BINUS UNIVERSITY DOCTORATE PROGRAM

Doctor of Computer Science

Promovendus
Andi Sama
(2540136324)

Promotor
Prof. Dr. Ir. Meyliana, S.Kom., M.M., IPU, CDMS, CBDMP, CME

Co-Promotor 1
Dr. Ir. Yaya Heryadi, M.Sc.

Co-Promotor 2
Ir. Taufik, S.T., M.M., Ph.D., IPM

Lightweight Advanced Encryption Standard (AES) Model to Secure Data Transfer in Industrial Control Systems for Smart Factory in Manufacturing Industry

Background

- ✓ Security threats in OT systems are a recent trend in ICS, Industrial Control Systems (Stouffer et al., 2023; Jayalaxmi et al., 2021).
- ✓ The IT/OT convergence introduces security risks to OT systems (Cyber attack), including PLCs, the core controller in ICS (Wu H, Geng Y, Liu K, Liu W., 2019)
- ✓ Lack of encryption in industrial protocols. A secure communication between IoT devices to protect the data is essential [Jayalaxmi, P. et al. (2021)]
- ✓ PLC has been the core automation in Industrial Automation and the manufacturing industry since the beginning of Industry 3.0 (Yadav R, Namekar S., 2020)
- ✓ Symmetric scheme is computationally inexpensive compared to the Asymmetric [Maqsood, F. *et al.* (2017)], suitable for ICS (low resource requirements).
- ✓ In 2000, NIST announced the selection of the Rijndael block cipher family for the AES for Symmetric Encryption [Morris J. Dworkin, 2023]
- ✓ For the security aspect and implementation complexity, AES is considered as one of the strongest and most efficient algorithms [John, S. k (2023)]
- ✓ Modifying the existing algorithm: AES for lightweight applications is possible [John, S. k (2023)]
- ✓ The Lightweight AES (LAES) algorithm increased higher than AES by 4.2969% in terms of avalanche effect, meaning increased security [Salman, R.S., Farhan, A.K. and Shakir, A. (2022); Acla, H.B., and Gerardo, B.D. (2019)]

In Industrial Control Systems (ICS) within Industry 4.0, lightweight cryptography (LWC) is crucial for securing the Internet of Things (IoT)/Industrial IoT (IIoT). IoT devices have limited resources (memory, CPU, and battery) and thus require light techniques for securing communications. LWC is a collection of solutions for encryption techniques that feature devices with low computational complexity. It aims to expand the applications of cryptography to limited-resource devices while providing a high level of security (Mammeri, 2024, p. 194).

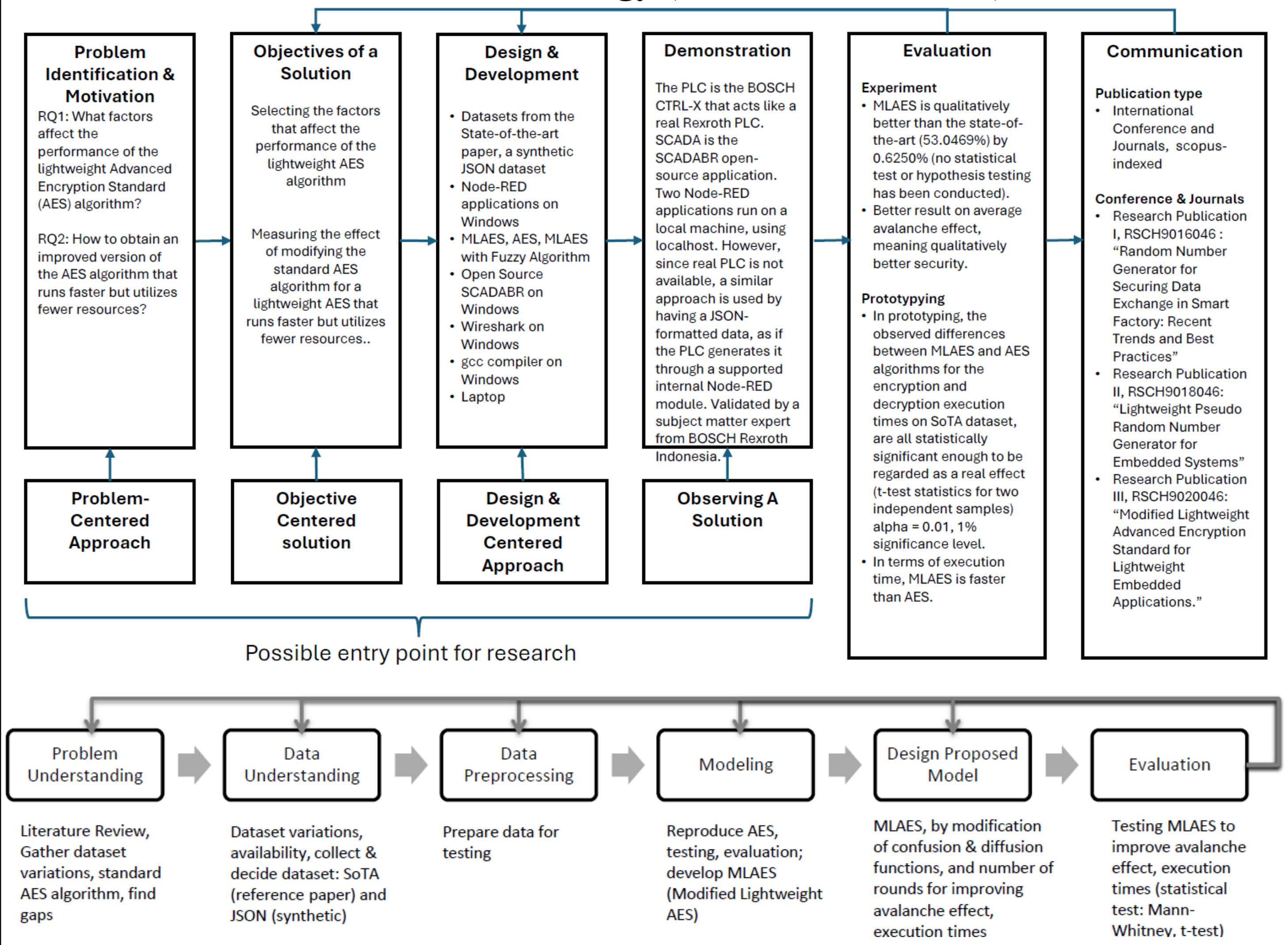
Objectives

Securing data exchange in ICS through the modification of the symmetric-based encryption algorithm, based on the AES, Advanced Encryption Standard, for lightweight applications.

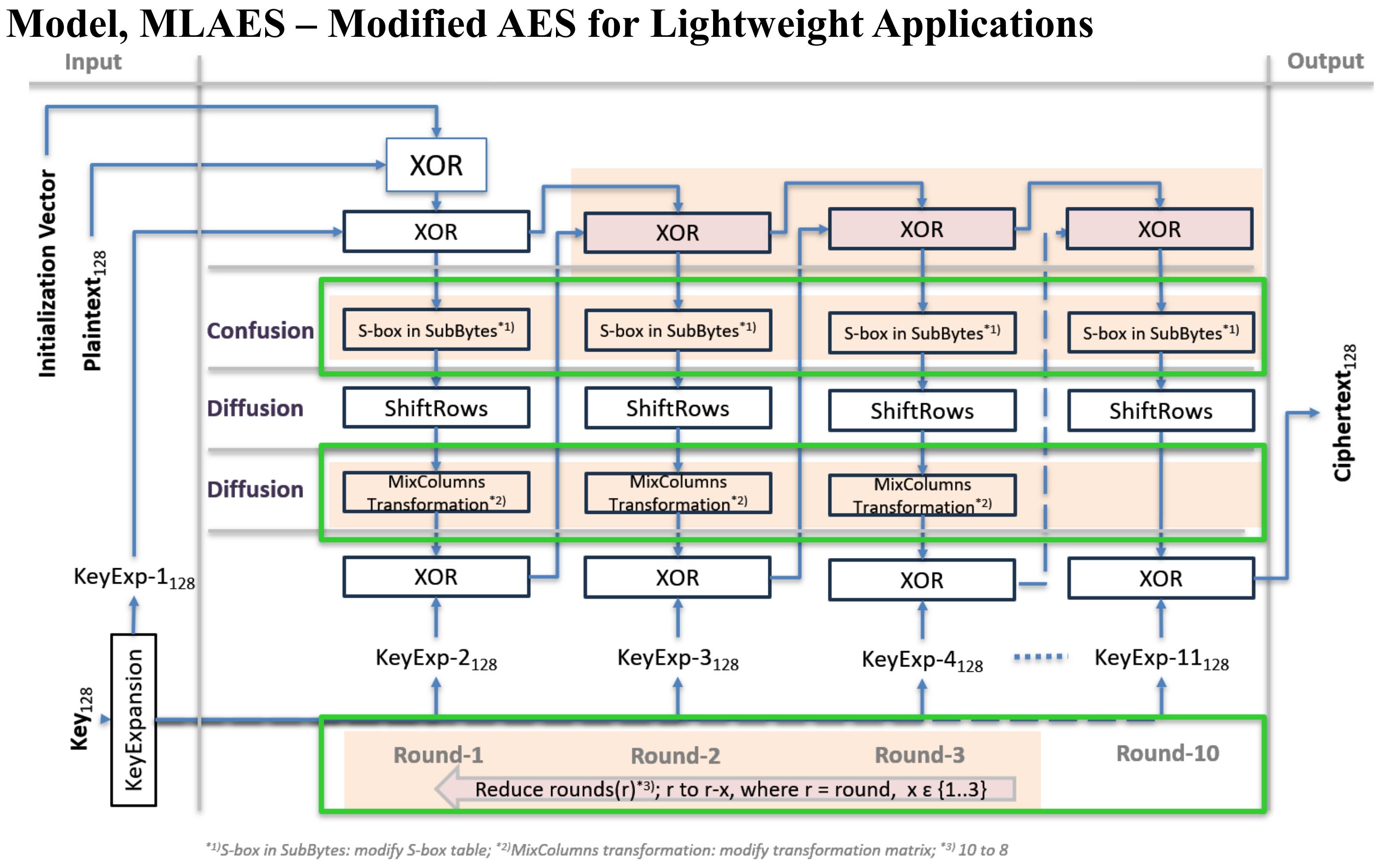
Research Questions

RQ-1: What factors that affect the performance of the lightweight Advanced Encryption Standard (AES) algorithm?
RQ-2: How to obtain an improved version of the AES algorithm that runs faster but utilizes fewer resources?

Research Methodology (DSRM, CRISP-DM)

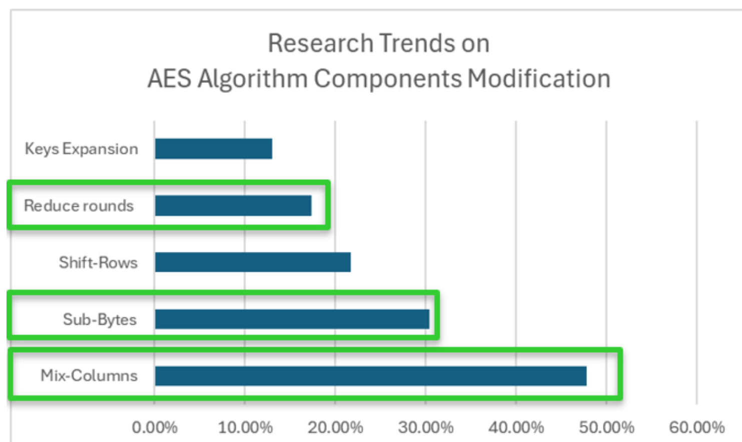


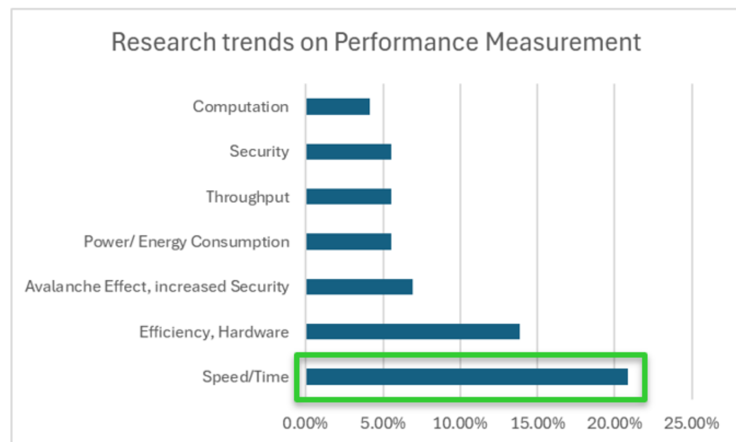
Model, MLAES – Modified AES for Lightweight Applications



[1] S-box in SubBytes: modify S-box table; [2] MixColumns transformation: modify transformation matrix; [3] 10 to 8

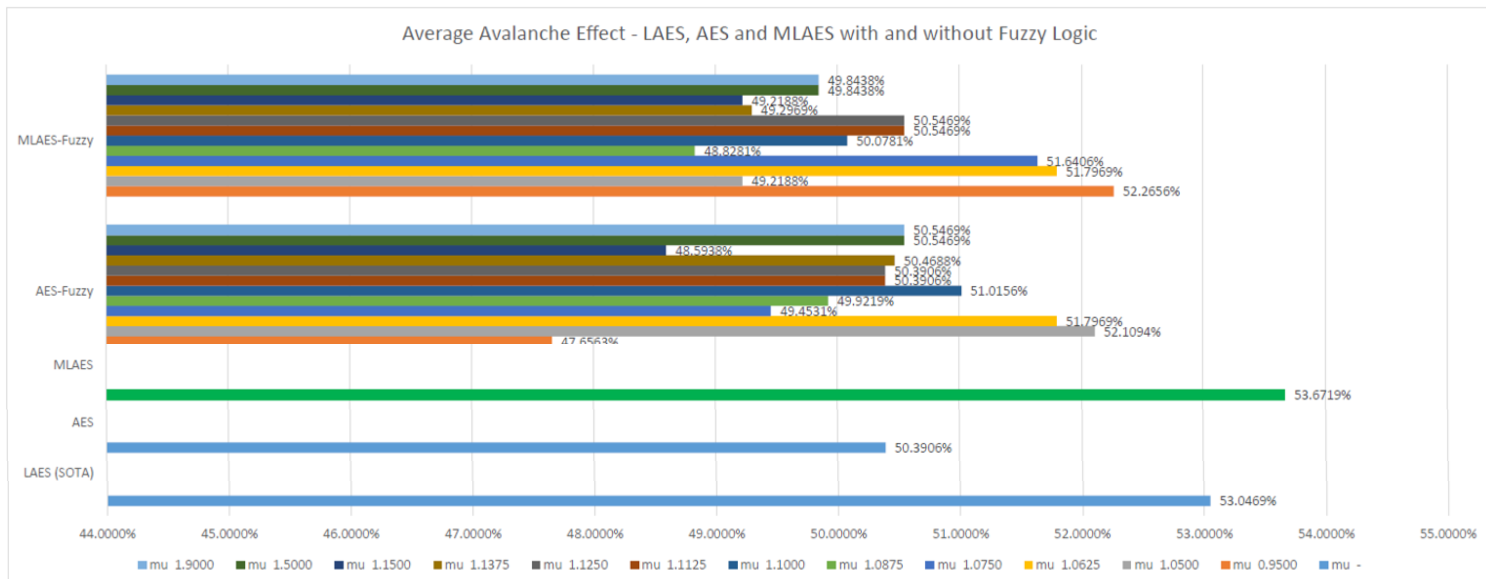
Results (Phase-1), Findings for RQ1



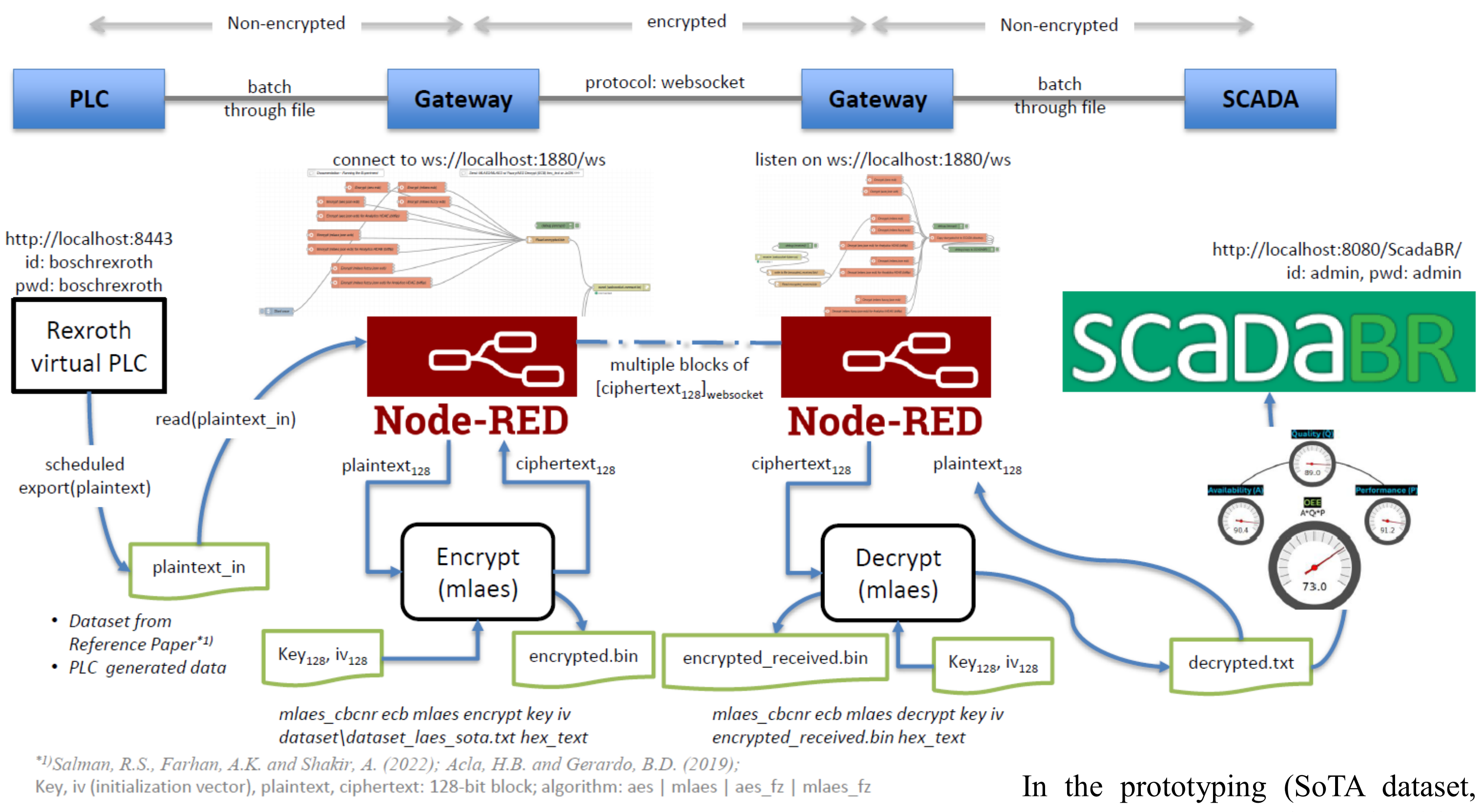


Research Results (Phase-2), Experiments

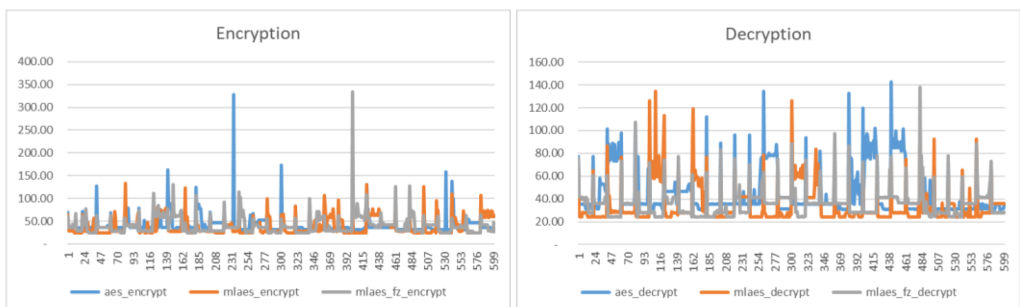
With SoTA (state-of-the-art) dataset from the reference paper (Acla and Gerardo, 2019; Salman, Farhan, and Shakir, 2022), the Modified Lightweight AES (MLAES) achieved **53.6719%** in average avalanche effect. MLAES is **1.5625%**, **1.4063%**, and **0.6250%** higher than AES with fuzzy logic (**52.1094**%, μ=1.0500), MLAES with fuzzy logic (52.2656%, μ=0.9500), and the SoTA Lightweight AES, LAES (**53.0469%**)—fuzzy logic with a tent chaotic map inference rule and a center-of-gravity method for defuzzification. Despite insignificant statistical performance improvement (fivefold dataset, SoTA+) with the Mann-Whitney statistical test, MLAES has qualitatively better average avalanche effect than the standard (AES), LAES, and MLAES with Fuzzy Logic (α=0.05).



Results (Phase-3), Findings for RQ2



[1] Salman, R.S., Farhan, A.K. and Shakir, A. (2022); Acla, H.B. and Gerardo, B.D. (2019);
Key, iv (initialization vector), plaintext, ciphertext: 128-bit block; algorithm: aes | mlaes | aes_fz | mlaes_fz



In the prototyping (SoTA dataset, N=600 for each algorithm (MLAES, AES) and mode of operations (encrypt, decrypt), α=0.01), there is a **statistically significant mean difference** in the **execution time** for the **encryption** and **decryption operations** between the **MLAES** and **AES** algorithms, validated by t-test statistics for two independent samples.

In terms of execution time, MLAES is faster than AES by using fewer resources (reducing the original AES rounds from 10 to 8).

Conclusion

The MLAES algorithm is based on the AES with the purpose of obtaining an improved version that runs faster while utilizing fewer resources, while providing secure data exchange within the ICS environment. In terms of execution time during prototyping, MLAES is faster than AES (statistically significant), while maintaining the level of security.

Benefits/Implications

MLAES provides lightweight security to improve computation time (faster execution) for low-resource devices such as IoT within ICS in the Manufacturing Industry or Industrial Automation in general. MLAES will provide lower latency in an FPGA-based hardware implementation than in a software implementation, such as PLC firmware or a Node-RED based application, in an edge computing gateway.

Limitations

MLAES, based on AES-128, is limited to 128-bit (key size). Prototyping is on the local network. However, it is expected that the execution times for MLAES/AES encryption/decryption will be approximately comparable to those in the actual PLC, e.g., with JSON.

Suggestion/Future Work

Future theoretical contributions could enhance the algorithm by further exploring the transformation into an S-box table within the SubBytes operation, modifying the ShiftRows and MixColumns algorithms, and considering the use of lightweight computing power and limited resources in embedded systems.
Future practical implementation research may involve implementing the MLAES on PLCs within the firmware or FPGA; or within PLCs that support Node-RED, edge computing, or IoT devices within ICS.

Publications

- Conference, Procedia Computer Science, 2023, Indexed, Acquiring Automation and Control Data in The Manufacturing Industry: A Systematic Review (citation: 4)
- Conference, ICICyTA, 2023, Indexed, Implementation of Lightweight PRNG on PLC for Industrial Control Systems
- Conference for RSCH9016 Publication I (ICCTech, 2024, Indexed), Random Number Generator for Securing Data Exchange in Smart Factory - Recent Trends and Best Practices
- Journal for RSCH9018 Publication II (IJSSE, 2024, Indexed), Lightweight Pseudo Random Number Generator for Embedded Systems
- Journal for RSCH9020 Publication III (IJSSE, 2025, Indexed), Modified Lightweight Advanced Encryption Standard for Lightweight Applications