UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

INVESTIGATION OF THE TRANSFERABILITY OF CONTROL PARAMETERS BY EMPIRICAL AND DIAGNOSTIC METHODS

THESES BOOKLET

PREPARED BY:

Ádám Móré
Electrical engineer

HATVANY JÓZSEF DOCTORAL SCHOOL OF INFORMATION SCIENCES

HEAD OF THE DOCTORAL SCHOOL:
Prof. Dr. László József Kovács
Professor

SUPERVISORS:
Dr. Attila Trohák
Associate Professor
Dr. Benotsmane Rabab
Associate Professor

Miskolc, 2026

Contents

1. INTRODUCTION

1.1. Topicality of the Research Topic and the Current State of Science

Programmable logic controllers are key components of industrial automation and, even in the 21st century, remain one of the fundamental platforms of reliable and deterministic process control. PLC-based systems typically have long life cycles: they often operate for more than a decade in the same hardware and firmware environment, while the associated technological process, control program, and controller parameters are gradually validated on the basis of operational experience [1]–[5].

Modernization, discontinued vendor support, replacement of peripherals, or production-line integration eventually make PLC architecture migration unavoidable. In practice, this often means that the existing control program and its PI controller parameters are transferred to the new CPU, firmware, or analog I/O environment without modification. This assumption is based on the idea that if the physical process and the high-level control logic remain unchanged, then the closed-loop control behavior should also remain unchanged. However, the migration-related literature primarily focuses on program conversion, platform compatibility, and standards-based transformation, while closed-loop dynamic equivalence is generally not treated as an independent problem [6]–[9].

This issue is critical because the discrete-time implementation of a PI controller depends not only on the theoretical algorithm itself, but also on cycle time, quantization levels, analog-to-digital and digital-to-analog conversion, and the timing characteristics of the execution environment.

Classical model-based control theory is suitable for describing a given system, but in the case of PLC architecture migration, an accurate model of the entire closed-loop system cannot be established reliably in practice. Quantization, sampling jitter, and internal execution differences may alter the effective discrete-time dynamics of the system even when the process and the formal controller structure remain unchanged [10]–[12].

PI control remains relevant from both scientific and industrial perspectives. In PLC-based environments, PI structures continue to be widely applied due to their robustness, simple parametrization, and deterministic execution. Pinto et al. demonstrated that PI control implemented in PLCs can be effectively adapted to industrial constraints [13], while Panchal et al. confirmed the practical applicability of PI control in level-control environments [14]. Huba also showed that the derivative branch of PID controllers is sensitive to measurement noise, and therefore many industrial implementations effectively reduce to PI-type control [15].

At the same time, classical and adaptive tuning methods do not investigate parameter invariance; instead, they explicitly seek to generate a new set of parameters. Autotuning and optimization-based approaches recalculate or modify the controller parameters based on the response of the target system, thus implicitly assuming that the original parameter set may not remain valid on another architecture. This is clearly reflected in methods that are sensitive to cycle time and numerical implementation, as well as in neural, fuzzy, genetic algorithm, and particle-swarm-based approaches [16]–[24].

Based on the above, the migratability of PI parameters cannot be treated as a mere implementation detail. In scientific terms, it constitutes a closed-loop dynamic compatibility problem, in which the key question is to what extent a parameter set validated on a reference architecture preserves its behavioral properties on a new PLC architecture. The literature does not provide a general, process-independent, and quantitative methodology for this problem. This gap motivated the starting point of the present research and justified the development of a model-free, empirical, then diagnostic and decision-support-oriented investigation framework.

1.2. Objective of the Dissertation

The aim of the research was to investigate the migratability of PI controller parameters under PLC architecture migration, with particular emphasis on the common industrial situation in which the control program and its associated PI parameters are transferred to a new hardware and firmware environment without modification. The central question of the dissertation was to what extent the closed-loop control behavior is preserved across different CPU, firmware, and analog I/O configurations under identical PI parameters.

To achieve this, a controlled and reproducible laboratory environment was first established in which all non-PLC-related elements of the control loop remained unchanged, thereby allowing the observed differences to be attributed directly to the controller-side architecture migration. Within this environment, an empirical database was created using multiple combinations of CPU types, firmware versions, and I/O resolutions.

A further objective was to develop a process-independent, closed-loop diagnostic method that does not require the explicit mathematical model of the physical process, yet is capable of revealing migration-relevant differences in stability, dynamics, and accumulation behavior. Subsequently, by arranging the diagnostic results into a unified decision space, the goal was to formalize a multicriteria framework for the quantitative evaluation of migratability and to compare it with a geometric TOPSIS-based ranking approach.

The final objective of the dissertation was to establish a practice-oriented yet scientifically grounded methodology that supports engineering decisions related to PLC replacement, reduces the uncertainty associated with post-migration retuning, and provides an objective basis for deciding whether a given PI parameter set can be migrated without modification, requires fine-tuning, or necessitates complete reparameterization.

2. NEW SCIENTIFIC RESULTS

The following chapter presents the methodological problem statements, the achieved new scientific results, and the thesis statements. In the present English version, the thesis statements themselves are intentionally omitted.

2.1. Empirical Migration Database

2.1.1. Methodological Problem Statement

The primary methodological challenge of empirical verification arose from the fact that, although the literature discusses the technical aspects of PLC program migration in detail, it provides only indirect information about the dynamic consequences of transferring PI parameters without modification. Sergeyev et al., Holtrop et al., and authors investigating standards-based migration focused mainly on program conversion, compatibility, and validation [6]–[9]. These works indicate that manual intervention is often required after platform migration, yet no empirical database is available that, under controlled conditions and with identical PI parameters, directly demonstrates how the closed-loop behavior changes.

The other side of the problem was the need to isolate the effect of migration as cleanly as possible. In a real industrial process, sensors, actuators, disturbances, and load variations may conceal or distort the differences resulting from architecture migration. Therefore, a reference architecture and a simple first-order sensorless process model were required in which uncertainty in the measurement chain could be minimized, while amplitude-based, time-based, and error-based differences relevant to PI control remained quantifiable.

2.1.2. Research Results

For the investigations, a first-order sensorless process model represented by an RC element was used, together with a fixed PI parameter set. Relative to the Basic reference architecture, a total of fifteen additional Case configurations were examined. These differed in CPU type, firmware version, and the resolution of the analog input and output modules. Throughout the entire measurement protocol, identical reference signals, identical cycle time, and identical numerical processing were applied; therefore, the observed differences can be attributed exclusively to the modification of the PLC architecture.

Sinusoidal excitation proved suitable for the comparison of quasi-stationary tracking behavior, phase shift, amplitude attenuation, and integrated errors. In contrast, square-wave excitation revealed changes in the transient regime more sensitively, allowing overshoot, rise time, settling time, and waveform distortions to be compared quantitatively. The results clearly confirmed that, under identical PI parameters, the closed-loop response differed from that of the reference architecture in a measurable and reproducible manner in several configurations.

It was demonstrated that the effect of migration does not appear along a single performance metric. In some configurations, the primary changes affected amplitude and phase; in others, transient behavior degraded; while in several cases integrated error measures and steady-state behavior changed significantly. This showed that migratability cannot be interpreted as a binary property. Based on the empirical database, architectures could be distinguished as directly migratable, conditionally migratable, that is, requiring fine-tuning, and non-migratable.

The methodological significance of the empirical database extended beyond the first result. On the one hand, it proved that the transfer of PI parameters without modification cannot be regarded as a universally valid procedure even under simple laboratory conditions. On the other hand, it provided a reference for the validation of the process-independent diagnostic and decision-support methods developed later. Thus, the empirical investigations played not only an initiating role, but also a validation role within the overall structure of the dissertation.

2.1.3. Formation of Thesis I.

I empirically demonstrated that, even in the case of a first-order process model, closed-loop control behavior changes in a measurable and reproducible manner during PLC architecture migration when identical PI controller parameters are applied across 15 migrated configurations relative to a reference architecture.

Based on sinusoidal and square-wave tracking tests, I showed that the effect of migration does not appear along a single performance indicator; rather, it is manifested in the combined deviation of amplitude-, time-, and error-based metrics. In this way, I proved that migration of PI parameters without retuning is not universally applicable, and that migratability was empirically classified into multiple categories (migratable, conditionally migratable, non-migratable), within the scope of empirical validation performed on a first-order process model.

Related publications: [S3], [S4], [S5], [S6], [S7], [S9].

2.2. Three-Stage Diagnostic Pipeline

2.2.1. Methodological Problem Statement

The establishment of the empirical database confirmed the existence of the phenomenon, but also highlighted its limitations. Although physical-process-based laboratory measurements are suitable for proving the migration problem, in industrial environments they cannot always be carried out safely, rapidly, and economically. Therefore, a methodological framework had to be developed that investigates migratability in a controlled closed-loop environment without relying on the explicit model of the technological process.

In the literature, behavior-based fingerprinting approaches typically rely on black-box system analysis. Yadav et al. pointed out that discriminative features can be extracted from input-output behavior and used to identify system characteristics [25]–[27]. In the PLC migration problem, this perspective had to be adapted in such a way that the investigation would not seek new parameters, but rather evaluate the compatibility of an already validated PI parameter set. Accordingly, the basic requirements imposed on the method were process independence, reproducibility, and the structured exploration of multidimensional behavior.

2.2.2. Research Results

To address this, a process-independent, closed-loop, three-stage diagnostic pipeline was developed, based on the successive logic of the Pkrit, P-only, and I-only examinations. The Pkrit stage acts as a structural pre-screening step: by disabling the integral branch, the critical proportional gain can be determined at which the closed-loop discrete-time system reaches the boundary of stability. The shift measured relative to the reference architecture directly indicates whether the stability margin has changed as a function of architecture.

The P-only examination captures the boundary-stable dynamic character corresponding to the critical gain. Here, the question is not merely whether the system remains stable, but also to what extent the waveform, period, and amplitude of the boundary-stable oscillation coincide with those of the reference architecture. The results confirmed that the boundary-stable response can be used as a diagnostic fingerprint: architectures exhibiting a Pkrit close to the reference value also displayed a dynamic pattern close to that of the Basic system, while configurations with a significant shift in stability margin showed a markedly altered oscillatory character.

In the I-only examination, the proportional branch was switched off and the accumulation behavior of the integral branch alone was investigated using a fixed, small Ki value. This stage proved highly sensitive to differences in sampling, quantization, and numerical implementation, because the discrete-time summation of the error signal cumulatively amplifies even very small architecture-dependent deviations. From the response functions, steady-state error, settling time, accumulation rate, and possible drift could all be distinguished clearly.

Taken together, the three stages of the pipeline no longer merely showed that migration may cause problems, but also identified the dimension in which the problem appears most strongly. Pkrit captures the shift of the stability structure, P-only reflects the modification of the boundary-stable dynamic character, and I-only reveals the change in the accumulation mechanism of the integral branch. In this way, a multidimensional, behavior-based interpretation of migratability became possible, directly providing the basis for later quantitative formalization.

2.2.3. Formation of Thesis II. and Sub-theses

Thesis II. - Main

I developed and empirically validated a process-independent, closed-loop, three-stage diagnostic method (Pcrit-P-only-I-only) for

the structured assessment of the migratability of PI controller parameters in the context of PLC architecture migration.

Sub-thesis II/1.

I demonstrated that migration of PI parameters without modification may alter the stability limit of the closed-loop discrete system in an architecture-dependent manner during PLC architecture migration. By determining the critical proportional gain across 16 PLC configurations, I verified that the Pcrit test can be applied as a structural pre-screening element of the diagnostic method.

Sub-thesis II/2.

I verified that the marginally stable dynamic character in the P-only configuration may differ between the reference and target architectures, thereby indicating an architecture-dependent modification of the closed-loop discrete pole structure and the effective dynamics. The waveform, oscillatory character, and dynamic pattern of the marginally stable response can be used as a diagnostic fingerprint in migratability assessment.

Sub-thesis II/3.

I demonstrated that the accumulation behavior of the integral component in the I-only configuration reacts sensitively to architecture-dependent differences in sampling, quantization, and numerical implementation. By revealing deviations in accumulation

dynamics and steady-state behavior, the I-only test constitutes a highly informative third element of the diagnostic method.

Based on the above, I verified that the method provides a reproducible and discriminative diagnostic representation of the investigated architectures through the separate examination of stability conditions, marginally stable dynamic character, and the accumulation behavior of the integral component.

Related publications: [S1], [S2], [S3], [S8].

2.3. Quantitative Decision Support for Migratability

2.3.1. Methodological Problem Statement

The diagnostic pipeline confirmed that migratability is not a phenomenon that can be described by a single numerical value. The differences between architectures appear jointly in stability-related, dynamic, and error-based metrics, which are partly correlated and partly mutually conflicting. Consequently, the evaluation of migratability is inherently a multicriteria decision problem, in which it is insufficient to rely on a single favorable or unfavorable metric.

The methodology of multicriteria decision support provides an appropriate mathematical framework for such a problem. According to the literature, MCDM approaches are especially justified when multiple criteria with different physical meanings must be arranged into a unified decision space [28], [29]. In the case of migratability, the fundamental task was to transform the metrics obtained from the Pkrit, P-only, and I-only examinations—differing in magnitude and interpretation—into a common comparable form, and then derive an objective compatibility indicator from them.

2.3.2. Research Results

As a first step of the formalization, the relative deviation of each metric was defined with respect to the reference architecture. The key equation can be written as:

$$\delta_{ij} = \frac{|\, x_{ij} - x_{0j} \,|}{|\, x_{0j} \,|}$$

By normalizing the relative deviations column-wise and applying equal weights, a unified decision matrix was created in which all criteria appear on the same scale and with the same significance. In accordance with the logic of the diagnostic pipeline, a behavioral compatibility index rather than a performance-optimization measure was constructed, interpreted as the sum of weighted normalized deviations:

$$C_i = \sum v_{ij}$$

The compatibility index $C_i$defined in this way is a dimensionless quantity between 0 and 1. A value of 0 corresponds to complete agreement with the reference architecture, while increasing values indicate increasing global deviation. The distribution of the calculated indices was not linear, but cluster-like in structure; therefore, categorization was based not on arbitrary threshold values, but on the statistical structure of the sample, namely the median and the quartiles. As a result, a four-zone migratability classification was introduced.

The zone structure orders the architectures from the Z1 range, which is closest to the reference architecture, to the Z4 range, which represents structurally incompatible cases. In accordance with the results of Chapter 6, configurations in zone Z1 showed behavior closest to the reference architecture, zones Z2 and Z3 represented cases requiring fine-tuning or being only conditionally migratable, while zone Z4 contained the architectures showing the largest global deviations.

The essential outcome of the quantitative formalization was that the migration categories previously identified empirically could be reproduced within an objective, reproducible, and process-independent decision framework. The model did not merely assign numerical labels to empirical findings retrospectively, but also preserved their structure: the larger the aggregate deviation in terms of stability, dynamics, and error characteristics, the more unfavorable the zone assigned to the architecture.

Table 1. *Definition of MCDM-based migratability zones*

Migratability zone	**Zone definition**
Z1 (strongly migratable)	$C_i \leq Q1$
Z2 (migratable)	$Q1 < C_i \leq \tilde{C}$
Z3 (conditionally migratable)	$\tilde{C} < C_i \leq Q3$
Z4 (non-migratable)	$C_i > Q3$

***Table 2.** MCDM-based compatibility indices and zone assignments of the investigated architectures*

PLC configuration	C_i value	Zone
Basic: PFC1001212	0	Z1
Case1: PFC100 1210	0.05366	Z1
Case2: PFC100 1612	0.5739	Z4
Case3: PFC100 1610	0.3870	Z3
Case4: PFC100FW 1212	0.3112	Z3
Case5: PFC100FW 1210	0.1823	Z1
Case6: PFC100FW 1216	0.5380	Z4
Case7: PFC100FW 1612	0.2078	Z2
Case8: PFC100FW 1610	0.2953	Z2
Case9: PFC100FW 1616	0.4802	Z4
Case10: PFC200 1212	0.1995	Z1
Case11: PFC200 1210	0.2504	Z2
Case12: PFC200 1216	0.4312	Z3
Case13: PFC200 1612	0.1995	Z1
Case14: PFC200 1610	0.2551	Z2
Case15: PFC200 1616	0.4461	Z4

Based on the tables above, it can be clearly seen that the multicriteria compatibility index expresses the global behavioral deviation from the reference architecture not through a single metric, but on the basis of the entire diagnostic fingerprint. The zone classification consistently reproduced the empirically observed behavioral differences.

2.3.3. Formation of Thesis III. and Sub-theses

Thesis III. - Main

By organizing the metrics derived from the diagnostic method I developed into a unified decision space, I formalized the quantitative evaluation of the migratability of PI controller parameters under PLC architecture migration.

I verified that, on the basis of relative deviations with respect to the reference architecture, a global compatibility index can be constructed that is suitable for the objective, reproducible, and process-independent characterization of the migratability of the investigated architectures. [S2]

Sub-thesis III/1.

I demonstrated that the stability-, dynamic-, and error-based characteristics derived from the Pcrit, P-only, and I-only diagnostic tests can be arranged into a unified metric space. I verified that expressing metrics with different physical meanings as relative deviations with respect to the reference architecture makes it possible to handle them jointly in a comparable and normalizable form. [S2]

Sub-thesis III/2.

I verified that a multicriteria compatibility index can be constructed from the normalized diagnostic deviations, expressing the global behavioral deviation of the investigated architectures in a single quantitative indicator. I demonstrated that this index evaluates migratability not along individual metrics, but on the basis of the aggregated structure of the overall diagnostic behavior. [S2]

Sub-thesis III/3.

I verified through 16 PLC architectures that the compatibility index can be organized into a data-driven zone structure in which quartile-based boundary formation reflects the natural distribution of the diagnostic space. I demonstrated that the resulting zones consistently reproduced the empirically identified differences among

the investigated architectures, thereby providing a process-independent classification framework for the evaluation of migratability. [S2]

Related publications: **[S2].**

2.4. Comparison of MCDM- and TOPSIS-Based Formalizations of Migratability

2.4.1. Methodological Problem Statement

After the introduction of the compatibility index, it became necessary to examine to what extent the linear MCDM-based formalization used for the quantitative evaluation of migratability can be regarded as a structurally stable decision model. According to the multicriteria decision-support literature, TOPSIS provides a suitable point of comparison, since it ranks alternatives on the basis of their Euclidean distances from ideal and negative-ideal points [29]–[31].

At this stage, the methodological question was no longer whether migratability can be described formally, but whether linear weighted aggregation or geometry-based ranking provides a more robust and engineering-interpretable representation. The purpose was not to construct a new set of metrics, but to compare two different formalizations of the same diagnostic decision space.

2.4.2. Research Results

The TOPSIS evaluation was based on the previously constructed weighted normalized decision matrix. The positive ideal point represented the behavior closest to the reference architecture, while the negative ideal point represented the most unfavorable combination. The relative closeness index is given by the following key equation:

$$T_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

For the T_i index, larger values indicate more favorable migratability. Based on quartile-based zone classification, TOPSIS produced an independent ranking operating on geometric principles, which proved especially useful in identifying extreme, clearly incompatible cases. The most unfavorable configurations—such as those shifted toward 16-bit output resolution and combined with firmware changes—were consistently classified into the Z4 range by TOPSIS as well.

However, the detailed comparison showed that TOPSIS is less stable in the middle range than the linear compatibility index. While the MCDM-based C_i values mapped the migratability spectrum more evenly and in accordance with the logic of the diagnostic pipeline, the Euclidean structure of TOPSIS reacted more sensitively to certain dominant deviations and could cause norm-geometric distortion near the zone boundaries.

Based on these findings, it was demonstrated that TOPSIS is a useful supplementary validation tool, but as a primary decision model the linear weighted MCDM formalization is more suitable. This model is not only quantitative, but also more interpretable from an engineering perspective: it is in more direct agreement with the internal logic of the Pkrit–P-only–I-only diagnostic pipeline and reproduces the empirically observed migration categories more stably.

Table 3. *Definition of TOPSIS-based migratability zones*

Migratability zone	Zone definition
Z1 (strongly migratable)	$T_i \geq Q3$
Z2 (migratable)	$\tilde{T} \leq T_i < Q3$
Z3 (conditionally migratable)	$Q1 \leq T_i < \tilde{T}$
Z4 (non-migratable)	$T_i < Q1$

Table 4. *TOPSIS-based relative closeness indices and zone assignments of the investigated architectures*

Configuration	T_i value	Zone
Basic: PFC1001212	1	Z1
Case1: PFC100 1210	0.922965	Z1
Case2: PFC100 1612	0.564559	Z2
Case3: PFC100 1610	0.737798	Z1
Case4: PFC100FW 1212	0.606645	Z1
Case5: PFC100FW 1210	0.903083	Z1
Case6: PFC100FW 1216	0.109924	Z4
Case7: PFC100FW 1612	0.496285	Z3
Case8: PFC100FW 1610	0.490976	Z3
Case9: PFC100FW 1616	0.169645	Z4
Case10: PFC200 1212	0.490330	Z3
Case11: PFC200 1210	0.500858	Z2
Case12: PFC200 1216	0.125069	Z4
Case13: PFC200 1612	0.521934	Z2
Case14: PFC200 1610	0.496479	Z3
Case15: PFC200 1616	0.126386	Z4

Based on the comparative analysis, the linear weighted MCDM compatibility index proved to be the primary decision model for migratability evaluation, while TOPSIS remained a useful supplementary tool for confirming extreme, clearly incompatible cases.

2.4.3. Formation of Thesis IV.

I demonstrated that the linear weighted multicriteria decision model (MCDM) provides a structurally more stable and methodologically more consistent formalization of compatibility for migratability assessment than TOPSIS ranking based on geometric norms. The linear model remains aligned with the logic of the diagnostic pipeline and yields a more stable decision structure across the decision space.

I showed that, while TOPSIS effectively identifies extremely incompatible cases, it may produce ranking distortions near zone boundaries due to its geometric norm formulation. These distortions can shift the ranking away from the structural interpretation of behavioral compatibility established by the diagnostic method. Therefore, the linear compatibility index provides a more methodologically justified and more reproducible primary decision framework for migratability assessment.

3. SUMMARY

In the dissertation, the problem of PI controller parameter migratability under PLC architecture migration was investigated within a model-free methodological framework. The point of departure of the research was the widely used industrial practice according to which the control program of an operating system, together with its PI controller parameters, is often transferred to a new hardware and firmware environment without modification. Based on a systematic literature review, it was established that although the literature addresses PLC program migration, controller tuning, and classical as well as adaptive methods in detail, the migration of PI parameters without modification—as a closed-loop dynamic compatibility problem—is not treated as an independent field of research.

In the empirical stage, a controlled and reproducible laboratory environment was established in which every element of the control loop independent of the PLC remained unchanged. Relative to the reference architecture, multiple CPU, firmware, and analog I/O configurations were investigated under identical PI parameters, identical cycle time, and identical excitation signals. Through sinusoidal and square-wave tracking tests, it was demonstrated that the migration of PI parameters without modification cannot be regarded as a universally valid procedure even in the case of a simple first-order sensorless process model: the amplitude, time characteristics, and error structure of the closed-loop response change as a function of the architecture.

Based on the empirical database, it was also shown that migratability is not a binary property, but a gradual phenomenon. The investigated configurations could be classified as migratable, conditionally migratable, and non-migratable. This finding also revealed the limitation of the empirical approach: although measurements based on a physical process are suitable for proving the phenomenon, they cannot always be performed safely and economically in industrial environments.

Starting from this point, a process-independent, closed-loop, behavior-based diagnostic framework was developed. The three-stage Pkrit–P-only–I-only pipeline made it possible to interpret migratability not through a single indicator, but through the stability boundary, the boundary-stable dynamic character, and the accumulation behavior of the integral branch in a structured manner. The results showed that PLC architecture migration may result not merely in slight performance degradation, but in a structural rearrangement of the effective closed-loop discrete-time dynamics.

By arranging the diagnostic results into a unified decision space, the quantitative evaluation of migratability was formalized. A global compatibility index was constructed from the relative deviations with respect to the reference architecture and then arranged into data-driven quartile-based zones. In this way, migratability was elevated from the level of engineering intuition to an objective, reproducible, and multicriteria decision framework. The linear MCDM formalization was also compared with TOPSIS-based geometric ranking. The results showed that TOPSIS has a confirmatory role in the identification of extreme incompatible cases, but the linear compatibility index is more suitable for the stable description of the entire migratability spectrum.

The most important result of the dissertation is considered to be the establishment of a unified, multistage, model-free, and quantitatively interpretable scientific framework for the migratability of PI parameters under PLC architecture migration. The practical relevance of the research lies in the fact that the method may contribute to reducing control-related risks, downtime, and retuning uncertainty associated with PLC replacements. Further research directions include the extension of the method to other PLC families, different vendor architectures, and more complex industrial processes and control structures.

4. LIST OF THE AUTHOR'S PUBLICATIONS

4.1. Indexed Publications Related to the Dissertation

[S1] Á. Móré, R. Benotsmane, A. Trohák, "Evaluating the effects of PID control parameter migration in PLC upgrades," Pollack Periodica, vol. 20, no. 3, pp. 96–102, May 2025, *https://doi.org/10.1556/606.2025.01213*

[S2] Á. Móré, "A Closed-Loop Diagnostic Method for Evaluating PI Controller Parameter Migration Across Architectures," J. Electr. Electron. Eng., vol. 18, no. 2, pp. 39–44, 2025, *https://doaj.org/article/ae28e064ae5c4258b61646a9509c13dc*

[S3] A. More, A. Trohak, "Examination of the possibility of adapting the PI algorithm," Proceedings of the 2023 24th International Carpathian Control Conference, ICCC 2023, pp. 289–293, 2023, *https://doi.org/10.1109/ICCC57093.2023.10178954*

[S4] Á. Móré, „PID algoritmus algoritmizálása irányítórendszerekben," Multidiszciplináris Tudományok, vol. 12, no. 1, pp. 46–57, May 2022, *https://doi.org/10.35925/j.multi.2022.1.4*

4.2. Other Publications Related to the Dissertation

[S5] Á. Móré, A. Trohák, "PI algoritmus adoptálásának vizsgálata intelligens adatgyűjtő módszerrel," in XXVI. Tavaszi Szél Konferencia 2023, Miskolc: Doktoranduszok Országos Szövetsége (DOSZ), 2023, pp. 413–423.

[S6] Á. Móré, A. Trohák, "Szabályozandó szakasz digitális modelljének algoritmizálása ipari vezérlő környezetben," in Doktoranduszok fóruma, Miskolc: Miskolci Egyetem Tudományos és Nemzetközi Igazgatóság, Nov. 2024, pp. 75–78.

[S7] Á. Móré, "Ipari automatizálás új szintje: Siemens S7-300 és S7-1500 PLC-k közötti migráció lehetőségei és kihívásai," in 120 éves az Elektrotechnikai és Elektronikai Intézeti Tanszék elnevezésű Jubileumi Konferencia kiadványa, Miskolc, 2024, pp. 138–141.

[S8] Á. Móré, B. L. Bódi, "PID szabályozó modellezése PLC kimeneti és bemeneti oldalain: kártyacsere hatásának vizsgálata," in 120 éves az Elektrotechnikai és Elektronikai Intézeti Tanszék elnevezésű Jubileumi Konferencia kiadványa, Miskolc, 2024, pp. 122–129.

[S9] Á. Móré, A. Trohák, "PI, PID algoritmus paramétereinek adaptálásának vizsgálata genetikus algoritmussal," in PCS Science 2023: Konferencia kiadvány, Miskolc: Eclipse Solutions Ltd, 2023, pp. 49–56.

5. REFERENCES

[1] K. C. Yao, C. L. Lin, és C. H. Pan, „Industrial Sustainable Development: The Development Trend of Programmable Logic Controller Technology", Sustainability 2024, Vol. 16, Page 6230, köt. 16, sz. 14, o. 6230, júl. 2024, *https://doi.org/10.3390/su16146230*

[2] M. Foster és C. Hammerquist, „A review of Programmable Logic Controllers in control systems education", ASEE Annual Conference and Exposition, Conference Proceedings, 2010, *https://doi.org/10.18260/1-2--16238*

[3] E. L. Cesar, G. S. Fernandes, M. T. N. Kagami, és T. N. Calisto, „Technological obsolescence management of electrical equipment and automation systems", 2019 IEEE Petroleum and Chemical Industry Committee Conference, PCIC 2019, o. 303– 310, szept. 2019, *https://doi.org/10.1109/PCIC30934.2019.9074525.*

[4] E. V. Nascimento, V. dos Santos, és R. V. Aroca, „An Applied Approach for Integrating Legacy PLC-Based Systems into Industry 4.0 Environments using Low-Code Platforms", jan. 2026, https://doi.org/10.21203/rs.3.rs-8503985/v1

[5] A. Alqoud, D. Schaefer, és J. Milisavljevic-Syed, „Industry 4.0: a systematic review of legacy manufacturing system digital retrofitting", Manuf. Rev. (Les. Ulis)., köt. 9, o. 32, 2022, *https://doi.org/10.1051/mfreview/2022031*

[6] A. Sergeyev, S. Thompson, L. Stambeck, A. Posa, és P. Hazaveh, „Efficient Way of Converting outdated Allen Bradley PLC-5 System into Modern ControlLogix 5000 suit", júl. 2020, *https://doi.org/10.18260/1-2-370.620-35989*

[7] K. L. Holtrop, P. A. Anderson, és P. S. Mauzey, „Improvements to the cryogenic control system on DIII-D", Proceedings - Symposium on Fusion Engineering, o. 401– 404, 2003, *https://doi.org/10.1109/fusion.2003.1426669*

[8] S. M. Salman, A. V. Papadopoulos, S. Mubeen, és T. Nolte, „A systematic migration methodology for complex real-Time software systems", Proceedings - 2020 IEEE

23rd International Symposium on Real-Time Distributed Computing, ISORC 2020, o. 192–200, máj. 2020, *https://doi.org/10.1109/ISORC49007.2020.00041*

[9] W. W. Dai, V. N. Dubinin, és V. Vyatkin, „Migration from PLC to IEC 61499 Using Semantic Web Technologies”, IEEE Trans. Syst. Man Cybern. Syst., köt. 44, sz. 3, o. 277–291, márc. 2014, *https://doi.org/10.1109/TSMCC.2013.2264671*

[10] D. F. Delchamps, „Stabilizing a Linear System with Quantized State Feedback”, *IEEE Trans. Automat. Contr.*, köt. 35, sz. 8, o. 916–924, 1990, *https://doi.org/10.1109/9.58500*

[11] W. Zhang, M. S. Branicky, és S. M. Phillips, „Stability of networked control systems”, *IEEE Control Systems Magazine*, köt. 21, sz. 1, o. 84–97, 2001, *https://doi.org/10.1109/37.898794*

[12] W. Yu, D. I. Wilson, és B. R. Young, „Control performance assessment in the presence of sampling jitter”, *Chemical Engineering Research and Design*, köt. 90, sz. 1, o. 129–137, jan. 2012, *https://doi.org/10.1016/j.cherd.2011.06.007*

[13] J. E. M. G. Pinto és mtsai., „PLC Implementation of Piecewise Affine PI Controller Applied to Industrial Systems with Constraints”, *Journal of Control, Automation and Electrical Systems 2019 30:3*, köt. 30, sz. 3, o. 311–322, febr. 2019, *https://doi.org/10.1007/s40313-019-00456-z*

[14] P. Panchal, A. Patel, és J. Barve, „PI control of level control system using PLC and LabVIEW based SCADA”, *2015 International Conference on Industrial Instrumentation and Control, ICIC 2015*, o. 1196–1201, júl. 2015, *https://doi.org/10.1109/IIC.2015.7150929*

[15] M. Huba, „Filter choice for an effective measurement noise attenuation in PI and PID controllers”, *Proceedings - 2015 IEEE International Conference on Mechatronics, ICM 2015*, o. 46–51, ápr. 2015, *https://doi.org/10.1109/ICMECH.2015.7083946*

[16] K. H. Kim, J. E. Bae, S. C. Chu, és S. W. Sung, „Improved Continuous-Cycling Method for PID Autotuning”, *Processes 2021, Vol. 9, Page 509*, köt. 9, sz. 3, o. 509, márc. 2021, *https://doi.org/10.3390/pr9030509*

[17] I. Naşcu, R. De Keyser, S. Folea, és T. Buzdugan, „Development and evaluation of a PID auto-tuning controller”, *2006 IEEE International Conference on Automation, Quality and Testing, Robotics, AQTR*, o. 122–127, 2006, *https://doi.org/10.1109/AQTR.2006.254510*

[18] J. Lima, R. Menotti, J. M. P. Cardoso, és E. Marques, „A methodology to design FPGA-based PID controllers”, *Conf. Proc. IEEE Int. Conf. Syst. Man Cybern.*, köt. 3, o. 2577–2583, 2006, *https://doi.org/10.1109/ICSMC.2006.385252*

[19] L. L. T. Chan, T. Chen, és J. Chen, „PID based nonlinear processes control model uncertainty improvement by using Gaussian process model”, *J. Process Control*, köt. 42, o. 77–89, jún. 2016, *https://doi.org/10.1016/j.jprocont.2016.03.006*

[20] S. Ganjefar és M. Farahani, „Damping of subsynchronous resonance using self-tuning PID and wavelet neural network”, *COMPEL - The international journal for computation and mathematics in electrical and electronic engineering*, köt. 31, sz. 4, o. 1259–1276, júl. 2012, *https://doi.org/10.1108/03321641211227537*

[21] C. F. Hsu, C. J. Chiu, és J. Z. Tsai, „Auto-tuning PID controller design using a sliding-mode approach for DC servomotors”, *International Journal of Intelligent Computing and Cybernetics*, köt. 4, sz. 1, o. 93–110, márc. 2011, *https://doi.org/10.1108/17563781111115813*

[22] V. Chopra, S. K. Singla, és L. Dewan, „Comparative Analysis of Tuning a PID Controller using Intelligent Methods”, *Acta Polytechnica Hungarica*, köt. 11, sz. 8, o. 235–249, 2014, *https://doi.org/10.12700/APH.11.08.2014.08.13*

[23] M. H. Ahmad, K. Osman, és S. I. Samsudin, „Design of proportional integral and derivative controller using particle swarm optimization technique for gimbal system”, *Indonesian Journal of Electrical Engineering and Computer Science*, köt. 26, sz. 2, o. 714–722, máj. 2022, *https://doi.org/10.11591/ijeecs.v26.i2.pp714-722*

[24] T. Shiohara és Y. Maeda, „Enhanced Auto-Tuning of Feedback Controllers with Aggressive Search Ensuring Stability and Its Application to Galvano Scanner”, *IEEJ Journal of Industry Applications*, köt. 13, sz. 5, o. 539–546, szept. 2024, *https://doi.org/10.1541/ieejjia.23013778*

[25] P. Yadav, A. Feraudo, B. Arief, S. F. Shahandashti, és V. G. Vassilakis, „Position paper: A systematic framework for categorising IoT device fingerprinting mechanisms”, AIChallengeIoT 2020 - Proceedings of the 2020 2nd International Workshop on Challenges in Artificial Intelligence and Machine Learning for Internet of Things, köt. 20, o. 62–68, nov. 2020, *https://doi.org/10.1145/3417313.3429384*

[26] O. Lountain, J. Tuke, H. Brown, K. Redman, S. Wilczek, és M. A. Humphries, „A multivariate extension to the standard 4σ criterion for comparison of forensic glass evidence”, *Forensic Sci. Int.*, köt. 338, o. 111386, szept. 2022, *https://doi.org/10.1016/j.forsciint.2022.111386*

[27] N. S. Aghili, M. Rasekh, H. Karami, V. Azizi, és M. Gancarz, „Rapid identification of multiplex camellia oil adulteration based on lipidomic fingerprint using laser assisted rapid evaporative ionization mass spectrometry and data fusion combined with machine learning”, *LWT*, köt. 228, o. 118078, júl. 2025, *https://doi.org/10.1016/j.lwt.2022.113863*

[28] S. S. Bohra és A. Anvari-Moghaddam, „A comprehensive review on applications of multicriteria decision-making methods in power and energy systems”, Int. J. Energy Res., köt. 46, sz. 4, o. 4088–4118, márc. 2022, *https://doi.org/10.1002/er.7517*

[29] E. M. Mohamed, B. Bouikhalene, F. Ouatik, és S. Safi, „AHP and TOPSIS methods applied in the field of scientific research”, Indonesian Journal of Electrical Engineering and Computer Science, köt. 14, sz. 3, o. 1382–1390, jún. 2019, *https://doi.org/10.11591/ijeecs.v14.i3.pp1382-1390*

[30] Wd. S. R. Naura, St. H. Mansyur, és P. Purnawansyah, „APPLICATION OF GROUP DECISION MAKING IN DETERMINING CULINARY TOURISM WITH TOPSIS AND BORDA METHODS”, JITK (Jurnal Ilmu Pengetahuan dan

Teknologi Komputer), köt. 9, sz. 2, o. 236–246, febr. 2024, *https://doi.org/10.33480/jitk.v9i2.5017*

[31] C. Kahraman, S. C. Onar, és B. Oztaysi, „Fuzzy Multicriteria Decision-Making: A Literature Review”, *International Journal of Computational Intelligence Systems*, köt. 8, sz. 4, o. 637–666, júl. 2015, *https://doi.org/10.1080/18756891.2015.1046325*