels of functional complexity and semantic interpretation of raw data.
- **Y-axis (horizontal axis to the right) – Analysis and Maintenance Processes:** This axis models the procedural flow from data collection to fault diagnosis, maintenance planning, and system reconfiguration. It reflects the temporal and logical sequence of actions applied to maintain or enhance system performance.
- **Z-axis (vertical axis) – Access Control Levels:** This axis captures the vertical segmentation of system access permissions, from low-level device access (e.g., automated processes or field operators) to higher-level administrative or supervisory roles. It enables the modeling of security policies and role-based data accessibility across the system.

By structuring the system along these three axes, the cubic lattice model allows for a granular representation of each component and its interactions.

To simulate the behavior of the proposed cRAMI 4.0 architecture, we formally map each lattice node (x_i, y_j, z_k) to a Petri net **place** representing a system state. Each node in the lattice denotes a specific configuration defined by a triplet: (x_i, y_j, z_k), where x_i a specific detection-level function (e.g., sensor activation, data acquisition), y_j to a stage in the analysis or maintenance process (e.g., fault diagnosis, reconfiguration), and z_k to an access control level (e.g., field operator, supervisor, administrator)

This mapping provides a powerful abstraction for identifying, analyzing, and optimizing information flows across the IoT system. It enables a spatial understanding of data paths, process dependencies, and security constraints, offering a comprehensive perspective that bridges functionality, operations, and governance within Industry 4.0 environments.

We model a cloud-connected smart manufacturing system comprising: a **Perception Layer**: temperature and vibration sensors on industrial machines; a **Network Layer**: edge gateways and routers; and an **Application Layer**: cloud-based analytics and decision support. Each layer is encoded in the lattice and mapped to Petri net zones. The system includes: 18 places (P) representing discrete states; 12 transitions (T) modeling actions and data movement and 3 zones: IoT, connection interface, and cloud. **Transitions** in the Petri net represent the data flow between adjacent detection levels, the procedural advancement in analysis/maintenance and the role-based access control enforcement.

Figure 2 presents the main architectural model presented above. In the lattice representation, the X-axis corresponds to detection level functions (left to right), the Y-axis represents the progression of analysis and maintenance processes, and the Z-axis extends in depth, capturing the hierarchical access control levels.

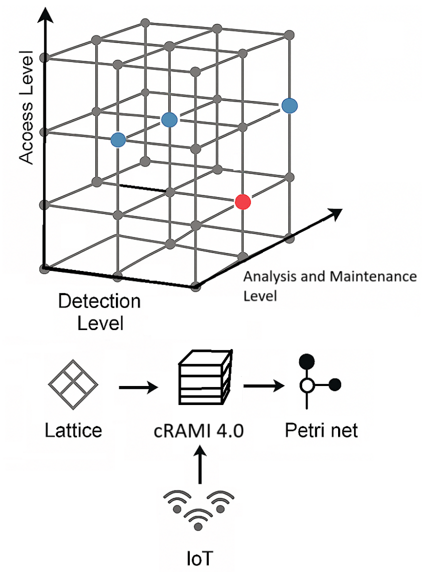


Figure 2. The proposed cRAMI 4.0 Architecture.

The current study's contributions are based on three main goals related to IoT and Cloud, which are also essential elements of RAMI 4.0 [3]:

1. The fundamental study of Petri nets for analysis and validation within discrete systems.

2. Application of Petri nets for modeling and analyzing discrete-event systems, particularly within the detection and analysis layers of IoT architectures.

3. Compare deterministic vs. stochastic behavior in process transitions. Validation methods and results obtained from the analysis of the subject model, which are used to reorganize and reevaluate the system and increase its flexibility. Stochastic modeling introduces variability in transition delays.

This hybrid architecture combines formal modelling (Petri nets), distributed computing (cloud), cyber-physical sensing (IoT) and structured analysis (3D lattices). It exemplifies the integration of computational models [2, 5] with domain-specific goals, such as those in smart manufacturing, health, or molecular biology.

4.2. Simulations using Petri nets

To model and simulate the proposed architecture, we adopt Petri nets (the simulations were performed in Visual Object Net++ application software [7]), which are relatively easy to use, cost-effective, provide real-time insight, and support dynamic intervention without deviating from the systems original purpose.

Table 1. Simulation parameters and variables.

Parameter	Description	Value Range
Sensor activation rate	Frequency of data generation	1–10 Hz
Transition delay	Time between state changes	0.1–2.0 s
Access level	Role-based permission tier	1 (low) to 3 (high)
Token count	Number of active processes	0–100
Fault injection rate	Probability of error occurrence	0–0.2
Data throughput	Volume of data per unit time	10–1000 KB/s

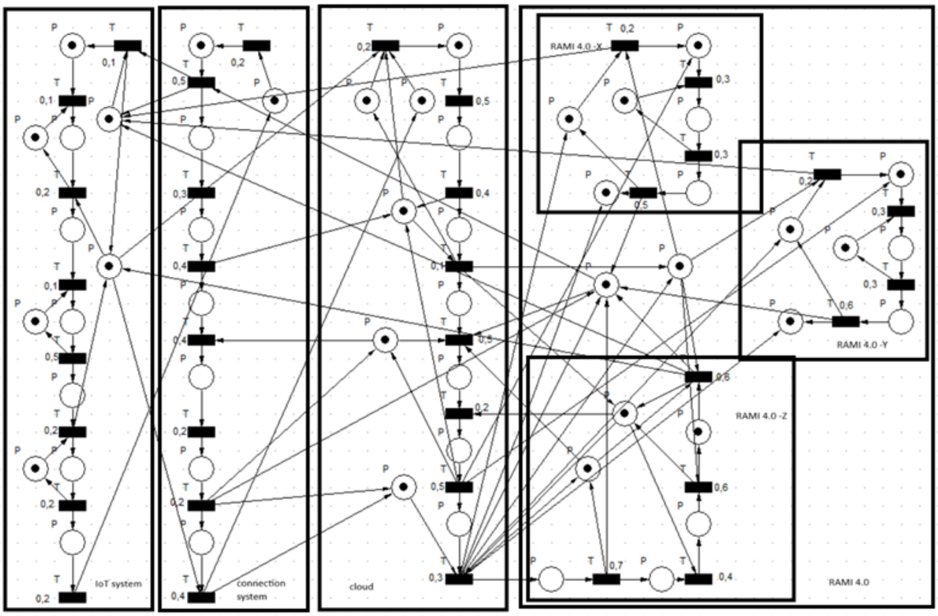


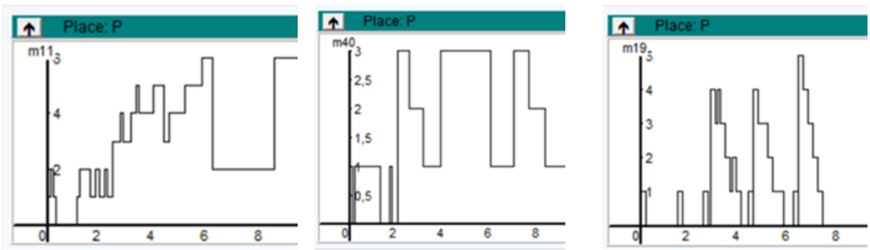
Figure 3. General Petri nets model architecture.

Figure 3 illustrates the key stages of an ideal cloud manufacturing system built based on the cRAMI architectural model Petri net structure: P = place (state), T = transition (action), mXX = monitored metric. All elements used in the simulation are discrete, which can be difficult to achieve in practice. The modeled system is schematic and contains the basic components of IoT, cloud, cRAMI 4.0, and their interconnections. It is a generic system designed to capture the main structural elements.

During the simulations, intense activity is observed throughout the requested time window in the IoT zone. In the Figures 4–6, flow variations across IoT, connection, and cloud zones takes place. In the Cloud zone, responses occur only at required levels. The diagram displays three fundamental levels: initial, intermediate (monitoring), and final stages of the process. This branch serves as a bridge between the IoT and the rest of the system, ensuring data security and seamless information transfer throughout the entire structure (see Figure 4).

Figure 5 presents both the variation in input data flow and the dynamics of information handled within the cloud system, with real-time accessibility from both RAMI 4.0 and IoT. Figure 6 shows variation in information flow caused by input data and the systems processing capacity.

Figures 7, 8 and Figure 9 illustrate the ordered information dynamics along each cRAMI axis (X = detection, Y = analysis, Z = access control). Variations are caused by either the high volume of data or complex data structures in the system. As seen in Figure 9, large variations can arise due to an error within the analysis process. Since the system is secure, other components are not severely impacted. The error may stem from sudden data fluctuation, hardware malfunction, or even human error in the case of incorrect data routing.



(a) Variation of Information flow in Critical point in the IoT System section.

(b) Variation of Information flow in Critical point in the connection system section.

(c) Variation of Information flow in Critical point in the connection system section with direct implications for the IoT system section.

Figure 4. Information flow variation between the IoT system and the connection system.

5. Discussion

This complex system benefits from a well-developed and relatively accessible IoT component, crucial for monitoring and communication. In our model, the IoT

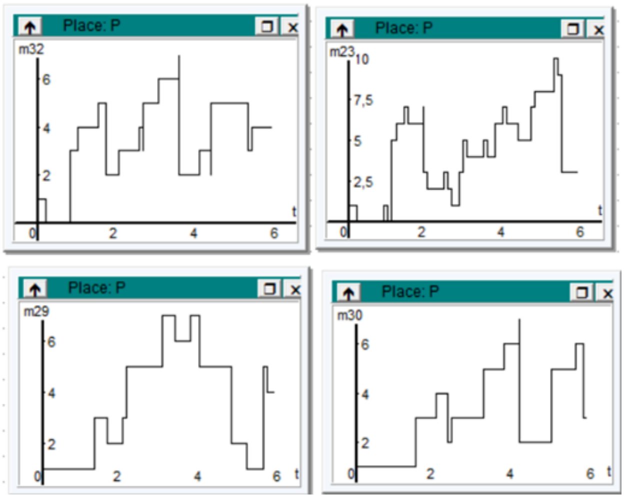


Figure 5. Information flow variation within the cloud system.

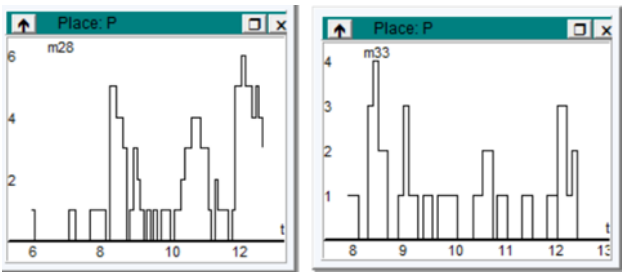


Figure 6. Information flow between RAMI 4.0 and the system connected to the cloud.

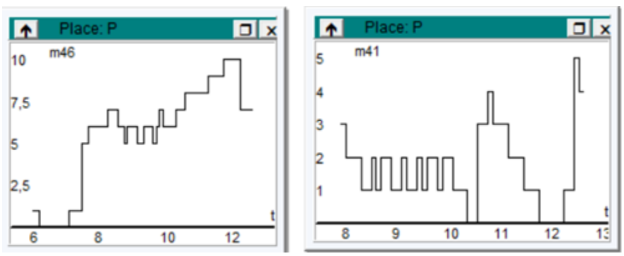


Figure 7. Information flow along RAMI 4.0 - X direction.

system is linked to the cloud via a dedicated connection component that ensures data security and facilitates efficient information flow. cRAMI 4.0 decomposes into its three core axes, each mapped to its specific structure, with no overlap in data,

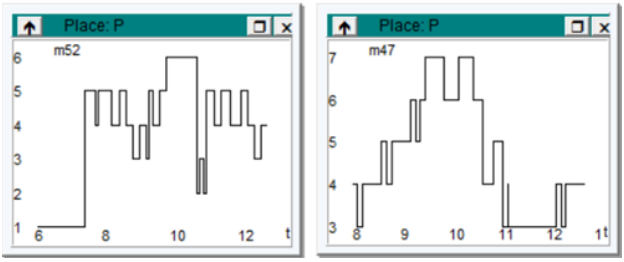


Figure 8. Information flow along RAMI 4.0 - Y direction.

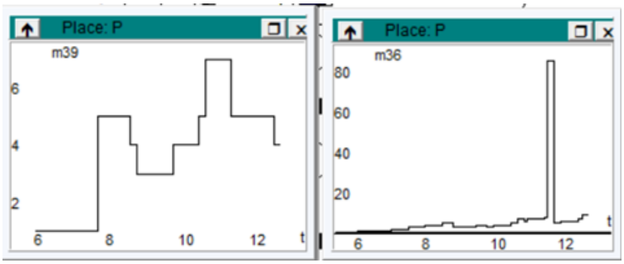


Figure 9. Information flow along RAMI 4.0 - Z direction.

thanks to the interconnectivity of the cube surface. Functional and communication mappings are preserved for every axis.

Challenges related to this approach include the need for novel data models and coordination mechanisms between cloud devices, cloud servers, and artificial intelligence systems. Also, important integration of advanced data quality assessment methods like those presented in [12]. Consequently, the IoT architecture for cloud-based devices has been conceived as a modular framework that supports low-power wearable and implantable devices, compatible with others using similar data formats and capable of wireless interaction.

Limitations and challenges. Existing models and systems still face significant limitations that must be addressed to ensure the effective use of cloud devices in dedicated systems. These include issues such as energy consumption, optimal data scheduling, low-latency models, privacy, joint offloading, limited data availability, data security, system downscaling, and overhead costs. To overcome these, further exploration of new architectures, development of optimised training techniques, interpretable models and architectures for resource-constrained environments are needed. Ethical and concerns also require attention to prevent bias and discrimination, especially in sensitive application areas.

6. Conclusions

This paper proposed a three-dimensional cubic lattice model for structuring and optimizing information flows in IoT systems, based on a customized interpretation of the RAMI 4.0 framework, called cRAMI 4.0. This paper proposes a three-dimensional cubic lattice model for structuring and optimizing information flows in IoT systems, based on a customized interpretation of the Reference Architectural Model for Industry 4.0 (RAMI 4.0), referred to as **customized RAMI 4.0 (cRAMI 4.0)**. The model defines three orthogonal axes, detection level functions, analysis and maintenance processes, and access control levels, allowing a spatial representation of the system's operational, procedural, and security dimensions. The specific lattice-based representation enables a clear visualization of interactions, supports granular system analysis, and facilitates optimization of data flow and security mechanisms. Systems based on cRAMI 4.0 can be utilized, offering grouped benefits, real-time responsiveness, and low data and energy consumption. It supports the development of multiple applications across different sectors, tailored to user-specific requirements. The knowledge obtained is more structured, and more relevant for decision-making in developing Industry 4.0 developments.

To validate this approach, simulations were conducted using Petri nets in Visual Object Net++, enabling graphical representation and analysis of information flow dynamics across all three axes. The results confirm the models suitability for identifying critical paths, analyzing interdependencies, and supporting optimization strategies in complex IoT architectures. Future work will focus on extending the model with dynamic reconfiguration capabilities and integrating real-time system data.

Acknowledgements. This research received financial support from '1 Decembrie 1918' University of Alba Iulia, Romania, through Order no. 3259 of 13th February 2025. The authors thank the Research Group on Artificial Intelligence and Data Science for Healthcare Innovation (REFLECTION) and the Research Center on Artificial Intelligence, Data Science, and Smart Engineering (ARTEMIS), of the George Emil Palade University of Medicine, Pharmacy, Science and Technology of Targu Mureş, Romania, for support of research infrastructure. The WG6 Benchmarking Workgroup within CA22137 COST Action, Randomized Optimization Algorithms Research Network (ROAR-NET), concerned with identifying benchmarking issues.

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