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*Minden jog a kiadvány kivonatos utánnyomására, kivonatos vagy teljes másolására
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CUSTOMER RELATED RISK ASSESSMENT ISSUES IN THE CASE OF INNOVATIVE INDUSTRIAL PRODUCTS

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Abstract

The paper examines some risk assessment issues related to the distribution of innovative products in particular B2B markets. The products are sold on global markets and provide competitive advantage in terms of market leading. In the topic we have chosen, the primary source of risk is the customer themselves. Through a case study, we establish a connection between risk assessment processes and the customer relationship management. Based on research conducted on the flagship product of an American company, distributed through their Romanian branch, we present a risk identification model that establishes a link between the identified risk level and customer type, and it proposes a risk analysis algorithm based on these factors. We propose a multi-step analysis which evaluates risks that can be identified early in the technical documentation and quotation stages.

Keywords: *risk assessment, customer relationship management, CRM, conformity.*

1. Introduction

Starting from the premise that the innovative products of market-leading firms are commercialized on global markets, participation in international markets presupposes that such products comply with the legal regulations and standards applicable in the jurisdictions in which they are deployed [1, 2]. Even technical characteristics and parameters that are widely recognized and accepted at the global level may, in certain specific cases, preclude commercialization. Such limitations may arise either because the product fails to conform to local regulatory requirements or because it is intended for a highly specialized field of application subject to particular restrictions. For instance, the European Union establishes a regulatory framework governing measuring instruments placed on the market within its Member States. The harmonization of Member State legislation in this domain is ensured through Directive 2014/32/EU [3].

Modern industry is confronted with unprecedented challenges, a condition that is particularly pronounced in sectors of strategic importance.

These business to business (B2B) markets are even more characterized by intense competition through continuous innovation. The competitive advantage is expected to be maintained by innovative products and technologies. At the same time, this market is characterised by high-value transactions and risk management procedures that are not typically observed in other domains. The identification and systematic classification of the risk factors inherent to these specialized markets could, in itself, constitute the subject of a separate study. Each industry has particularities that should be considered during international transactions.

Such constraints are only rarely the result of firm level business policy decisions; rather, as demonstrated above, the conditions governing the commercialization of certain products are most frequently determined by international agreements and regulatory frameworks. A particularly high degree of restriction can be observed in sectors such as pharmaceuticals, defence technologies, and nuclear energy; however, industry-specific standards and regulatory best prac-

tices also play a significant role in fields such as the automotive industry, the energy sector, and certain domains of information technology. In the pharmaceutical industry, for example, compliance is largely structured around the widely adopted framework of Good Manufacturing Practices (GMP), which establishes the highest level of regulatory conformity not only for manufacturers but also for suppliers and distributors across the entire value chain. Within the European Union, this is further exemplified by guidelines such as the 2015/C 95/02 Guideline, which specifically address the application of appropriate good manufacturing practices for excipients used in medicinal products intended for human use. [4]

Non-compliance with such requirements referred to in professional terminology as nonconformity entails adverse consequences and must therefore be treated as a significant risk factor. As with all categories of risk, the primary objective is prevention. Upon failure of mitigation measures and manifestation of risk events, the focus shifts to coordinated response and recovery functions, ensuring restoration to baseline system performance while reinforcing resilience and adaptive capacity. [5, 6]

Within these specialized B2B markets, commercialization cannot be governed exclusively by the objective of profit maximization. Although it is axiomatic that the primary purpose of any enterprise is to generate profit and to maximize the volume of its sales. Considering these restrictions, in these particular markets risk assessment assumes additional dimensions.

Within the scope of our research in the present analysis, the primary source of risk is the customer. Whether acting as an intermediary in the supply chain or as an end user, the customer may consciously or otherwise seek to acquire a product or service whose commercialization is not permissible due to one or more of these constraints. In such cases, the commission of a legal infringement or, in other instances, a regulatory violation is attributable to the distributor or manufacturer. Consequently, the responsibility for conducting comprehensive risk assessment rests with these actors.

2. Customer relationships as strategic activity

In the context of industrial products within B2B markets, the assessment of compliance interpreted in both technical and legal terms is by no

means the responsibility of a single individual or organizational unit [7, 8, 9]. It is not the objective of our research to provide a precise and comprehensive analysis of the specific organizational units or responsible individuals tasked with compliance assessment. This is in part determined by the characteristics of the given industry and organization, and is furthermore contingent upon the competencies and professional qualifications of the available workforce.

Instead, through a case study, this paper seeks to highlight that customer related risk assessment originates within the domain of CRM activities typically facilitated through a software application, implying that technical experts and engineering teams assume a primary role in the analytical process.

Customer Relationship Management systems support the core processes of market-oriented organizations by facilitating the collection, processing, and utilization of customer-related information in order to optimize business operations. According to the literature, CRM is a strategic concept that integrates processes, people, and technology with the aim of improving customer relationships and enhancing organizational performance [10].

The importance of this set of activities is further underscored by the fact that the CRM software market has become the largest enterprise software segment since 2018. According to forecasts, it is expected to reach 145.6 billion USD by 2029 [11]. Today, Customer Relationship Management has evolved from a tactical marketing tool into a fundamental strategic pillar of sustainable competitive advantage. [12, 13] Fig. 1 provides a schematic illustration of the relationship and integration between the Customer Relationship Management (CRM) system and the Enterprise Resource Planning system. As illustrated in the figure, cus-

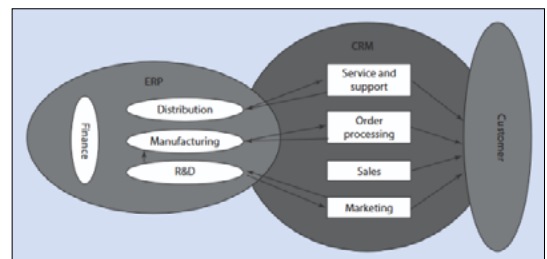


Fig. 1. The connection between the Enterprise Resource Planning (ERP) system and the Customer Relationship Management (CRM) system.

tomer relationship management is not only linked to sales and marketing activities, but is also interconnected with production process optimization, research and development, and finance. It constitutes a serious managerial misconception to assign Customer Relationship Management (CRM) exclusively to the scope of responsibility of marketing and/or sales functions [14].

3. Customer relationships as a computer science-based information system

Data serves as the core operational backbone of CRM, enabling the systematic collection, integration, and analysis of customer information to support informed decision-making and strategic planning. It enables the storage of customer profiles, the systematic recording of individual interaction events, as well as the updating and structuring of collected information. The objective is to create a unified, transparent dataset about the customer and to support data-driven decision-making [14].

The CRM activities can generate a substantial volume of relevant data for manufacturing processes. In practice, CRM applications refer to an integrated information system, underpinned by a database that is customer-centric while simultaneously aligned with the internal processes of the enterprise. A distinctive characteristic of CRM

data is that large volumes of information are not necessarily linked to a specific product. Such data may become available to the organization even prior to the first order, precisely to enable the recommendation of the most appropriate product to the customer. In earlier systems, these data were typically stored in separate, functionally independent systems across different organizational units, without integration into a unified framework. A key advantage of CRM systems is that they operate on shared databases, ensuring consistency and organizational-wide accessibility of information. [14] In Fig. 2 we present an overview of the complexity of this information management process.

From a risk management perspective, it is of the utmost importance to examine how CRM software systems identify risks, and to what extent they may themselves constitute a source of risk. It is, in itself, a risk to conceptualize CRM merely just as an IT system. Undoubtedly, the rapid storage, analysis, and dissemination of the vast amount of data generated through CRM operations requires robust information technology capabilities. However, it represents a fundamental error to treat the implementation of CRM solely as an IT initiative, while neglecting its underlying purpose, namely, the creation of profitable customer relationships and the value that CRM generates for the enterprise [14].

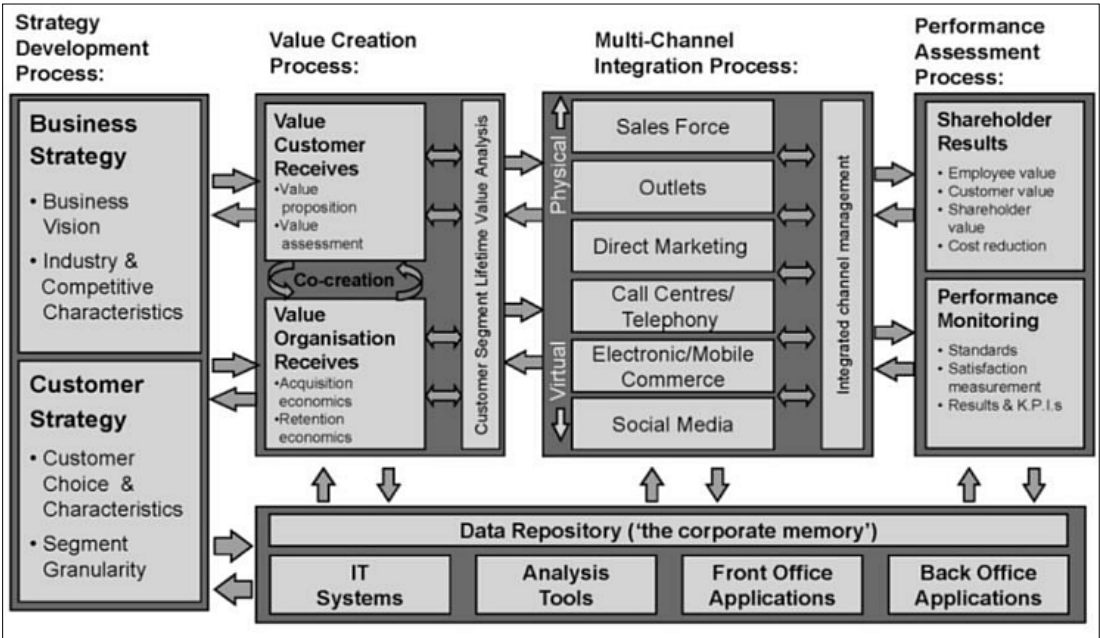


Fig. 2. The position of the CRM system within the enterprise information management system [15]

4. Risk management and customer relationships

Due to the specific thematic focus of the present study, we depart from the dominant contemporary approach, according to which risk is not limited to negative outcomes but may also entail positive deviations from organizational objectives, as reflected in the ISO 31000 standard [16] and in commonly applied project management [17]. In this instance, we deliberately adopt the traditional (in some references referred to as the “German” approach [18, 19]), and use the interpretation of risk as something primarily associated with danger. The manifestation of risk factors in our particular context is understood to entail almost exclusively negative consequences, primarily for the manufacturer. Accordingly, the emphasis is placed on prevention and regulatory control. During the research phase of the case study, we did encounter certain success stories in which customers initially classified as low reliability customers during the risk assessment process, later evolved into stable and trustworthy partners. Such examples, whereby a risk might be associated with a positive outcome, merely reinforce the fact that the organization operates an effective risk assessment system, which only occasionally produces false-positive signals. In other words, a customer is classified as risky despite not presenting an actual risk.

In a broader sense, risk analysis begins already at the stage of the identification process of the stakeholders. During the assessment of critical stakeholders, might appear some organized (typically institutional) or non-organized (typically individuals or latent) actors to whom constraints and risk factors related to commercialization can be attributed.

Among institutional stakeholders to which distribution-related constraints can be linked, we may mention various government agencies, regulatory authorities overseeing trade, and organizations supervising international agreements (e.g., specialized agencies of the United Nations and the European Union, the International Atomic Energy Agency, the World Trade Organization, or even NATO).

Fig. 3 These duties may extend from the customer-identification process to aftersales monitoring. Customer-related risks may be present in all technical activities. Their identification and prevention require a range of instruments that are explicitly technical in nature, such as multi-layer



Fig. 3. Levels of risk analysis related to customers.

data leakage protection and professional filtering mechanisms. These complement well-established legal and administrative solutions, including confidentiality agreements, data protection policies, and the development of employee awareness.

An increasingly common situation is that highly innovative products incorporate not only technical protection systems but also mechanisms aimed at preventing unauthorized copying and improper operation. This often implies that, in a legal sense, the rights and ownership of the product are just partially transferred to the customer. In some cases, it is not transferred at all. Here we are referring to the increasingly widespread solution within the software domain, where the buyers are users, with specific rights. Similarly, the solutions applied by high-tech companies in which maintenance of the equipment, supply of consumables, and often even the after sales setting or the product configuration during operation remain the responsibility of the manufacturer. In such cases, the manufacturer frequently provides continuous online monitoring of how and where the product is used.

Among the numerous customer related activities on B2B to markets, this paper focuses on risk assessment related to the first contact with the customer and on sending the quotation and technical solution related to their inquiry. The risk analysis arising in this context cannot be treated as an isolated activity. **Fig. 4** illustrates that multiple risk factors may merge during interactions with customers. The experts involved in these processes may contribute independently, yet mutually reinforcing each other, to ensure that certain risk factors do not materialize. The CRM activities, and risk management related to it, become particularly critical in the case of innovative products that constitute a source of competitive advantage for market-leading firms. In B2B markets, it is especially common that, during distribution processes, communication with customers



Fig. 4. Risk factors on customer related interactions.

may involve the exchange of sensitive technological data and confidential business information. As an initial step, risks associated with protected data can be identified primarily through the use of customer management software systems.

Compared to established industrial standards (ISO 9001, 31000, 27001, 14001), significantly more stringent procedures are required; moreover, these procedures must be deeply embedded into the organization's DNA [20]. Such precautionary measures contribute not only to the preservation of competitive advantage but also to compliance with various internal and international regulations. This is particularly relevant considering recent geopolitical developments, where embargoes and their associated complex regulatory requirements are increasingly prevalent.

This paper presents a specific risk management procedure characteristic of particular B2B markets, in which both actors are industrial organizations employing advanced technologies, and where the subject of transactions consists of highly innovative industrial products.

5. Case study based on the Rosemount™ 3051S Multivariable Transmitter manufactured by Emerson

The selected company, as one of the global market leaders in the field of automation, offers a wide range of technical solutions for industrial

systems. In the domain of measurement instrumentation, it manufactures products across numerous categories that are at the forefront of technological development. In the specific area examined in this study—namely the production of devices for integrated pressure, temperature, and flow measurement—the company is a clear global market leader. [21, 22, 23, 24]

A leading position is particularly evident in the case of instruments that measure two or three types of variables. These multivariable instruments are capable of simultaneous and high-precision determination of multiple physical quantities. The Rosemount 3051S represents the most prominent product within this category.

The Rosemount 3051S MultiVariable Transmitter is a best-in-class solution customized to obtain measurement combinations of differential pressure, static pressure and process temperature. This multivariable transmitter is a cost-effective device that reduces pipe penetrations, impulse piping, and connection systems. This device is also engineered with built-in flow calculations for fully compensated mass flow measurements. [25]

From a technical classification perspective, it is a self-diagnostic, multiparameter monoblock measuring instrument, which, in terms of measurement accuracy within its class, is unique on the market. It is a cost-effective device that significantly reduces the need for pipe penetrations, im-

pulse lines, and connection systems. The primary source of competitive advantage lies in the product's high measurement accuracy across a wide operating range.

In the case of crude oil or other high-value measured media, the use of this device can result in annual savings of \$60,000 or more [26]. For example, in crude oil applications, annual savings of approximately \$240,000 have been reported [27, 28], while one partner company has reported savings of \$300,000 per year in the steel industry [29]. These benefits are achieved through more accurate measurements and reduced measurement uncertainty compared to competing products, resulting in more stable process control. Fig. 5 presents the measuring instrument used as a sample in this study.

During the research we applied social sciences methodologies to investigate the studied topic. As a methodological tool, we used content analysis and semi-structured interviews. The content analysis was based on the company's website and publicly available documents presenting the examined product. The three semi-structured interviews were conducted with sales professionals and middle managers from the Romanian subsidiary of the company.

Based on the available data, it was established that the company's products are marketed on global markets, within industries of strategic importance. Although profit maximization is a key objective in distribution, unconditional commercialization is not feasible due to multiple internal and external constraints. Beyond profit maximization, the distributing company has a funda-

mental interest in full compliance with applicable legal norms, and moreover, in adhering to additional constraints defined through corporate social responsibility (CSR) principles. These constraints do not apply solely to a specific production site (or a particular distribution unit) but extend to the entire corporate group and must be strictly observed. Furthermore, such restrictions often apply to the entire supply chain, including the company's business partners. [31]

Since the Rosemount 3051S transmitter, manufactured and distributed by Emerson, may be deployed in strategically important industries and geographical regions, it is subject to oversight by international authorities. Thus, all high-risk customers are subject to a screening process [32]. As these restrictions require knowledge of international legal frameworks, such expertise cannot be expected from all employees. Consequently, these requirements are embedded into the company's CRM system and are part of its internally defined, widely understandable distribution policy. Screening is applied both to existing and former customers, as well. Depending on the customer profile and the type of specific order, risk analysis is likewise conducted.

The assessment of compliance with internal, national, or international requirements is the responsibility of the manufacturer/distributor. Although the source of risk is the customer, the responsibility for concluding the supply contract lies with the manufacturer/distributor, regardless of whether the customer knowingly or unknowingly attempts to purchase a product or service for which they are not authorized. During our analysis, we did not have access to confidential data or internal company regulations; however, it was identified that compliance assessment is far from being the responsibility of a single individual or organizational unit. The study also revealed that the nature of customer interactions, from a risk analysis perspective, may vary significantly depending on the type of customer.

Based on examples discussed during the interviews, we have developed and proposed a customer classification framework derived from the procedural logic applied by the company. It should be noted, however, that we do not present the company's actual procedures, but the concept developed by the authors is based on general information obtained from the company. The model, inspired by the Emerson case, is intended to be generally applicable to many enterprises distributing high-innovation products. Based on



Fig. 5. Rosemount 3051S transmitter. [30]

the analysis of Emerson's practices and the collected data, customers can be categorized into the following three main risk groups:

- Trustful partner;
- Neutral partner;
- High-risk partner.

Trustful partners are reliable customers and represent the lowest risk category. These are customers who are classified as such on the basis of their reliability rather than the volume or frequency of their orders. Although, in practice, they are typically recurring customers. Moreover, they are almost without exception end users. End users generally pose lower risk and are therefore more readily categorized as reliable customers. In contrast, resellers are not necessarily assigned to this category, even though they tend to place orders more frequently and in larger quantities than end users.

In the case of reliable customers, risk analysis is less detailed, as both the identity of the customer and the location of use of the delivered product are relatively well known. It should be emphasized that if the transaction involves a highly innovative product, the risk assessment procedure is conducted with greater rigor than in standard commercial transactions.

For neutral customers, a prerequisite is the existence of prior transactions. This category typically includes resellers, as well as end users for whom brand loyalty has not yet been established. In these cases, risk analysis is more thorough. When the transaction involves a highly innovative, market-leading product, it is necessary to complete a dedicated questionnaire, as a precondition for issuing a quotation. Beyond enabling product customization, the primary objective of this requirement is the identification of the end user. End users may represent a risk particularly in cases where international regulations restrict distribution. Such restrictions may arise, for example, if the product does not comply with the standards of the destination country, or in the event of temporary embargoes. In such situations, organizations must maintain a database—effectively a restricted or denied parties list—covering countries, regions, and industries to which the company is prohibited from supplying products.

The purpose of the customer assessment is to ensure that employees do not initiate transactions with entities included on such restricted lists, nor accept orders from intermediaries or customers associated with them. In the case of resellers, the

customer questionnaire includes detailed information both about the reseller and the end user. If any inconsistency or unverifiable information arises during data collection for either party, the risk management mechanism triggers an alert. After successfully passing the initial screening, a final quotation will be issued, followed by contracting and invoicing.

For neutral customers, a five-stage screening process is required. The first level involves sales personnel, followed by the engineering team responsible for technical configuration, then the legal/accounting department, the implementation engineering team, and finally the logistics unit. Each of these expert groups, independently and either directly or indirectly, evaluates both the order and the customer.

In the case of high-risk customers, the risk analysis process is the most complex. In addition to the above steps, specialists dedicated specifically to risk analysis must also be involved in the information processing workflow. High-risk customers are typically new clients. While in the previous two categories the risk assessment is carried out by the personnel of the manufacturing unit, in the case of high-risk customers, the evaluation is performed at the corporate headquarters level by globally specialized experts. After the evaluation, the data of all new partners subsequently become accessible across all operational units worldwide. If a new customer is placed on a restricted list during the risk assessment process, this restriction may apply across the entire corporate group.

The above classification primarily reflects categorization based on risk levels and places less emphasis on the purpose of the purchase. Based on the analysis of the distribution of the Rosemount™ 3051S transmitter at Emerson, the following customer classification was developed. While this categorization is grounded in structured interviews conducted within the company, it should be emphasized that the classification itself was developed by the authors, and the company's internal classification system (if such exists) may differ.

Based on the purpose of purchase the following customer types can be distinguished:

- End users;
- Integrator;
- E&C partners;
- Traders.

End users are customers who purchase products for their own use and typically install and set them within their existing systems. Integra-

tors are customers who develop industrial systems and incorporate the purchased products into these developments. These organizations may subsequently become end users themselves; however, in many cases, the developed industrial structures are operated later by their clients commissioning the development.

E&C (Engineering and Construction) partners are companies that combine various components and technologies into a unified, functional system. They usually develop a subsystem of a larger industrial structure, and they are not the final users of the products. Traders are customer-specialized commercial entities focusing on industrial clients, distributing the given products without providing added technical services (installation, training, consulting, and other). In essence, they act as agents or intermediaries of the manufacturer toward the end users.

The categories outlined above imply distinct risk analysis strategies, similar to the previously presented risk-based classification. Different partner types can be associated with different risk-level classifications. This correspondence is illustrated in Fig. 6.

As previously described, different risk groups entail distinct analytical procedures depending on their type. Fig. 7 schematically illustrates the phases of the risk analysis process for customers with different classifications.

The phases illustrated in the figure are often carried out in different geographical locations by groups of experts with different professional backgrounds. As shown on the left side of the figure, the risk analysis process begins with sales personnel in the first phase. They typically operate within the same geographical region from which the order originates. The role of sales staff is highly important for risk analysis purposes, as they are assumed to possess extensive local mar-

ket knowledge. Given the diversity of customer types (e.g., the customer and the end user are not always identical), sales personnel cannot be fully certain where a given piece of equipment will ultimately be used, nor can they implicitly determine whether any restrictions apply to its distribution. Therefore, it is essential to collect general information regarding the order and the customer, enabling the company to further assess the feasibility of the transaction. The primary objective of sales representatives/resellers is to sell products at the highest possible volumes; consequently, at this stage the focus is on contract initiation and maximization of contract value. Although risk analysis is present, it is not the primary activity, which justifies further examination. In this initial assessment, a general evaluation of customer-related risks is conducted regardless of customer type.

The subsequent two steps are required only in the case of new partners. These two phases are carried out at multiple locations. Initial data collection takes place at the manufacturing site of the product and involves the completion of a detailed data collection questionnaire, which also anticipates a potential solution aligned with the customer's technical requirements. In principle, it is possible that the proposed technical solution itself reveals a high-risk partner rather than the data provided by the customer. The third phase, as indicated above, is carried out at the corporate group coordination level and applies uniformly to all factories within the company. Data generated in the previous two phases are reviewed by experts, who may request additional information in the event of identified risks, and may also block contract conclusion and production. If the partner successfully passes this assessment, the quotation phase follows.

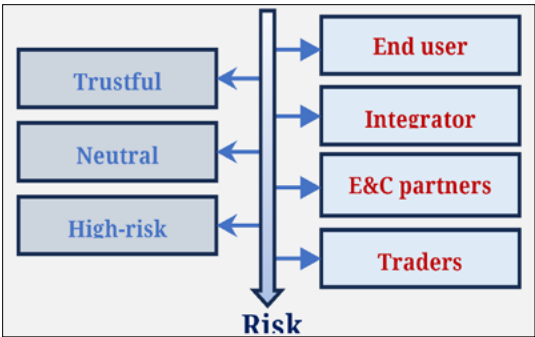


Fig. 6. Comparison of customer types.

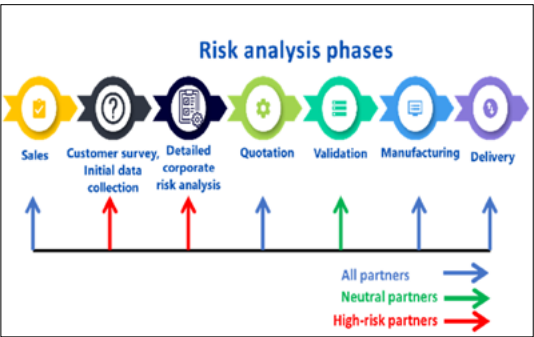


Fig. 7. Phases of risk assessment.

In the fourth step, the engineering team at the manufacturing site fulfills the customer's request from a risk-analysis perspective. At the same time, any deviation from standard conditions must also be treated as a risk factor. This is the phase in which potential anomalies can be identified from a technical perspective. In the case of the studied company, for example, it raises concerns if a partner that previously ordered measuring instruments used in the oil industry suddenly requests equipment intended for entirely different fields of application, or requests product certification according to standards applicable in another country.

Pre-production validation, which includes contract conclusion, legally finalizes the agreements reached in previous phases. At this stage, the handling of risk factors identified during risk analysis is also formalized, including the allocation of responsibilities in the event of their occurrence. If a risk factor has been identified earlier with a high probability of occurrence and severe consequences, or if there is an inherent risk of regulatory noncompliance, this constitutes a so-called "killer condition" in terms of risk analysis, and the contract is not concluded.

Multidimensional risk analysis is also carried out during production and delivery. Although contractual obligations are the primary documents at this stage, if it is later discovered that the fulfilment of any part of the contract violates regulations, the contract is suspended. No contractual agreement between partners can be in contradiction with legal regulations.

6. Conclusions

This paper addresses specific products in B2B markets that are innovative industrial goods distributed on global markets. In such cases, profit maximization is often not feasible due to legal and business policy constraints. Given these limitations, risk analysis in these contexts has additional dimensions compared to other product categories. In our particular study, the primary source of risk is the customer themselves.

Through a case study, we have established a link between certain risk analysis methods and customer relationship management activities. As emphasized throughout the paper. Technical experts should be primarily able to perform initial assessments through CRM systems. From a risk management perspective, it is crucial to assess how CRM systems identify risks, or to what extent they themselves constitute a risk.

Based on semi-structured interviews conducted regarding the distribution of the Emerson Rosemount 3051S multivariable pressure transmitter, we present a risk analysis model that establishes a relationship between risk level and customer type and which proposes a corresponding risk analysis algorithm.

In the course of our research, we applied methodologies used in the social sciences. Among the available methodological tools, content analysis and semi-structured interviews were selected. The content analysis was based on the company's website and publicly available documents describing the examined product. The three semi-structured interviews involved sales professionals and middle managers of the company's Romanian subsidiary. As a result of the research, we present a risk management procedure applicable to transactions in which both parties are industrial organizations operating advanced technologies and where the subject of the transaction consists of highly innovative industrial products.

The model derived from the Emerson case is intended to be generally applicable to companies distributing high-innovation products. The presented customer categories imply different risk analysis strategies. Individual phases of risk analysis are often conducted in different geographical locations by expert groups with different professional backgrounds. The proposed multistage general analytical model helps eliminate risks characteristic of the given industry, which can already be identified during technical documentation and quotation preparation processes in these specific B2B markets.

Differentiated risk classification supports efficient customer service for traditional clients, while also identifying high-risk potential customers at an early stage of cooperation. The multistage analysis ensures compliance with standards and regulations, assures long-term competitive advantage. We posit, the analysis of risks related to quotation and customer relationships are far more complex than it initially appears.

Acknowledgement

We would like to express our gratitude to Emerson Romania, Cluj-Napoca Factory, and its employees for allowing us to use the company's product as an illustrative example. Their best practices may serve as a model for ensuring competitiveness and compliance with international market requirements for other companies.

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ARCHIVAL SOURCES ON THE EARLY HISTORY OF THE TEHNOFRIG FACTORY (1954–1965)

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Abstract

This study examines the early history of the Tehnofrig factory in Cluj, founded in 1949–1950, based on archival sources. For the first time, it draws on the earliest documents preserved in the Tehnofrig fonds of the Cluj County Branch of the Romanian National Archives. The analysed material, dating mainly from 1954–1965, includes autobiographies, applications, labour contracts, personnel records, political registers, and work-force-management correspondence. These sources make it possible to reconstruct labour recruitment practices, vocational training mechanisms, and the social composition of the factory's early workforce. They also provide valuable information on the local dimensions of socialist industrialization, the integration of rural populations into industrial labour, and the relationship between technical education and industrial production. A particular value of the material lies in the coexistence of Romanian- and Hungarian-language documents, which reveal the multilingual character of the factory's early institutional environment. The study contributes new findings to the history of Tehnofrig and to the social history of post-war industrialization in Romania.

Keywords: *Tehnofrig, industrialization, archival research, labour recruitment, industrial heritage.*

1. The Background and Sources of Research on the Early History of Tehnofrig Factory

Romania's industrialization following World War II was one of the most significant processes of transformation in 20th-century economic and social history. Following the nationalization of 1948, the rapid development of industrial production became a primary goal of the socialist state's economic policy; as part of this effort, new companies were established, while existing plants also underwent significant expansion. Industrialization was not merely an economic program; it also fundamentally transformed the structure of society: new working-class groups emerged, the migration of the rural population to cities accelerated, and the institutional framework for technical and vocational training was established. [1, 2, 3, 4]

This process was particularly evident in the big cities of Transylvania. In the decades following the war, Cluj-Napoca not only continued to devel-

op as a cultural and educational center, but also came to play a significant role in industry. The establishment of new industrial facilities and the expansion of existing companies have transformed both the economic and social landscape of the city. [5, 6] Among the companies established or strengthened during this period was Tehnofrig, which, over the course of a few decades, developed into one of the leading centers for the manufacture of refrigeration and food processing equipment in Romania.

The Tehnofrig factory in Cluj-Napoca was one of the most prominent industrial facilities in Transylvania during the socialist era. The company, which specializes in the manufacture of refrigeration equipment, industrial tanks, heat exchangers, and food processing equipment, has played a key role in the city's economic and social life for nearly half a century. The plant was founded in the 1949–1950s and was closely aligned with communist Romania's industrialization policy. We have recollections, personal documents, com-

pany publications, and handwritten accounts regarding the later stages of the company's history, particularly those related to the life of Chief Engineer Dezső Jenei and the factory's technical development. [7, 8] However, a study of the company's early history based on archival sources has so far taken a back seat. The present study draws on the earliest surviving documents in the Tehnofrig collection.

Research into the history of companies during the socialist era has undergone a significant methodological renewal in recent decades. In addition to approaches based on economic and technological history, increasing emphasis has been placed on studies focusing on the social consequences of industrialization, the mechanisms of labor recruitment, the institutional forms of vocational training, and the development of corporate communities. [9, 10]. Company documents are thus not only records of the institution's operations, but also important sources for the social history of the period.

Archival sources play a key role in uncovering a company's history. The economic collections of Romanian archives contain numerous documents that have so far received only limited attention in historical research. [11] Particularly valuable from this perspective are personnel and labor records, which not only provide data on the company's organizational operations but have also preserved important information regarding the employees' social backgrounds, educational qualifications, and professional careers. Autobiographies, petitions and personal records shed light on individual life stories that generally cannot be reconstructed from other types of sources. As a result, research on the history of institutions is enriched with a social history dimension, and this also enables a more nuanced examination of local processes of industrialization.

The primary source material for this study consists of documents from the "Fond Întreprinderea Tehnofrig Cluj" (No. 626) collection, held at the Cluj County Office of the Romanian National Archives (Direcția Județeană Cluj a Arhivelor Naționale, hereinafter DJAN-CJ). The research is based on the analysis of the first 2 document bundles in the collection: the bundles titled „Cadre. Repartizări. Contract de muncă (1954–1965)” (Management. Assignments. Employment Contracts) and „Diversă, corespondență cu forțele de muncă (1958–1965)” (Other, correspondence with the labor office). The preserved documents include CVs, job applications, employment contracts, political records, personnel rosters, and official cor-

respondence related to workforce management. The unique value of this source material lies in the fact that it provides an opportunity to examine the factory's first community of employees, its recruitment practices, early forms of training the next generation of professionals, and the company's multi-ethnic social environment.

The purpose of this study is twofold: first, to systematically process and present the earliest documents in the Tehnofrig collection; and second, to explore the connections in industrial, social, and technological history that emerge from these archival documents. The study focuses on the period when the company was founded, the composition of its workforce, the methods used to ensure a supply of skilled workers, and the social processes that shaped Tehnofrig's development during the early stages of industrialization in Romania.

2. Records and the Record-Generating Institution

2.1. The nature and content of the examined source material

The archival source material on which this study is based, comes primarily from document set 1 and 2 of the Tehnofrig fonds.¹ The research examines 3 main types of sources from the materials in Document Set 1: (1) handwritten autobiographies (autobiografii) prepared by applicants for employment at the factory and by students and trainees completing their internships at the company; (2) applications submitted to the company's board of directors; and (3) the plant's internal administrative documents, including a political registry classified as “Strict Secret” (Strictly Confidential). Document Set 2 contains the official correspondence between Tehnofrig and the labor management agencies, which makes it possible to reconstruct the company's recruitment and workforce management practices.

The vast majority of the documents examined were produced between 1954 and 1965. The source material provides insight into the company's personnel policy, its system for training the next generation of professionals, the social composition of the workforce, and certain aspects of how industrial management operated at the time.

1 DJAN-CJ, Fond Întreprinderea Tehnofrig Cluj nr. 626. (hereinafter: Fond Tehnofrig), dos. 1. Cadre. Repartizări. Contract de muncă (Management. Assignments. Employment Contracts), 1954–1965, 356 file; dos. 2. Diversă corespondență cu forțele de muncă (Other, correspondence with the labor office), 1958–1965, 369 file.

2.2. The Founding and the Early Years of the Tehnofrig Factory

The organizational origins of the Tehnofrig factory date back to 1949, but it was legally established as a state-owned enterprise on December 26, 1950. The factory was located in Cluj-Napoca on Str. Fabrica de Chibrituri at numbers 5–7, and later at numbers 5–11. The plant's core business was the design, manufacture, and installation of refrigeration equipment and industrial cooling systems—hence its name, derived from the Romanian word “frigorific” (refrigeration).

The name of the factory has changed several times over the years: early documents refer to it as *Uzinele Tehnofrig Cluj*, which was later replaced by *Întreprinderea Tehnofrig Cluj*. From its founding, Chief Engineer Dezső Jenei was a key figure at the factory; he joined the company on December 6, 1949, and held the position of chief engineer until 1973. He was responsible for overseeing the factory's technical developments during its early decades; he was also the founder and first president of the Technical Sciences Section of the Transylvanian Museum Society.²

The factory soon outgrew the boundaries of Cluj-Napoca: it carried out installation work in numerous cities across Romania, including Bistrița, Suceava, Iași, Pitești, and Timișoara. The penguin emblem, designed by László András, an art teacher and metalworker—who had been an art teacher at the Reformed College before the 1948 educational reform and subsequently worked as a graphic artist at Tehnofrig—became a defining element of the company's image.³

2.3. The Structure and Content of Document Collections

The inventory of documents to be permanently preserved from 1954 to 1968 indicates the existence of 100 document collections. The fonds spans the period from the 1950s to the late 1960s and covers virtually every aspect of the company's operations: from management decisions and laboratory analyses to employee hiring records and contracts for installation work, as well as innovation documents.⁴

This study provides a detailed analysis of document sets 1 and 2. The original label on the cover of document Set 1 reads: 1 – Tehnofrig – *Cadre. Repartizări. Contract de muncă. 1954–1965. T. păst. permanentă* (Management. Assignments. Employment Contracts. Permanent retention period – to be preserved indefinitely). 356 files. It contains a total of 337 digitized pages; the difference can be explained by the fact that some pages were photographed on both sides, and a few blank pages may be missing from the digitization process.⁵ Cover inscription of document Set 2: *Diversă Corespondență cu Forțele de muncă, years: 1958–1965* (Miscellaneous Correspondence with the Labor Management Office, 1958–1965), 369 pages.⁶

The material in Document Set 1 is not uniform but consists of several different groups of documents: (1) autobiographies of local village workers (Baciu) – ff. 1–3; (2) resumes of applicants – ff. 4–10; (3) the résumé of a student at the Technical University of Cluj – f. 11.; (4) the program, assignment list, and résumés of students at the for the summer 1954 internship – pp. 12–25; p. 21 is missing; (5) assignment list for the Cluj Secondary Technical School of Refrigeration Technology – f. 26, ff. 28–31; (6) Resumes of students from the same school – ff. 32–60.; (7) Applications and resumes in Hungarian from students at the Cluj Commercial High School – ff. 61–75.; (8) internal administrative documents—notice of dismissal (ff. 76–83), “Strictly Secret” political records (ff. 84–87), inventory list (f. 96), directories (ff. 98–105), evening school statements (ff. 121–127); as well as (9) employment contracts—in the form of partly completed and partly blank forms, which constitute the bulk of the document collection (ff. 128–356).

The content of the second document set is more uniform: it contains a series of letters exchanged between Tehnofrig and the Cluj Labor Recruitment and Placement Office (*Secția Orașului de Recrutare și Repartizare a Forțelor de Muncă*), which were handled by the factory's Personnel and Staff Training Service (*Serv. Personal și Formare Cadre*). The set, consisting of 369 pages, was closed on December 9, 1965. The letters contain job postings, recruitment notices for skilled work-

create în perioada 1954–1968) contain documents to be permanently preserved, comprising a total of 100 files (dossiers).

5 DJAN-CJ, Fond Tehnofrig, dos. 1. (Repartizări, Contract de muncă, 1954–1965), 356 lap.

6 DJAN-CJ, Fond Tehnofrig, dos. 2. (Diversă Corespondență cu Forțele de muncă, 1958–1965), 369 lap.

2 For a detailed overview of Dezső Jenei's professional career and his role at Tehnofrig, see [7].

3 Letter from Attila Ferencz, retired design engineer, to Enikő Bitay, as part of the research project she initiated on the history of the Tehnofrig factory. Cluj-Napoca, August 21–23, 2015. Tehnofrig Collection, EME, KIK (Library and Information Center), Cluj-Napoca.

4 DJAN-CJ, Fond Tehnofrig. The Fond's archives (Inventarul pentru documentele care se păstrează permanent,

ers and technical staff, announcements of entrance exams, requests for internal workforce re-assignments, and circulars regarding workforce management regulations. The documents cover the period from 1958 to 1965 and provide direct insight into the day-to-day practices of the factory's workforce management, the factory's development, and the labor regulations of the time.

The structure of the documents allows us to examine the company's early operations from personal, organizational, and social-historical perspectives simultaneously. In the following, we will reconstruct the most important characteristics of the factory's workforce and the recruitment of skilled workers based on Sets 1 and 2.

3. The Composition of the Workforce and Its Recruitment Mechanisms

3.1. Resumes of Local Village Workers (1954)

Among the earliest personnel documents surviving from the early days of the Tehnofrig factory are the handwritten Hungarian-language résumés of 3 workers from Baciú, dated October 1, 1954. The documents trace the life stories of Lajos Balázs, Gyula Gáspár, and Dénes Turós, while also offering insight into the world of the social groups from which the company's first employees came. The 3 autobiographies were written on the same day, and their content and structure clearly reflect the requirements for personnel records in the 1950s. The authors not only provided details about their birth and education but also described their family backgrounds, employment histories, military service, and political pasts.

All 3 men were from the village of Kisbács (Baciú), which lay within the immediate catchment area of Cluj-Napoca. Although they all came from agricultural backgrounds, their social status was not the same. Lajos Balázs was born on September 2, 1908, into a family of day laborers. He attended elementary school in Kisbács from 1915 to 1919, after which he made a living working in agriculture and as a casual day laborer. In his autobiography, he noted that, as the head of his household, he was exempt from regular military service; however, in 1943, he served for a short time with the 60th Rifle Battalion in Cluj. He did not belong to any political organization.⁷

Gyula Gáspár was born on February 14, 1907, in Kisbács to a middle-class farming family. He had six siblings, completed six years of elementary

school, and then worked as a farmer. According to his autobiography, his financial situation was characterized by ownership of one hectare of land. He was married and raising 4 children. He completed his military service in 1929 in Pitești, with the 6th Regiment. The document emphasizes that he had not participated in the activities of any political organization, either previously or at the time of writing his autobiography.⁸

Dénes Turós was born on September 12, 1912, in Kisbács to a poor peasant family. He grew up with 8 siblings and attended elementary school from 1919 to 1924. According to his autobiography, the family owned only 0.73 hectares of land. From childhood, he worked in agriculture and as a day laborer, then moved to Kolozsvár in 1931. During World War II, between 1942 and 1943, he served in the military. In his own words, he was not a member of any political party or organization.⁹

The 3 autobiographies share numerous common features. Each is a handwritten document in Hungarian that presents the author's life story in chronological order. The texts place particular emphasis on social background, educational attainment, military service, and political history, which aligns well with personnel practices during the state socialist era. At the same time, the documents also show that Tehnofrig's first employees represented various social strata from the surrounding villages. Day laborers, poor peasants, and middle-class peasants were all represented, suggesting that the agricultural population in the Cluj-Napoca area constituted one of the company's most important sources of labor. At the same time, the documents clearly illustrate the process of social mobility through which a portion of the rural population gradually became integrated into the world of industrial production.

3.2. Resumes of job applicants (1955)

Among the personnel files, 7 résumés submitted with the intention of seeking employment have been preserved from February 1955. The documents are dated February 8–9, 1955, and reflect the circumstances of young applicants, most of whom were born between 1933 and 1938, as they were just starting their careers. Among the résumés are 4 documents in Romanian and 3 in Hungarian, all of which provide insight into both

8 Ibid., f. 2.

9 Ibid., f. 3.

the recruitment practices of the time and the social backgrounds of the applicants.¹⁰

The authors of the Romanian-language autobiographies—Ileana Osváth, Anna Osváth, Anasztázia Veres, and Aurélia Buda—were all young women from rural farming families. The autobiographies provide detailed information about the parents' occupations, the number of siblings, educational background, and social origin. In several cases, UTM membership is also mentioned, which was a piece of information regularly included in personnel records of the era.¹¹

The authors of the Hungarian-language autobiographies—György Hideg, Károly Jakab, and Pál Pác—also came from farming or middle-peasant family backgrounds, though in their cases, secondary commercial education is also mentioned. György Hideg and Károly Jakab were students in the fourth grade of the Commercial School, while Pál Pác pursued commercial studies after completing 7 grades of elementary school. In addition to mentioning their membership in DISZ, the autobiographies also prominently highlight their intentions to continue their education and enter the workforce.¹²

Based on the documents, it can be concluded that Tehnofrig was considered an attractive workplace for young workers in the mid-1950s. As evidenced by the surviving résumés, the majority of applicants came from rural or small-town backgrounds, and their origins in farming families played a decisive role in their social background. The collection of documents examined (ff. 4–10) also clearly illustrates the process of social mobility through which young people with agricultural backgrounds sought employment opportunities and career advancement in industrial plants. F. 11 contains the résumé of a student at the Technical University of Cluj-Napoca, dated 1954, presumably related to an internship.

3.3. Internship at Tehnofrig: Students from the Bucharest Institute of Food Industry (1954)

The documents from July 1954 describe professional internship completed at Tehnofrig by students of the Bucharest College of Food Industry (Institutul Industriei Alimentare București, Facultatea Mașini și Utilaje). The roster lists thirteen

participants, of whom the resumes of twelve students have survived; f. 21 is missing. According to the surviving documents, thirteen students participated in the internship and were divided into 3 work groups. Each group was led by a student representative: Ion Colofeteanu, Megidet Geafar, and Ion Constantinescu.¹³

The interns' résumés feature young college students from various regions of Romania. Among the participants are Eugenia Amaranu from Râmnicu Sărat, Iont Colofeteanu from Vela near Plenița, Elena Șarpe from Budieni, Gabriela Vasilu from Galați, Mariana Georgescu from Bragadiru, and Megidet Geafar from Veleni in Dobruja. Based on the surviving autobiographies, the students' social backgrounds were extremely diverse: the group included children from families of workers, farmers, small artisans, civil servants, cooperative employees, and technical professionals alike.¹⁴

Particularly noteworthy is the presence of 2 Chinese students. Cioi Guan-Pil was born on October 10, 1934, in the town of Hai-Zu in the Juan-He region, while Cia-Kuk-Iun was born on October 8, 1933, in the city of Tianjin. Both studied in Bucharest starting in the 1953 academic year and completed their internships at Tehnofrig in the summer of 1954. Their presence documents the early local manifestation of technical and educational ties among socialist countries, as exemplified by Tehnofrig.¹⁵

The internship program provides a detailed picture of the factory's organization at that time. Students worked in a rotational system across the various workshops, allowing them to become familiar with the entire production process. The program included the foundry (Turnătorie), the locksmith's shop (Lăcătușerie), the welding department (Sudură), the machine shop (Mașini Unelte), the carpentry shop (Tâmplărie), the assembly shop (Montaj), and the forge (Forje). The practical training was supplemented by field trips to the Cluj slaughterhouse, a brewery, a confectionery factory, and the local branch of the food industry design institute.¹⁶

The significance of these documents extends beyond educational activities. The workshops and production units listed above show that by mid-1954, Tehnofrig already had a complex metal-

10 DJAN-CJ, Fond Tehnofrig, dos. 1, ff. 4–10. Handwritten resumes in Romanian and Hungarian. Dated February 8–9, 1955.

11 Ibid., ff. 4–7.

12 Ibid., ff. 8–10.

13 Ibid., f. 12v.

14 Ibid., ff. 13–20., 22–25.; f. 21. is missing.”

15 Ibid., ff. 16, 24.

16 Ibid., f. 12.

working production structure. The company operated not only as a manufacturing plant but also as a training facility for higher-level technical education, which indicates the early consolidation of its workforce of specialists and its production infrastructure.¹⁷

3.4. Internship at Tehnofrig: Students majoring in refrigeration technology at the Food Industry High School (1954)

One of the valuable source collections in Document Set1 consists of the records from June 1954 of the Refrigeration Technology Department at the Cluj Secondary Technical School of Food Industry (Școala Medie Tehnică de Industrie Alimentară, secția frigotehniei) (f. 26., ff. 28–60.). According to the header of the assignment list dated June 14, 1954 – Vocational training for students of the Food Industry Technical High School (Practica elevilor de la Școala Medie Tehnică Alimentară) – 29 students (19 girls, 10 boys) from the second year of the Refrigeration program completed their vocational training at the Tehnofrig plants. On the summary sheet, the name of the institution is listed as the Cluj Technical Secondary School of Refrigeration Technology (Școala Medie Tehnică Frigotehnică, Cluj).¹⁸

The autobiographies constitute a remarkable collection of sources in terms of both content and form. Each student handwrote their own autobiography in Romanian, with most following a consistent structural pattern: place and date of birth, parents' names and occupations, social class (poor peasant, middle peasant, civil servant), the location and year of completion of elementary school, the circumstances of admission to high school, and finally, the date of membership in a political organization—the Union of Young Workers (Uniunea Tineretului Muncitoresc, UTM). The autobiographies concluded with a mandatory political closing formula. This standardized structure reflects the widely used practice of compiling cadre files during that era, which was intended to document the student's political reliability and social background.¹⁹

What makes this collection particularly significant is that the Tehnofrig factory established its own apprenticeship school on Moșilor Road in 1956. The 1954 documents thus document the period preceding the establishment of Tehnofrig's own school: at that time, the factory still ensured its supply of skilled workers through cooperation with the refrigeration technology department of the Cluj Secondary Technical School of Food Industry. This partnership was in line with the vocational training practices of the era: the collaboration between food industry schools and industrial companies served to ensure a steady supply of skilled workers.²⁰

The school's locations in Cluj are precisely documented in the autobiographies: the school building was located at 22–23, 23 August Street (Király Street), while the students' dormitories were located at 44–46 Petőfi Street and 12 Bőszörményi Street.²¹

Students were assigned to workshops on a rotational basis among the six workshops: machine shop (Mașini Unelte), locksmith's shop (Lăcătușerie), sheet metal, blacksmithing, and welding shop (Țevărie-Forjă-Sudură), assembly workshop (Montaj), foundry (Turnătorie), and carpentry workshop (Tâmplărie)—the students rotated weekly from June 14 to July 2, 1954. Their attendance was recorded.²²

According to their autobiographies, the students were typically between the ages of 15 and 18 in 1954, most of them were born between 1936 and 1939. A few began their studies later than their classmates: Cutean Patriciu was delayed due to illness, while Zbucea Teodor and Ciungan Emilian enrolled in 1952. The students came mainly from several counties in the Cluj region/Regiunea Cluj – a Szamosújvár/Gherla, Kolozs/Cluj, Dés/Dej and Torda/Turda counties –, but there were also students from Nagysármás/Sărmaș, Nagyenyed/

17 DJAN-CJ, Fond Tehnofrig, dos. 1, ff. 12–12v.

18 Ibid., f. 26., ff. 28–31. Header: Întreprinderea Tehnofrig Cluj. Practica elevilor dela Școala Medie Tehnică Alimentară. Tehnofrig Cluj Enterprise. (Internship for students from the Technical Secondary School of Food Technology). Date: Cluj, June 14, 1954. Summary: Technical Secondary School of Refrigeration Technology, Cluj, June 14, 1954. There are 29 students: 19 girls and 10 boys.

19 Ibid., ff. 32–60. The resumes are in Romanian, handwritten, and dated: Cluj, 14. VI. 1954.

20 The apprenticeship school (Școală de Ucenici) founded on Monostori Road (Calea Moșilor) later evolved into the "Tehnofrig" Industrial School Complex, for which the factory had a new campus-style building constructed in 1973 using its own budget on Maramureșului Street (now Liceul Tehnologic nr. 1, Str. Maramureșului nr. 165A, Cluj-Napoca).

21 DJAN-CJ, Fond Tehnofrig, dos. 1., ff. 32–60. A bentlakások és az iskola címe az egyéni önéletrajzokban szerepel.

22 Ibid., f. 26. (initial class assignment plan, typewritten, 3 groups, 3 sections); f. 28. (final class assignment list, typewritten, 5 groups, 6 sections); f. 29. (the same, handwritten); f. 30. (handwritten summary roster with group assignments, 29 students, 19 girls, 10 boys); f. 31. (attendance record; absent on the first day: Gheorghe Opriș, Eugenia Turc, Emilian Ciungan). Note: f. 27 is missing from the document set.

Aiud és Topánfalva/Câmpeni counties. 3 of them came from Cluj, and one student came from Marosújvár/Ocna Mureș, Aiud District (Nagyenyed járás/Raionul Aiud). The others came from villages and communities: Retteg/Reteag (Dés járás/Raionul Dej), Móró/Morău (Szamosújvár járás/Raionul Gherla), Magyarszarvaskend/Cornești (Szamosújvár járás/Raionul Gherla), Nyikula/Nicula (Szamosújvár járás/Raionul Gherla), Nagycég/Tagu (Nagysármás járás/Raionul Sărmaș), Kolozs/Cojocna (Kolozs járás/Raionul Cluj), Felsőtök/Tiocu de Sus (Szamosújvár járás/Raionul Gherla), Mezőszopor/Soporul de Câmpie (Torda járás/Raionul Turda), Indal/Deleni (Torda járás/Raionul Turda), Kolozsgyula/Giula (Szamosújvár járás/Raionul Gherla), Kolozsbós/Boju (Kolozs járás/Raionul Cluj), Csicsó Mihályfalva/Ciceu-Mihăiești (Dés járás/Raionul Dej), Kolozspata/Pata (Kolozs járás/Raionul Cluj), Kalotaszentkirály/Sâncrai (Bánffyhyunad járás/Raionul Huedin), Aranyosvágás/Vadu Moților (Topánfalva járás/Raionul Câmpeni), Erdőszombattelke/Sâmboieni (Szamosújvár járás/Raionul Gherla), Salamás/Sărmaș (Nagysármás járás/Raionul Sărmaș), Ispánlaka/Spálnaca (Nagyenyed járás/Raionul Aiud). There were 2 exceptional cases in the group: Fluerică Maria was born in Moldavia (Vorniceni, Săveni District/Raionul Săveni, Suceava Region/Regiunea Suceava), while Bălăeș Elisabeta was born in Chișinău (U.S.S.R.). The identified localities and their current administrative affiliations are listed in detail in the footnote. Their parents were mostly poor or middle-class farmers (agricultor), and in some cases civil servants (funcționar).²³

23 DJAN-CJ, Fond Tehnofrig, dos. 1., ff. 32–60. (autobiographies): f. 32. (Mesaroș Teodor – Retteg/Reteag, Dés járás/Raionul Dej, Kolozs régió/Regiunea Cluj, ma Beszterce-Naszód megye/Bistrița-Năsăud); f. 33. (Oprîș Gheorghe – Ispánlaka/Spálnaca, Nagyenyed járás/Raionul Aiud, Kolozs régió/Regiunea Cluj, ma Fehér megye/Alba); f. 34. (Suciú Maria – Marosújvár/Ocna Mureș, Nagyenyed járás/Raionul Aiud, Kolozs régió/Regiunea Cluj, ma Fehér megye/Alba); f. 35. (Cristea Rodica – Kolozsbós/Boju, Kolozs járás/Raionul Cluj, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 36. (Szatmári Juliana – Nagycég/Tagu, Nagysármás járás/Raionul Sărmaș, Kolozs régió/Regiunea Cluj, ma Beszterce-Naszód megye/Bistrița-Năsăud); f. 37. (Dordei Maria – Kolozsvár/Cluj, Kolozs járás/Raionul Cluj, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 38. (Pop Vasile – Nyikula/Nicula, Szamosújvár járás/Raionul Gherla, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 39. (Cutean Patriciu – Kolozsvár/Cluj, Kolozs járás/Raionul Cluj, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 40. (Sașu Georgeta – Salamás/Sărmaș, Nagysármás járás/Raionul Sărmaș, Kolozs régió/Regiunea Cluj, ma Maros megye/Mureș); f. 41. (Ranga Maria – Kolozs/Cojocna, Kolozs járás/Raionul Cluj, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 42. (Moraru Eugenia – önéletrajz nem azonosítható); f.

Among the 29 students listed, Romanian names are in the majority; the name ‘Juliana Szatmári’ can be clearly identified as a Hungarian name, while in the case of a few other names (Cutean, Redai), it is not possible to determine their native language with certainty based on the name alone. This distribution is not surprising: the Refrigeration Technology Department of the Secondary Technical School of Food Industry was a Romanian-language institution. During the same period, there were also Hungarian-language technical vocational schools for Hungarian youth in Cluj-Napoca – including the Hungarian-language Technical School of Mechanical Engineering on Farkas Street – which offered opportunities for further education in Hungarian to young people whose native language is Hungarian.²⁴

43. (Cecan Cornelia – Magyarszarvaskend/Cornești, Szamosújvár járás/Raionul Gherla, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 44. (Roman Augustin – Guga, Dés járás/Raionul Dej, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 45. (Crăciun Ștefan – Móró/Morău, Szamosújvár járás/Raionul Gherla, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 46. (Nechita Otilia – Diós/Deus, Kolozs járás/Raionul Cluj, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 47. (Cădariu Nastasia – Indal/Deleni, Torda járás/Raionul Turda, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 48. (Rusu Maria – Mezőszopor/Soporul de Câmpie, Torda járás/Raionul Turda, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 49. (Olteanu Maria – sz. Bukarest, lakhely: Erdőszombattelke/Sâmboieni, Szamosújvár járás/Raionul Gherla, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 50. (Turc Eugenia – Kolozsgyula/Giula, Szamosújvár járás/Raionul Gherla, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 51. (Ciungan Emilian – Ispánlaka/Spálnaca, Nagyenyed járás/Raionul Aiud, Kolozs régió/Regiunea Cluj, ma Fehér megye/Alba); f. 52. (Sabău Petru – Kolozspata/Pata, Kolozs járás/Raionul Cluj, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 53. (Redai Ioan – Csicsó Mihályfalva/Ciceu-Mihăiești, Dés járás/Raionul Dej, Kolozs régió/Regiunea Cluj, ma Beszterce-Naszód megye/Bistrița-Năsăud); f. 54. (Bălăeș Elisabeta – Kisinyov/Chișinău, U.R.S.S.); f. 55. (Rațiu Maria – Felsőtök/Tiocu de Sus, Szamosújvár járás/Raionul Gherla, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 56. (Roșca Cecilia – Nagycég/Tagu, Nagysármás járás/Raionul Sărmaș, Kolozs régió/Regiunea Cluj, ma Beszterce-Naszód megye/Bistrița-Năsăud); f. 57. (Jepure Elena – Csűrűle/Ciurila, Kolozs járás/Raionul Cluj, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 58. (Zbucea Teodor – Kalotaszentkirály/Sâncrai, Bánffyhyunad járás/Raionul Huedin, Kolozs régió/Regiunea Cluj, ma Kolozs megye/Cluj); f. 59. (Ana Sabina – Aranyosvágás/Vadu Moților, Topánfalva járás/Raionul Câmpeni, Kolozs régió/Regiunea Cluj, ma Fehér megye/Alba); f. 60. (Fluerică Maria – Vorniceni, Săveni járás/Raionul Săveni, Szucsáva régió/Regiunea Suceava, ma Botoșani megye/Botoșani). See: *The alphabetical list of localities in the People's Republic of Romania/Indicator alfabetic al localităților din Republica Populară Română*. [12]

24 Following the 1948 educational reform, the building on Farkas Street that had housed the Reformed College—

The archives also contain some unusual cases. Elisabeta Bălăeș was born in 1938 in Chișinău, which was still under Romanian rule at the time; her father was a staff sergeant (plutonier major) in the Romanian army—he presumably returned to Romania after World War II. Maria Dordei's older brother, a student in Cluj, attended the Air Force Officer Academy in Timișoara—this remark offers a rare glimpse into the military career opportunities of the era. The case of Juliana Szatmári is noteworthy: in her autobiography, she notes that her father had never been a member of any political organization, but today he is a member of the Romanian Workers' Party (Partidul Muncitoresc Român, PMR), and her brother is also a PMR member and works at the Tehnofrig factory—which documents the connection between the factory and the school even at the immediate family level. Cutean Patriciu, a student from Cluj, lived on Józsa Béla Street.²⁵ The street name is a particular example of Cluj-Napoca's naming policy during the socialist era: the street formerly known as Vasvári Pál Street was renamed after Béla Józsa after 1945, a Transylvanian Hungarian labor movement martyr – a figure whose name was acceptable even to the communist regime.²⁶

According to the assignment list, the students were assigned in groups to Tehnofrig's plants for vocational training, this took place within the framework of an institutional agreement between the school and the factory. Two students explicitly state this in their resumes: both mention that they were assigned directly from school to Tehnofrig for their training.²⁷

which had been nationalized—first became home to the Hungarian-language Technical School of Mechanical Engineering, and later to the Secondary School of Electrical Engineering.

25 DJAN-CJ, Fond Tehnofrig, dos. 1., f. 54. (Elisabeta Bălăeș – Chișinău, father: staff sergeant); f. 37. (Maria Dordei – her brother was a student at the Timișoara Air Force Officer School); f. 36. (Juliana Szatmári – her brother is a member of the PMR and works at Tehnofrig: “my brother, a member of the PMR, is married and works at this enterprise”); f. 39. (Cutean Patriciu – Str. Józsa Béla Nr. 24.).

26 Béla Józsa (Hodgya, December 4, 1898 – Cluj, November 29, 1943): publicist, editor, poet, and labor movement activist. He came from a family of farmers in the Székely region; in the 1920s and 1930s, he was one of the leading figures in the Cluj labor movement and a supporter of the policies of the Romanian Communist Party (KRP). In November 1943, he was arrested by the military authorities of the Horthy regime and tortured to death. After his martyrdom, streets in several cities in Transylvania were named after him.

27 DJAN-CJ, Fond Tehnofrig, dos. 1., f. 50. (Eugenia Turc: “From here, I was assigned to Tehnofrig for my intern-

The students conclude their autobiographies with the era's mandatory political slogan—however, the closing formulas are not uniform but appear in several variations, so in addition to the prescribed political content, they also retain individual phrasing. The most common version is: “We are actively fighting for peace!”—the phrase “Long live the struggle for peace!” also appears. A unique case is the closing phrase in Juliana Szatmári's autobiography: she chose a different phrase than her classmates—she concluded her autobiography with the exclamation “Long live the Romanian People's Republic!”²⁸

At the end of the document group (f. 61), an individual application has also been preserved, which clearly illustrates that Tehnofrig accepted interns from various schools in Cluj-Napoca not only through institutional channels but also on the basis of individual applications. Ferenc Tódor, a fourth-year student at the Cluj Commercial High School, submitted a request to the Tehnofrig Board of Directors on January 28, 1954, asking to be accepted for an internship from February 9 to May 9. His address was Madách Street, Cluj.²⁹

3.5. Internship at Tehnofrig: Students from the Cluj-Napoca Girls' Commercial School and the Cluj-Napoca Electrical Engineering High School (1954)

In addition to the documents pertaining to employees and vocational school students, Tehnofrig's personnel records also include applications and résumés related to high school students' internships. According to documents dating from January and February 1954, the company regularly accepted interns from secondary schools in Cluj, primarily from the Cluj Girls' Commercial School and the Cluj Secondary School of Electrical Engineering. These documents provide insight into both the practices of vocational training during that era and the social backgrounds of the students.³⁰

ship”); f. 51. (Emilian Ciungan: “From there, he was assigned to Tehnofrig”).

28 Ibid.: “In the active struggle for peace” – f. 33.; “In the active struggle for Peace” – ff. 32., 40. verso, 54., 55., 59., 60.; “Long live the struggle for peace” – ff. 50., 51.; “We are actively fighting for ‘Peace!’” – ff. 58., 59.; “Long live the Romanian People's Republic[?]” – f. 36. verso (Szatmári Juliana).

29 Ibid., f. 61. Petition by Ferenc Tódor, dated Cluj, January 28, 1954.

30 Ibid., ff. 62–75. Applications and résumés written in Hungarian, mostly handwritten. Dated January–February 1954.

Among the documents of the students at the Cluj Girls' Commercial School are the applications and résumés of Mária Farkas, Borbála Takács, Sidónia Turói, and Éva Alvai. The nearly identical structure of the applications and their overlapping time periods indicate that the internships were conducted within an organized, institutional framework. Most of the students wished to complete their internships at the Tehnofrig plant between February 15 and May 10, 1954.³¹ The autobiographies provide detailed information about family circumstances, academic progress, and participation in youth organizations. Mária Farkas came from a working-class family; in the case of Borbála Takács, a family background in small-scale craftsmanship emerges; while Éva Alvai entered business school as the child of a civil servant. The documents thus clearly illustrate the diverse social backgrounds of young people enrolled in secondary education. The source material also includes the applications and résumés of 2 male students, Ferenc Zágoni and Attila Orbán. Both approached the company's management in early 1954 with requests for vocational training. Their autobiographies, in a manner typical of cadre-style documents of the time, describe their family backgrounds, their studies, and their social origins.³²

At the end of Document Bundle 1 are the autobiographies of 3 students from the Cluj-Napoca Electrical Engineering High School—Ferenc Kovács, Sándor Ladó, and Sándor Both. According to the documents, all 3 received technical training, though they came from different social backgrounds. Ferenc Kovács came from a farming family; Sándor Ladó's life story alternates between military service and his studies; while Sándor Both's autobiography provides a detailed account of his large family background and his siblings' careers. Participation in youth organizations also appears regularly in the autobiographies, primarily in the form of mentions of UTM membership.³³

Based on the applications and résumés, an early form of the relationship between Tehnofrig and secondary schools in Cluj-Napoca begins to emerge. The company also served as a practical training site, while the surviving documents preserve valuable information about the family backgrounds, studies, and organizational affilia-

tions of the students of that era. According to the examined collection of documents (ff. 62–75), Tehnofrig was already involved in the training of the next generation of professionals by the mid-1950s and maintained ties with various institutions of commercial and technical education in Cluj.

4. Internal documents of the plant

4.1. The Top-Secret Political Registry (1955)

Perhaps the most source-rich document in the first batch is a list dated June 27, 1955, classified as "Top Secret": *Tabel nominal pentru tovarășii care au posturi de răspundere în uzină* (List of comrades holding positions of responsibility in the factory). Nineteen people are listed.³⁴

The list's particular historical value lies in the fact that Dezideriu Jenei—the factory's founding chief engineer and one of the founders of the Technical Sciences Section of the Transylvanian Museum Association—is the first name on the list: chief engineer, date of entry: December 6, 1949, political affiliation: union member (Sindicat), note: former workshop owner (Fost proprietar de atelier).³⁵

The list documents the practice of political classification in the socialist-era workers' administration; the factual accuracy of the entries cannot be verified based on this source. Chief accountant Gustav Szakács was expelled from the Romanian Workers' Party for having traveled abroad. Production department head Alexandru Nagy was arrested. Technical department head Octavian Pop was sentenced to one and a half years in prison for failing to report members of an organization classified as subversive (organizație subversivă). Ioan Boieriu, the laboratory director, is listed for his past as a former Iron Guard member (fost legionar). Tiberiu Székely, the head of the technical inspection department, was expelled from the party for acting as a strike-breaker. Engineer Tiberiu Tenkei was expelled from the party because his parents were kulaks (chiabur).³⁶

34 Ibid., ff. 84–87. Header: Tehnofrig Cluj, 5–7 F-ca de Chibrituri St. Strictly Confidential. List of comrades holding positions of responsibility at the plant. Date: Cluj, June 27, 1955. Signatories: The Director and the Head of the Personnel Department (Foránk[ly])

35 Ibid., f. 84. From Jenei Dezideriu's entry: Chief Engineer. Hired: Dec. 6, 1949. Political affiliation: Union. Notes: Former workshop owner.

36 Ibid., ff. 84–87. The term "fost legionar" refers to a former member of the Legiunea Arhanghelului Mihail (Legion of the Archangel Michael)—a far-right, anti-Semitic, and nationalist movement in interwar Romania that was banned by the communist regime, which also

31 Ibid., ff. 64–70.

32 Ibid., ff. 62–72.

33 Ibid., ff. 62–72.

On the second page of the directory (f. 87), another aspect comes to light: in the column titled “Ce politică a făcut înainte de 1944?” (“What political activities did they engage in before 1944?”), the entry “Nu a făcut” (“Did nothing”) appears next to almost every person’s name. This data speaks for itself: for the majority of the individuals listed in the registry, no political activity prior to 1944 was recorded, yet they were still included – solely because of their class background, lack of union membership, or other circumstances deemed suspicious by the regime. The individuals identified on the second page are: Bare Andrei (carpenter), Luka Iuliu (unskilled laborer), Petru Măcin (engineer), Emerich Toth (civil servant), Mauritiu Tischler (carpenter), Tiberiu Tenkei (engineer), Alexandru Ingăr (dispatcher), Elisabeta Campor (locksmith).³⁷

The list thus provides an extremely vivid picture not only of the composition of the factory’s workforce but also of the political climate of the era: the political backgrounds of workers in leadership positions were documented and evaluated from a political perspective.

4.2. Notice of dismissal – resignation from employment contracts (1956)

The 1956 documents in File 1 consist of a series of notices based on a standardized template, dated August 31, 1956, terminating the employment contracts of the affected employees effective September 1, 1956. The legal basis—the H.C.M. (Hotărârea Consiliului de Miniștri – Council of Ministers Decision) No. 1360/1956 and Article 20(b) of Decree No. 369/1956 – refers to the termination of employment, for which the affected individuals were entitled to compensation equivalent to 14 days’ average earnings.³⁸

Identified employees who were laid off: Ana Băgăceanu, Ana Pálfi, Georgeta Ilian, Viorica Muradin, Aurelia Georgescu, Carol Lukács, Zoltán

Orosz. The list of those dismissed included individuals with both Romanian and Hungarian names; however, the ethnic aspects of these measures cannot be assessed based on this list.³⁹

4.3. Staff List (1955)

The documents in Set 1 include the 1955 staff roster (Stat de funcțiuni al Întreprinderii de Stat “Tehnofrig”), which was approved by the Ministry of Finance (Ministerul Finanțelor) on April 5, 1955. Under the “Management” (Conducerea) section: Béla (Adalbert) Orosz, director, category XIV/2, 1,567.50 lei; Dezső (Dezideriu) Jenei, chief engineer, also category XIV/2; Gusztáv (Gustav) Szakács, chief accountant.⁴⁰

The staff roster is of exceptional historical value because it is the first to enable a documented reconstruction of Tehnofrig’s early management and employee structure.

4.4. List of Office Employees and Their Positions (1956)

The 2 complementary documents in File 1—the list of office employees (Tabel nominal despre angajații Uzinei Tehnofrig în posturi de funcționari administrativi, ff. 98–102) and the list of job titles (Situația despre denumirea funcției a salariaților, ff. 105–106)—together provide the most comprehensive picture of the factory’s administrative staff. Both documents date from 1956 and were certified by Eugen (Jenő) Kovacs, head of the personnel department, and are dated Cluj, November 12, 1956.⁴¹

The list includes a total of 148 people. The figures at the bottom of the summary reflect striking proportions: of the 148 people, 125 have Hun-

39 Ibid., ff. 76–83.

40 Ibid., f. 96. Document header: Ministry of Food Industry (Ministerul Industriei Alimentare). Staff roster of the State-Owned Enterprise “Tehnofrig” (Stat de funcțiuni al Întreprinderii de Stat „Tehnofrig”). In the “Management (CONDUCEREA)” section: Adalbert Orosz – director, XIV/2, 1,567.50 lei; Dezideriu Jenei – chief engineer, XIV/2, 1,567.50 lei; Gustav Szakács – chief accountant. The names of all three leaders appear in the document in their Romanian forms; their Hungarian forms are also known from other sources.

41 Ibid., ff. 98–102. Nominal list of employees at the Tehnofrig Plant in administrative positions. Cluj, November 12, 1956. Certified by Eugen Kovacs, head of the personnel department. Total: 148 people—125 with Hungarian names, 23 with Romanian names. Some of the identified names from the list: Béla (Adalbert) Orosz, Dezideriu Jenei, Gusztáv Szakács, Emerich Igdorovits, Ildikó Brekes, Edmund Adorján, Zoltán Éger, Magdalena Halmay, Magda Reisman, Szidonia Turós, Magdalena Molnár, Rozália Balázs, Eva Török, Terezia Szappanos, Ghézela Balogh, Tiberiu Tenkei, Ioan Winkler—and 131 others.

persecuted its members. The term “organizație subversivă” (subversive organization) could, in the language of the socialist regime, refer to any non-communist or anti-regime organization. The term “chiabur” referred to the wealthier peasantry, whom the communist regime classified as class enemies.

37 DJAN-CJ, Fond Tehnofrig, dos. 1., f. 87.

38 Ibid., ff. 76–83. Text of the notices: We hereby inform you that, in accordance with Article 10 of H.C.M. 1360/1956 and Article 20(b), effective September 1, 1956, your employment contract in Cluj, dated August 31, 1956, is hereby terminated. Decree No. 369 of July 24, 1956, was part of Romania’s labor law reform package, which regulated the termination of employment contracts at the employer’s initiative.

garian names, while 23 have Romanian names, meaning that Hungarian names account for nearly 84% of the list. It is important to note that this is a classification based on name forms; the actual ethnic or native language self-identification of the individuals concerned is unknown. The ratio of women to men is also noteworthy: in the list of 148 people, the two genders are represented in nearly equal proportions, which shows that the office positions examined were filled by women and men in nearly equal proportions.

The organizational chart, alongside the directory, lists the roles of each individual. At the top of the list are Director Béla (Adalbert) Orosz and Chief Engineer Dezideriu Jenei. The diversity of positions—ranging from the director to designers, lab supervisors, accountants, quality control specialists, and warehouse managers, all the way to administrative staff—shows that by 1956, the factory had developed into a fully-fledged, complex organization. Technical and managerial positions were also predominantly held by individuals with Hungarian names: Emeric Igdorovits, head of technical studies; Ildikó Brekes, lecturer on technical innovations; Edmund Adorján and Zoltán Éger, designers; Vasile (László) Regöczi, head of the design department; Carol (Károly) Kovács, head of the personnel department; Tiberiu (Tibor) Székely, department head; Andrei (András) Gáll, designers Alfréd Klima and Francisc (Ferenc) Tóth—to name just a few.⁴²

Taken together, these 2 documents show that the vast majority of Tehnofrig's workforce in 1956 consisted of employees whose names were recorded in Hungarian form.

4.5. Employment Contracts – The Factory's Earliest Employees (1954)

The bulk of the document set—pages ff. 128–356—employment contracts, which can be classified into three different types of documents and record the two main methods of hiring. The first type consists of blank, unfilled-out “Contract de Muncă”/Employment Contract forms (ff. 128–135, ff. 142–231), which bear the letterhead of the Direcția Generală a Rezervelor de Muncă and in-

clude the name of Director Adalbert Orosz. These forms document the bureaucratic framework of centralized labor allocation.⁴³

The second type consists of completed contracts brokered by the General Directorate of Labor Reserves (Direcția Generală a Rezervelor de Muncă), dated March 13, 1954. These were signed by delegate Carol Kovacs on behalf of the factory. The identified individuals—Béla Callo, Béla Jiga, Francisc Both, and Ioan Varga, who were unskilled workers, and Petru Naș, a locksmith—were all placed at the factory through state mediation. This type of contract documents that the state centrally managed the distribution of labor through the General Directorate of Labor Reserves.⁴⁴

The third and most common type consists of Tehnofrig's contracts bearing the company's own letterhead and signed by Director Béla (Adalbert) Orosz, dated July and August 1954. The identified individuals are: Eugen Dimény—strungar (lathe operator), Béla Márton, Iosif Mátyás—strungar, Simion Hanciu—lăcătuș (locksmith), Ioan Iosif, Margit Jakab, Elisabeta Zoványi – sculer-lăcătuș, Gheorghe Bányai, Pál Erdélyi – strungar, Ioan Androne, Piroska Drăgan, Ilona Varga – montator (assembler), Ioan Suciu – turnător (caster), Mihai Cseke – autogenous welder, Nicolae Újvári – sheet metal welder, Ioan Dârjan – electric welder, Simion Balea, Carol Gerő. As the names indicate, a significant proportion of these workers had Hungarian names.⁴⁵

43 Ibid., ff. 128–135. (empty “Contract de Muncă” (Employment Contract) forms, Type I, header: Director Adalbert Orosz); ff. 142–231. (empty “Contract de Muncă” (Employment Contract) forms, various types).

44 Ibid., ff. 238–239. (Callo Béla – unskilled worker, Kovacs Carol aláírásával); ff. 240–241. (Jiga Béla – unskilled worker, 1954. III. 13., signed by Kovacs Carol); ff. 242–243. (Both Francisc – unskilled worker, 1954. III., signed by Kovacs Carol); ff. 246–247. (Varga Ioan – unskilled worker, 1954. III., signed by Kovacs Carol); ff. 248–250. (Naș Petru – locksmith, 1954. III., signed by Orosz Adalbert).

45 Ibid., ff. 151–334. Contracts bearing the Tehnofrig letterhead and signed by Director Béla (Adalbert) Orosz, July–August 1954. Identified individuals and folio numbers Dimény Eugen – lathe operator (ff. 154–155.), Márton Béla (ff. 258–259.), Mátyás Iosif – lathe operator (ff. 260–261.), Hanciu Simion – lăcătuș (ff. 265–266.), Iosif Ioan – tools maker-locksmith (ff. 275–276.), Jakab Margit – toolmaker-locksmith (ff. 279–280.), Zoványi Elisabeta – toolmaker-locksmith (ff. 281–282.), Bányai Gheorghe – lathe operator (ff. 283–284.), Pál Erdélyi – lathe operator (ff. 285–286.), Ioan Androne – assembler (ff. 291–292.), Piroska Drăgan – assembler (pp. 295–296), Ioan Suciu – foundry worker (pp. 299–300), Mihai Cseke – oxy-acetylene welder (pp. 305–306), Nicolae Újvári – sheet metal welder (pp. 307–308), Dârjan Ioan – electric welder (pp. 313–314.), Varga Ilona – assembler (pp. 323–324.), Balea

42 DJAN-CJ, Fond Tehnofrig, dos. 1., ff. 105–106. Information on the job titles of employees. Some key positions from the organizational chart: Béla (Adalbert) Orosz – director, Dezideriu Jenei – chief engineer, Gusztáv Szakács – chief accountant, Emeric Igdorovits – technical researcher, Ildikó Brekes – technical innovator, Edmund Adorján – designer, Zoltán Éger – designer, Adalbert Szilágy – chief sales engineer, Magdalena Reisman – accountant.

Taken together, these 3 types of contracts show that Tehnofrig's recruitment in 1954 took place both through state-mediated placement and through direct contracts signed by management, and that the factory employed a wide range of skilled workers even in the first few years after its founding.

4.6. Miscellaneous Administrative Documents

The collection also contains numerous smaller documents that are valuable from a historical source perspective, offering insight into the factory's day-to-day operations. In January 1955, Tehnofrig's personnel department sent a circular letter to the Cluj slaughterhouse (Abator) and the tobacco factory (Fca Tutun), requesting confirmation of the names of Tehnofrig employees working at those locations. This document suggests that some workers were employed at multiple workplaces simultaneously—a phenomenon that was not uncommon during that era.⁴⁶

Also dating from 1955 is a list of temporary masonry workers: Petru Fodor (1913, Cluj), Alexe Tecari (1911, Cluj), and Adalbert Süle (1923, Tureni), who were hired on a temporary basis starting January 27, 1955. This information indicates that the factory was also carrying out construction and expansion work during this period.⁴⁷

Under Decree No. 2047/1954 of the H.C.M., workers were required to submit a declaration stating that they were attending evening school and would therefore be switching shifts. Document bundle 1 contains a series of such declarations (Declarație) (pp. 117–133), which were signed by various Tehnofrig employees during 1955–1956: Márton Szöllösi, Nicolae Sass, Károly Simon, Tiberiu Nanași Țicariu, and others. The mixed list of Hungarian and Romanian signatories shows that workers of both nationalities participated in the evening classes—the factory was thus not only a workplace but also a venue for socialist adult education.⁴⁸

4.7. Operational Correspondence in Workforce Management (1958–1965)

Document Set 2 of the collection (Miscellaneous Correspondence with Labor Authorities, 1958–1965, 369 files) contains a series of letters exchanged between Tehnofrig and the Cluj Labor Recruitment and Allocation Office (Secția Orașului de Recrutare și Repartizare a Forțelor de Muncă, or Oficiul de Repartizare a Forțelor de Muncă Cluj). The file was closed on December 9, 1965.⁴⁹

Based on the signatories of the letters, it can be determined that the last identifiable signature of Director Béla (Adalbert) Orosz is dated June 30, 1960 (f. 254), while the first clearly identifiable signature—that of Director Ing. T. Simedrea, appears on October 3, 1961 (f. 199). The change in directorship can therefore be placed between the second half of 1960 and the end of 1961; the exact date cannot be determined from this collection of documents. Based on the signatures and typewritten names in the letters, the following individuals served as heads of the personnel department in succession: Gy. Kirkos (May 1959), I. Mezei (1959–1960), B. Nagy (December 1959), Görög (1960–1961), Adalbert Salamon (1961–1962), Teodor Mudura (1963), and Constantin Bolba (1964–1965).⁵⁰

The subject of the letters is the labor requests sent by Tehnofrig to the labor allocation agencies in Cluj-Napoca—whose names and organizational structures changed several times over the years. The positions requested, listed in chronological order, reflect the factory's development: in 1958, they requested a chief accountant, high-level locksmiths (cat. 6–8), toolmakers, an electrician, a fireman, and a CFR transportation specialist (expeditor spec. transp. CFR); in 1959, foundry workers, refrigeration specialists in ammonia compressors, laboratory physicists and chemists with higher education, telephone operators, wood model makers, vulcanizers, and heliographers; in 1960, in a single letter, 40 lathe operators, 30 locksmiths, 10 mechanics, 15 toolmakers, and other specialists, including 2 certified Rus-

Simion (pp. 329–330.), Gerő Carol (pp. 331–332.). Dir.: Orosz Adalbert, 1954. VII–VIII.

46 DJAN-CJ, Fond Tehnofrig, dos. 1., f. 107. Date of letter: -. Header: To Fca Tutun Cluj / To Abator Cluj.

47 Ibid., f. 108. Temporary bricklayers hired from 27 Jan. 1955: Fodor Petru (1913, Cluj.), Tecari Alexe (1911, Cluj), Süle Adalbert (1923, Tureni).

48 Ibid., ff. 117–133. Basis for these statements: H.C.M. No. 2047/1954 on the organization and operation of evening schools for general education.

49 DJAN-CJ, Fond Tehnofrig, dos. 2. (Miscellaneous Correspondence with Labor Authorities, 1958–1965), 369 pages. Date of closure: December 9, 1965.

50 Ibid., f. 254. (Adalbert Orosz's last signature, June 30, 1960); f. 199. (T. Simedrea's first identifiable signature, October 3, 1961); f. 298. (Kirkos Gy., 1959. V.); ff. 279–305. (Mezei I.); f. 278. (Nagy B., 1959. XII. 29.); f. 210. (Görög, 1960. VIII. 30. – 1961. V. 20.); f. 182. (Salamon/Solomon Adalbert, 1962. I. 17.); f. 92. (Mudura Teodor, 1963. X. 2.); ff. 6., 9., 14. (Bolba Constantin, abbreviated as C-tin, 1964–1965).

sian translators and 9 engineering technicians; In 1961, 20 lathe operators, 10 locksmiths, technicians, a mechanical draftsman (Edita Islik), and a librarian with secondary or higher education who knows 2–3 foreign languages; In 1962, an installation engineer, a civil engineer, and a metallurgical engineer; In 1963, a photographer and a technical draftsman; In 1964, bookkeepers, design engineers, 3 tractor drivers, and 2 truck drivers with crane operator certification, as well as student workers.⁵¹

Document bundle No. 2 also contains numerous individual documents that provide insight into the day-to-day operations of the factory. On September 12, 1959, the factory received a certificate from the ISCIR (Inspectia de Stat pentru Controlul Cazanelor, Recipientelor sub Presiune și Instalațiilor de Ridicat – State Technical Inspectorate) to join the workforce (f. 289.). A letter dated September 14, 1960, reveals that the factory had a cafeteria—they were looking for a cook to replace the one who was retiring (f. 242). A letter from 1959 reveals that the factory also had a stable: the position of stable hand (grăjdar) was filled (f. 277.). The factory also operated a telephone switchboard—they sought a telephone operator in 1959 (f. 312) and in 1958 as well (f. 337). In the summer of 1964, the factory organized a training course for crane operators based on a training plan approved by MICM; four female workers (Margareta Fluieraș, Berta Kerekes, Sára Orbán, Ana Gocan) took the exam before the Cluj Regional Branch of ISCIR (ISCIR-Regionala Cluj) and received their crane operator licenses on August 17,

1964 (f. 12.). Ștefan (István) Fejes, tool shop chief engineer In June 1964, wrote two internal letters to the personnel department: in one, he requested a replacement for tool distributor Iosif Racz (primer-distribuitoare de scule) due to his retirement (f. 26), in the other, he proposed the transfer of Ioan Boros, a milling machine toolmaker (frezor-sculer), explaining that there was a severe shortage of workers in this high-level trade at the factory (f. 44.). Incidentally, the labor shortage had already forced the factory to place job ads earlier: On June 8, 1960, it published a recruitment notice in both Cluj-Napoca daily newspapers—the Romanian *Făclia* and the Hungarian *Igazság*—seeking 40 lathe operators, 30 locksmiths, and other skilled workers.⁵² In 1964, the factory announced a competition for the position of master lathe operator, which was held on August 15, 1964 (f. 23). Also preserved from that year is a handwritten reinstatement request by Alexandru Király (Sándor Király), in which the technician—who had previously worked at the factory as a master painter—requests his reinstatement; the closing phrase of the request employs the characteristic phrasing of the era: “Long live friendship among peoples!” (f. 31.).⁵³

52 Ibid., f. 258. (1960. VI. 8.: advertisement in *Făclia* and *Igazság* newspapers, for 6 consecutive days; 40 lathe operators, 30 locksmiths, 10 mechanics, 15 toolmakers, 1 production engineer, 1 standardization engineer, 10 mechanical engineers, 2 architectural engineers; signatories: Dir. Orosz Adalbert, Head of the Organizational and Labor Standards Department: Zeck Gh.)

53 Ibid., f. 289. (1959. IX. 12.: deaf and mute Kadar Francisc, blacksmith, allocated by the Ministry of Health and Social Welfare, signatories: Orosz Adalbert, Mezei Iosif); f. 242. (1960. IX. 14.: cook for our cafeteria); f. 277. (1959. XII. 28.: 1 unskilled laborer (stable hand), signatories: Orosz Ad., Mezei I.); f. 312. (1959. II. 10.: telephone operator); f. 337. (1958: 1 telephone operator, 1 bricklayer); f. 79. (1964. I. 7.: 3 tractor operators, 2 drivers with crane operator certification); f. 336. (1958. IX. 16.: fireman, Specialist Refrigeration Technician, CFR Transportation Dispatcher); f. 12. (three-page document; crane operator training course, May 4–August 17, 1964, approved by MICM; ISCIR-Regionala Cluj examination committee, August 10, 1964, Minutes No. R40-226; licenses issued on August 17, 1964: Margareta Fluieraș – No. 22,399, average 8.14%; Berta Kerekes – No. 22,403, average 5.57%; Sára Orbán – No. 22,406, average 6.72; Ana Gocan – No. 22,407, average 8.09); f. 26. (1964. VI. 23.: Racz Iosif Retirement of a tool distributor, signatory: ing. Fejes Ștefan foreman); f. 44. (1964. VI. 19.: Boros Ioan milling cutter, cutting tool hiring by transfer 1964. VI. 22-től, signatory: ing. Fejes Ștefan Chief Technician, Approval: Planning Department and Mihacea A. Serv. Org. Prod.); f. 23. (1964. VII. 17.: advertisement in *Făclia* and *Igazság* newspapers, 1964. VII. 24–26.: maistru strungar verseny 1964. VIII. 15-én; signatories: ing. Simedrea T., Bolba C-tin, Florian V. contabil șef); f. 31. (1964.

51 DJAN-CJ, Fond Tehnofrig, dos. 2.: f. 362–359. (1958. IV. 28: 2 locksmiths, 3 toolmakers, 1 electrician); f. 311. (1959. II. 17.: tehnician frigotehnist specialist compresoare amoniac); f. 292. (1959. VII. 14.: laborant chimist fizician cu studii superioare și 1 lansator, signatories: Orosz Ad., Mezei J.); f. 312. (1959. II. 10.: telefonistă); f. 317. (1959. I. 21.: modelar în lemn specialist); f. 315. (1959. I. 31.: 5 turnători); f. 309. (1959. III. 12.: 5 turnători categoria 5 și 8); f. 316. (1959. I. 27.: vulcanizator); f. 283. (1959. XII. 28.: 1 grăjdar, 2 desenatori tehnici); f. 290. (1959. VI. 19.: dactilografă să cunoască la perfecție limba română); f. 255. (1960. VI. 10.); f. 181. (1961. XII. 12.: 2 traducători autorizati pentru limba rusă și 9 tehnicieni, signatories: ing. Simedrea T., Salamon Adalbert); f. 295. (1959. VI. 6.: desenatoare tehnică mecanică – Islik Edită, alăirók: Orosz A., Mezei I.); f. 160. (1962. VI. 27.: inginer instalator, inginer constructor, inginer metalurg); f. 130. (1963. III. 4.: fotograf, pescet; Ministerul Metalurgiei și Construcțiilor de Mașini); f. 79. (1964. I. 7.: 3 tractoriști și 2 conducător auto cu autorizație macaragist); ff. 40–41. (1964. VII. 1.: studenți și elevi în timpul vacanței); f. 204. (1961. VIII. 10.: 2 calculatoare salar, 15 tehnicieni mecanici, 5 desenatori tehnici, 2 maistrii turnători, 1 dactilografă, 1 Bibliotecar cu studii medii sau superioare să cunoască 2-3 limbi străine, 5 sudori electrici și autogen, 5 electricieni cu autorizație, signatory: Görög).

File Group 2 also preserves documents related to vocational training and internal workforce development. The list dated September 20, 1960 (f. 241) includes the second-year students from the master craftsman training school who were completing their vocational internships at Tehnofrig. The 1964 crane operator training course (f. 12.) also documents the factory's internal vocational training activities. Of particular note is the letter dated August 10, 1961 (f. 204), in which the factory requests a librarian who knows 2–3 foreign languages—this refers to the operation of the factory's technical library, as well as the demand for foreign-language technical literature and documentation. The letter dated December 12, 1961, requests two certified Russian translators (f. 181), which also documents the contemporary significance of technical and official communication in Russian.⁵⁴

Document set 2 also contains documents regulating labor management. The Sfatul Popular (People's Council) circular dated December 20, 1961 (ff. 177–178) regulated the recruitment of workers from rural collective farms to the cities, thereby preventing labor migration from the collective farms. A circular dated December 13, 1963, issued by Regional Director Andrei Farkas (f. 129), stipulated restrictions on the employment of rural workers who did not possess a Cluj-Napoca residence card (buletin). As a direct consequence of this, on September 6, 1963, a minutes document (f. 101) was drawn up at the factory in the presence of a delegate from the Sfatul Popular, during which all workers from Cluj-Napoca who were working without a registered residence were checked. The applications for permanent status (pp. 126–128, p. 130) also document this regulatory process: the factory sought to grant permanent status to its indispensable rural workers living in its dormitory.⁵⁵

The second set of documents also included the official paperwork related to recruitment and personnel transfers. A minute dated July 1958 (f. 345) attests that Anton Groza, a delegate of the Regional Directorate, transferred ten unskilled workers to the Tehnofrig's representative the attached Recruitment Contract (ff. 349–351) provided for the recruitment of 30 workers in three installments, pursuant to HCM No. 371/1955. The transfer roster dated June 10, 1960 (f. 257.) shows that the factory also accepted workers transferred from various plants in Cluj-Napoca—among the lathe operators and locksmiths: from the CFR plant, the printing plant, the auto repair shop, and from the János Herbák plant. Of particular note is the letter dated November 22, 1960 (f. 231), in which the factory requested approval to employ 14 temporary unskilled workers on a commuter basis: the individuals listed were from villages in the Cluj-Napoca area—Kajántó (Chinteni), Türe (Turea), Vista (Viștea), Füzesmikola (Fizes-Nicula), Szék (Sic), and Magyarszentpál (Sânpaul)—commuted to the factory by train every day.⁵⁶ According to

the Commune People's Council, pursuant to HCM No. 371/1955; f. 129. (1963. XII. 13.: Farkas Andrei Director Regional circular); f. 101. (1963. IX. 6.: MINUTA, attendees: Mudura Teodor, S.D.R.R.F.M. delegate Costăchind Oprea, People's Council delegate Velican Petru; inspected workers: Szekely Martin, Tupea Elena ing., Bonda Victor, Kallos Ioan, Nicolae Nicolae, Popuța Augustin, Kotik P. Ioan, Moldos Mihai, Laszlo Martin, Cuc Simion, Viton Anica, Litan Alexandru, Bonda Ioan, Bonda Simion, Boita Alexandru, Fircas Ignat, Bodea Ioan, Dan Petru); ff. 126–127. (1963. IV. 2.: Request for Finalization Nr. 456/1963, signatories: ing. Simedrea T., Mudura T.; list of 21 commuter workers: Pop Eremie – Baci, Csiki Ioan, Neamtu G. Ioan – Gîrbău, Litan Alexandru, Kovacs Martin – Vistea, Diosi Ioan, Gaspar Ioan, Matyas Stefan, Szekely Ioan, Antal Martin, Szallos Pal Stefan, Pintea Vasile – Chinteni, Barta Ioan, Baci Ioan – Sânpaul, Abrudan Ioan – Turea, Nagy Francisc – Vistea, Pop Gavril – Fizeș, Szabados Ioan – Chinteni, Szallos Martin – Vistea, Matyas Stefan – Gîrbău, Sarca Nicolae – Gălăseni); f. 128. (1963. IV. 2.: Request for Finalization Nr. 455/1963, in the name index are listed: Boita Alexandru, Bonda Ioan, Bonda Simion, Fircas Ignat, Bodea Ioan stb. – from villages Lita-Turda and Hăsdade); f. 130. (1963. III. 4.: from villages– photographer, signatories: ing. Simedrea T., Mudura T.).

IV. 7.: Király Alexandru, Str. Budai Nagy Antal 158., mechanic technician diploma Nr. 20/1950, industrial painting foreman, closing formula: „Trăiască Prietenia între popoare” – Long live friendship among nations!).

54 DJAN-CJ, Fond Tehnofrig, dos. 2., f. 241. (1960. IX. 20.: elevii anului II maistri care practică la uzinele Tehnofrig Cluj; névjegyzék: Bollai Stefan, Bab Gavril, Boanca Vasile, Bojau Teofil, Cimpean Alexandru, Codreanu Gheorghe, Iordai Ioan, Gruz Iosif, Hora Ioan, Moldoran Roman, Ostoce Ioan, Pesteanu Grigore, Puiescu Moise, Rusu Petru, Tirnoveanu Vasile, Turatcy Carol); f. 181. (1961. XII. 12.: 2 traducători autorizați pentru limba rusă); f. 204. (1961. VIII. 10.: Bibliotecar cu studii medii sau superioare să cunoască 2-3 limbi străine, alăiró: Görög).

55 Ibid., ff. 177–178. (1961. XII. 20.: Sfatul Popular al Orașului Cluj Comitetul Executiv, Nr. 71007, Circular to

56 Ibid., f. 345. (1958. VII. 29.: Minutes No. 5420; Groza Anton DGRFM delegate hands over 10 unskilled workers, takes over Lucacs Ileana, a civil servant; 10 men); ff. 349–351. (Recruitment Contract for Unskilled Workers, based on HCM No. 371/1955; Regional Directorate representative: Anton Gaga, Chief; Tehnofrig representative: Adalbert Orosz, Director; 30 workers in three batches: June 1 – 10, August 1 – 10, September 1 – 10); f. 257. (1960. VI. 10.: transfer list, signatory: Mezei I.; Iosif Schuller – lathe operator – Trust Constr. Montaj Intr. 4 Cluj; Andrei Bobos – lathe operator – Trust Reg. Constr. Loc. Cluj; Albert Máté – merchandiser – O.C.L. Aprozar Cluj; Francisc Jakab – lathe operator – CFR-C Cluj Work-

other Documents Set 2, the group of commuting workers was even larger: other places of origin included Magyargorbó (Gărbău), Szamoshesdát (Hășdate), Olăhléta (Lita-Turda), and Kolozsborsa (Borșa-Gherla).⁵⁷

The list of commuting workers included in the letter dated November 22, 1960 (f. 231) clearly documents the ethnic composition of workers coming from the Cluj-Napoca metropolitan area: among the 14 individuals, there are workers with both Romanian and Hungarian names—all of whom lacked a permanent address in Cluj-Napoca and were temporary employees hired for the duration of the construction work.⁵⁸

The only surviving consolidated statement of the workforce in Document Set 2 records the status as of March 15, 1958, listing the number of employees by sections: I: 116 people; II: 177 people; III: 67 people; IV: 95 people; material cutting department: 33 people; support staff: 40 people; technical inspection: 19 people; warehouse: 29 people – for a total of 576 workers. This is the earliest aggregated headcount data from the documents examined, which clearly illustrates the factory's organizational and employment scale as of 1958.⁵⁹

shop; Francisc Blenyas – lathe operator – Cluj Printing Plant; Ioan Pescan – locksmith – Cluj Auto Repair Plant No. 5; Iosif Albert – locksmith – Fructexport Plant; Tintas Alex. – lathe operator – Intr. Tr. Com. Reg.; Olt Ioan – lathe operator – Autobaza Călători; Gavris Ioan – locksmith – Uz. Herbak Ianos; Lengyel Alex. – lathe operator – Uz. Herbak Ianos).

57 Ibid., ff. 126–127. (Sarca Nicolae – Gălășeni, Neamntu G. Ioan – Gărbău); without a folio number, attached to the letter dated March 30, 1962 (Fărcas Ignati – Hășdate, Bodea Ioan – Hășdate, Boita Alexandru – Hășdate, Bonda Ioan – Hășdate, Miklos Domide – Pădurea; Oltean Ioan – Boju); f. 265. (Pop Eremie – Baci, Litan Alexandru – Gărbău, Kovacs Martin – Vistea); ff. 272–273. (Gáspár Ioan – Vistea, Mátyás András – Vistea, Boita Alexandru – Lita, Antal Márton – Méra); f. 232. (Bonda Victor – Lita-Turda, Kallos Ioan – Borșa-Gherla).

58 DJAN-CJ, Fond Tehnofrig, dos. 2., f. 231. (1960. XI. 22.: Directory of names with Residential Address Information: Pintea Vasile – Com. Chinteni; Sochei Ioan – Com. Turea-Gărbău; Barta Stefan – Com. Vistea; Barta Ioan – Com. Vistea; Magyarosi Stefan – Com. Chinteni; Baci Ioan – Com. Simpaui; Kelemen Andrei – Com. Chinteni; Abrudean Ioan – Com. Turea-Gărbău; Nagy Francisc – Com. Vistea; Pop Gavril – Com. Fișeș-Nicula; Szabados Ioan – Com. Chinteni; Szallos Martin – Com. Vistea; Serestely Gheorghe – Com. Sic; Zsoldos Mihály – Com. Sic); f. 252. (1960. VII. 6.: Mărginean Ilie, steelworker foreman, Câmpia Turzi, signatory: Mezei I.).

59 Ibid., f. 351. Report on the Distribution of the Workforce, effective as of March 15, 1958. Signatories: Director Adalbert Orosz, Head of the Planning Department, Head of the Organization and Labour Standards Department.

The case of Ilie Mărginean, a steelworker (maistru oțelar)—who came from Câmpia Turzii and did not have a Cluj residence card—yet applied for admission on the grounds that his brothers-in-law would provide him with their own home and that he did not require state-provided housing (f. 252.) – it clearly illustrates the individual and corporate solutions that were used in an effort to ensure the employment of workers within the framework of state labor management.

The data in Document Set 2 indirectly document the early operations of the Tehnofrig iron foundry and its regular labor needs. Starting from January 1959, workers were repeatedly recruited for foundry positions: on January 21, 1959, a wood pattern maker (specialist in wood patterns, f. 317), who produced the wooden pattern blocks for the foundry's sand moulds; on January 31, 1959, five foundry workers (f. 315.); in February 1959, a highly skilled iron foundry worker (muncitor calificat la turnătorie /cubilo de fontă, f. 313.); On March 2, 1959, another 5 high-level foundry workers (cat. 5–8, f. 309); On March 21, 1959, additional foundry workers and boilermakers (forjari cazangii, f. 301); On November 3, 1959, seven heavy laborers for the foundry (muncă grea în turnătorie, f. 282); On May 26, 1960, a foundry worker (f. 260.); on December 7, 1960, a core maker (mezuitoare – no folio); and on August 10, 1961, two foundry foremen (maistrii turnători, f. 204.). The continuous and widespread demand for foundry jobs proves that Tehnofrig's iron foundry had been in continuous operation since at least early 1959—as evidenced by the simultaneous presence of casters, wood pattern makers, cupola furnace workers (cubilo de fontă), and core makers (miezuitoare) indicates the existence of a complete foundry production chain.⁶⁰

60 Ibid., f. 317. (1959. I. 21.: specialist wood modeller); f. 315. (January 31, 1959: 5 foundry workers); f. 313. (February 1959: skilled foundry worker /cast iron ladle/); f. 309. (1959. III. 2.: 5 foundry workers cat. 5–8); f. 308. (1959. III. 21.: 15 lathe operators (cat. 5–8), 5 foundry workers (cat. 5–8), 4 unskilled workers, 1 plumber); f. 301. (1959. III. 20.: 4 foundry workers, 30 unskilled workers for breaking up cast iron, 2 boilermakers); f. 282. (November 3, 1959: 7 unskilled workers performing heavy labor in the foundry); f. 260. (May 26, 1960: one foundry worker); without a folio (1960. XII. 7.: a hardworking, diligent woman); f. 204. (1961. VIII. 10.: 2 foundry foremen, signatory: Görög); f. 241. (1960. IX. 20.: practicum for second-year students at the teacher training college; list of names: Bollai Stefan, Bab Gavril, Boanca Vasile, Bojau Teofil, Cimpean Alexandru, Codreanu Gheorghe, Iordai Ioan, Gruz Iosif, Hora Ioan, Moldoran Roman, Ostoe Ioan, Pesteanu Grigore, Puiescu Moise, Rusu Petru, Tirnovanu Vasile, Turatcy Carol).

The second set of documents also documents the appearance of Tehnofrig's penguin logo in the archives: the penguin logo appears on letterhead as early as 1958 (f. 341), indicating the early institutionalization of the factory's corporate identity.

5. Evaluation of Archival Sources

5.1. Aspects of Source History

Document Set 1 is of exceptional historical value as a source. The collection contains documents from the founding generation—the earliest identified contract dates from 1954, and the latest documents are from 1956. The structure of the document collection is particularly complex: it includes, side by side, handwritten autobiographies of village day labourer, biographies of college students in Bucharest, Hungarian-language petitions from students in Cluj, secret political records, employment contracts, and statements from night school – all in a single volume that documents nearly every aspect of the factory's early operations.

Document Set 2 is also of exceptional historical value: the correspondence on labour management from 1958 to 1965 provides a detailed insight into the factory's development, strategies for addressing labour shortages, and the mechanisms for employing commuter workers. Of particular value is the only surviving consolidated statement of workforce numbers (March 15, 1958, 576 people), which is the sole archival record of workforce figures from the factory's early development.

Handwritten documents hold particular historical value as sources: the autobiography as a genre was a mandatory component of the bureaucratic apparatus during the socialist era, and its content and form were strictly regulated. The mandatory phrases—"We Fight for Peace!"/"La luptă activă pentru Pace!"—standardized the text, yet each autobiography still bears traces of individual life paths: parents' occupations, educational background, military service, and place of residence—all of which reflect the social reality of the era.

5.2. Documents on Recruitment Mechanisms

Document Set 1 is a unique source for understanding the mechanisms of socialist labour recruitment, documenting at least five different recruitment channels: state-mediated labour allocation through the General Directorate of Labour Reserves (Direcția Generală a Rezervelor de Muncă); professional internships for students at the Bucharest College of Food Industry; work-study programs for students at Frigo- tehnică High

School; the direct hiring of local day labourers; and volunteer applications from high school students in Cluj. This multi-channel recruitment approach demonstrates that the factory's labour needs were met simultaneously through state planning and spontaneous local initiatives.

Among the students at the institute in Bucharest were two Chinese engineering students who arrived in Cluj-Napoca in 1954 for an internship. Their presence documents the local manifestation of educational ties among socialist countries.

The correspondence in Document Set 2 supplements this; It documents the implementation of state labor recruitment contracts (HCM No. 371/1955), the organized employment of commuter workers from the Cluj metropolitan area, and the advertising practices used to address labor shortages in both Cluj daily newspapers.

5.3. Documents of the Multiethnic Workers' Community

One of the important scholarly findings of this collection of documents is the early documentation of the factory's multilingual and diverse workforce. This is supported by several groups of sources.

The first layer is language use: the documents in the archive were written in two languages—Romanian and Hungarian. The Hungarian-language documents bear the Tehnofrig factory stamp and were signed by the factory's management as a sign of approval. This shows that the factory administration accepted petitions written in Hungarian as well in 1954.

The second layer is the employee Nominal table: of the 148 office employees listed in the 1956 roster, 125 have Hungarian names—a proportion of 84%. It is important to note that we can only infer probable native language affiliation from the names; actual self-identification by ethnicity is unknown. This ratio shows that, among Tehnofrig's workforce in 1956, a significant majority of employees were registered under Hungarian names.

The third layer consists of the list of names from the evening school declarations: among the signatories of the "Declarații" series, prepared pursuant to Decree H.C.M. No. 2047/1954, are workers with both Hungarian and Romanian names—Károly Simon, Nicolae Sass, and Tiberiu Nanași Țicariu. This shows that the factory, as a community, was not only a workplace but also a venue for socialist adult education, where members of the two ethnic groups studied together.

The fourth layer consists of the lists of commuter workers from Document Set 2: ff. 126–127, f. 231, and other documents, the list of commuting workers from the Cluj-Napoca metropolitan area includes individuals with both Romanian and Hungarian names—which confirms that the factory's multi-ethnic character extended not only to the office staff but also to the manual laborers.

5.4. Documents on Political Surveillance

The “Strict Secret” classified directory (1955) is the most sensitive document in Set 1. Its value as a historical source is twofold: on the one hand, it documents the political control mechanisms of industrial administration during the socialist era; on the other hand, it provides indirect evidence regarding the composition of the factory's management.

The entries for the individuals listed on the first page—former workshop owner, traveled abroad, was arrested, Iron Guard past, kulak parents—reflect the system's class-based approach. Particularly noteworthy is the column on the second page of the list titled *Ce politică a făcut înainte de 1944?* (What political activities did he engage in before 1944?): for almost every individual, the answer is *Nu a făcut* (He did not engage in political activities). According to the entries, for the majority of those concerned, no political involvement prior to 1944 was recorded; nevertheless, they were included in the registry for political reasons. This illustrates the personnel screening practices of that era.

5.5. Educational Partnerships Between the Department of Refrigeration Technology and the Factory

One significant piece of information in Document Set 1 that has not been identified in the current literature, is that in 1954, the Refrigeration Technology Department of the Cluj Secondary Technical School of Food Industry, and from June 14, 1954, its students completed their vocational training at various facilities of Tehnofrig. This data indicates that an institutional relationship developed between the factory and the educational system early on—the operation of the Frigotehnică department may have been related to Tehnofrig's growing need for specialists. The school's precise institutional history requires further archival research.

The data in Document Set 2 confirm that this educational partnership continued throughout the entire period under review: the roster dated Sep-

tember 20, 1960, lists second-year students from the master craftsman training school who were completing their vocational training at Tehnofrig (f. 241), and the 1964 crane operator training course attests to the continuation of the factory's internal vocational training activities (f. 12.).

6. Conclusions

Together, File Sets 1 and 2 of the DJAN-CJ Tehnofrig Collection constitute a rich and diverse collection of sources on the early history of the Cluj factory. The data uncovered during the analysis allow us to draw the following main conclusions.

1. In 1954, labor recruitment took place through at least five different channels: workers placed through state agencies (Direcția Generală a Rezervelor de Muncă); direct hiring of local village day laborers; summer internships for students at the Bucharest College of Food Industry; workplace training for students at the Frigotehnică Secondary School in Cluj; and internships for students at the Cluj Commercial High School based on voluntary applications. This multi-channel recruitment process shows that the factory's labor needs were met simultaneously through state planning and spontaneous local initiatives.
2. As early as 1954, the factory hosted advanced technical internships: among the students of the Bucharest Institute of Food Industry were two Chinese engineering students who had traveled from Bucharest to Cluj-Napoca.
3. The sources document the linguistic and naming complexity of the factory's early workforce: in 1954, the factory's administration accepted submissions in Hungarian; of the 148 office employees listed in the 1956 directory, 125 (84%) are listed with Hungarian-style names; in the job classification list, the majority of those in technical and professional positions were also recorded with Hungarian-form names. However, the ethnic or native language affiliation of the individuals in question cannot be determined with complete certainty based on these name forms.
4. The archival documentation from the Refrigeration Technology Department (Frigotehnică) of the Cluj-Napoca Secondary Technical School of Food Industry, dating back to 1954, has not been cited in the literature currently under review. The relationship between the school and the factory also illustrates the educational policy aspects of industrialization.

5. According to the records, no political activity prior to 1944 was documented for the majority of those concerned; nevertheless, they were listed in a politically oriented registry.
6. The list of dismissals carried out pursuant to H.C.M. 1360/1956 includes individuals listed under both Romanian and Hungarian names. However, based on this list, it cannot be determined whether ethnic considerations played a role in the dismissals.
7. The earliest surviving employment contracts in Document Bundle 1 date from March 1954—these are contracts for unskilled workers arranged by the Direcția Generală a Rezervelor de Muncă. A series of contracts bearing Tehnofrig's own letterhead and signed by Director Adalbert Orosz begins in July 1954. Taken together, these two types of contracts demonstrate that in 1954, the factory relied simultaneously on state-run labor placement and direct contracts signed by the director.
8. The second file containing correspondence on labour management (1958–1965) documents the next phase of the factory's development: according to the workforce report dated March 15, 1958, Tehnofrig employed 576 people at that time; the hiring of commuter workers from Cluj-Napoca's wider catchment area took place within an organized framework; the change in management (Adalbert Orosz → T. Simedrea, Eng.) took place between 1960 and 1961; the iron foundry had been in continuous operation since at least early 1959; the fact that the penguin logo appeared on letterhead as early as 1958 indicates that the factory's corporate identity was established at an early stage.

The documents analysed in this study represent only a fraction of the factory's surviving archival collection. A systematic analysis of the collection's remaining document bundles is expected to provide an even more nuanced picture of Tehnofrig's development, organizational functioning, and role in economic, social, and technological history.

The documents examined are not only sources for the history of a single company, but also provide important insights into the local implementation of socialist industrialization in Romania, the contemporary system of technical training, and the transformation of the industrial workforce.

Acknowledgment

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PREPARATION FOR PARAMETER IDENTIFICATION IN A VEHICLE DYNAMICS MODEL

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Abstract

Vehicle dynamics models are important for understanding and predicting vehicle behavior under different operating conditions. However, their practical applicability depends largely on how well the simulated responses reflect the actual performance of the vehicle. Therefore, it is essential to validate the model with real measurement data. This study focuses on the validation of a MATLAB–Simulink longitudinal vehicle dynamics model and the parameter identification of rolling resistance using CAN bus data recorded during road driving. The measurement data were collected using a CANedge2 data logger. The measured signals were compared with the simulation results to assess the model's ability to reproduce real vehicle behavior under different driving conditions. The resistance forces causing the vehicle to decelerate were also examined. The presented workflow demonstrates a practical and reproducible approach for CAN-based model validation using real vehicle data.

Keywords: vehicle, model validation, data-based model, optimization, parameter identification.

1. Introduction

Modern vehicles are equipped with increasingly complex mechanical and electronic components, as well as mechatronic systems, which generate a significant amount of data through their onboard communication systems during operation. However, the constant introduction of new solutions demands continuous improvement in the standard of maintenance. Therefore, condition-based maintenance systems are playing an increasingly important role. The Controller Area Network (CAN) enables structured and standardized communication between the vehicle's various electronic control units (ECUs), thereby providing the ability to monitor and analyze numerous important operating parameters. This data can be used not only for diagnostic purposes but also provides valuable information for the development and validation of vehicle dynamics models.

Vehicle dynamics models are widely used tools for analyzing and simulating vehicle behavior [1]. The literature contains numerous different

models, such as quarter-vehicle [2], half-vehicle, or full-vehicle models [3, 4, 5], which describe vehicle motion with varying levels of detail. These models often emphasize lateral dynamics or ride comfort. [6, 7] For many applications, however, a simpler model that describes only the vehicle's longitudinal motion may prove sufficient. The advantage of such models is their simplicity and fast computation time; however, their accuracy depends largely on the correct selection of the parameters included in the model.

Among the most significant resistive forces affecting the vehicle's longitudinal motion are rolling resistance, aerodynamic drag, and drivetrain losses. Of these, rolling resistance plays a significant role, particularly in the low- and medium-speed ranges.

The aim of this research is to prepare the parameterization of a simple longitudinal vehicle dynamics model using measured vehicle data, with particular regard to determining the rolling resistance parameter.

2. Material and method

2.1. The measurement device

To measure vehicle data, the CANedge2 device (Fig. 1)), was used, which was developed by the Danish company CSS Electronics. It is capable of recording CAN network messages in a controlled manner. Thanks to its compact design and advanced features, this two-channel CAN/LIN data logger is ideally suited for automotive research and development testing, as well as for supporting predictive maintenance tasks.

One of the device’s key features is high-precision, continuous, and time-stamped data logging, which can be performed in parallel on up to two CAN channels. The CANedge2 is highly configurable: users can customize its operating characteristics using an online or offline configuration editor. The device begins data collection on the SD card immediately and fully automatically as soon as power is applied.

The system’s integrability is greatly enhanced by the built-in Wi-Fi module, which allows data to be transmitted wirelessly to remote servers or directly to a Python-based environment. It is also possible to connect a GPS module.

2.2. The vehicle

We conducted our measurements on a 2012 Toyota Avensis 2.0 D-4D, as shown in Fig. 2.

Table 1 shows the vehicle’s key technical data.

2.3. The vehicle model

As mentioned in the Introduction, vehicle models commonly found in the literature, such as bicycle, quarter-car, half-car, or full-car models, are generally designed for specific purposes and are not always suitable for general use. Initially, the goal was to use a simple, customizable model that could be adapted to measurement data recorded with the CANedge2 device. Most available models are based on lateral dynamics, i.e., they incorporate the effects of steering and cornering, while our primary objective was to investigate longitudinal behavior. Therefore, we developed a highly simplified longitudinal model in the MATLAB environment (Figure 3), in which we analyzed straight-line motion starting from a stationary position [8]. If this simple model adequately represents the real data, the model can be made more complex, and steering can also be incorporated, for example. The blocks used are as follows:



Fig. 1. The CANedge2 device and OBD2 cable.



Fig. 2. Toyota Avensis, 2012

Table 1. Technical data of the Toyota Avensis vehicle

Category	Specification
Drivetrain type	Front-wheel drive (FWD)
Engine type	Diesel
Transmission type	Manual
Number of gears	6
Engine capacity	1998 [ccm]
Maximum power	91 [kW], 310 [Nm]
Top speed	200 [km/h]
Fuel consumption	4.5 l/100 [km]
RPM at maximum power	3100 [rpm]
Length	4710 [mm]
Width	1810 [mm]
Height	1480 [mm]
Wheelbase	2700 [mm]
Curb weight	1555 [kg]
Tire size	205/60R16V
Distance of center of gravity from rear axle:	1.62 [m]
Distance of center of gravity from front axle:	1.08 [m]

- Vehicle Body 1DOF Longitudinal
- Simple Engine
- Ideal Fixed Gear
- Torsional Compliance
- Longitudinal Tire Disc Brake

In addition to these, Gain blocks were used for unit conversion, Memory and Delay blocks to avoid dependent signals, and Scope blocks to verify the model and display the outputs. From the measured CAN data, we imported the gas pedal position, brake pressure, vehicle speed, and later the calculated gear into the simulation environment in time-series format using Matlab code via the From Workspace blocks.

The relationship between the blocks:

Gearbox block

The transmission block modifies the engine torque based on the current gear ratio. The shift signal is provided by the current gear, which is determined from CAN bus data, allowing the model to replicate the behavior of a real vehicle. The block's inputs are the torques from the Simple Engine and Torsional Compliance blocks. Its outputs are the modified torque applied to the driven shaft and the torque feedback to the engine. The gear ratios had to be specified in the form of a row vector. Since the transmission and final drive ratios could not be measured directly, the actual total gear ratios for each gear were estimated

from the measured engine and wheel speed ratios under steady-state driving conditions.

Tire block

The block describes the interaction between the wheel and the road surface based on Pacejka's Magic Formula model [9]. Since our model is longitudinal and we did not simulate transverse (lateral) effects, it is not necessary to use two wheels per axle. Therefore, a total of two wheel blocks were used: one for the front wheels and one for the rear wheels. Based on the input torque, the block calculates the traction force and the slip ratio. Additional inputs include the forces and velocities from the vehicle body, as well as the measured brake pedal position. One output of the block is the force acting on the vehicle's longitudinal motion, and the other is the wheel angular velocity, which is fed back into the Torsional Compliance block. The loaded wheel radius and the maximum wheel slip had to be specified for the model.

1 DOF Vehicle Body block

This block models the vehicle's motion restricted to a single degree of freedom: the longitudinal direction. It calculates the vehicle's acceleration, velocity, and displacement based on the driving and braking forces from the Tire block. The calculated velocity is compared to the measured reference velocity, and the MSE (Mean Square Error)

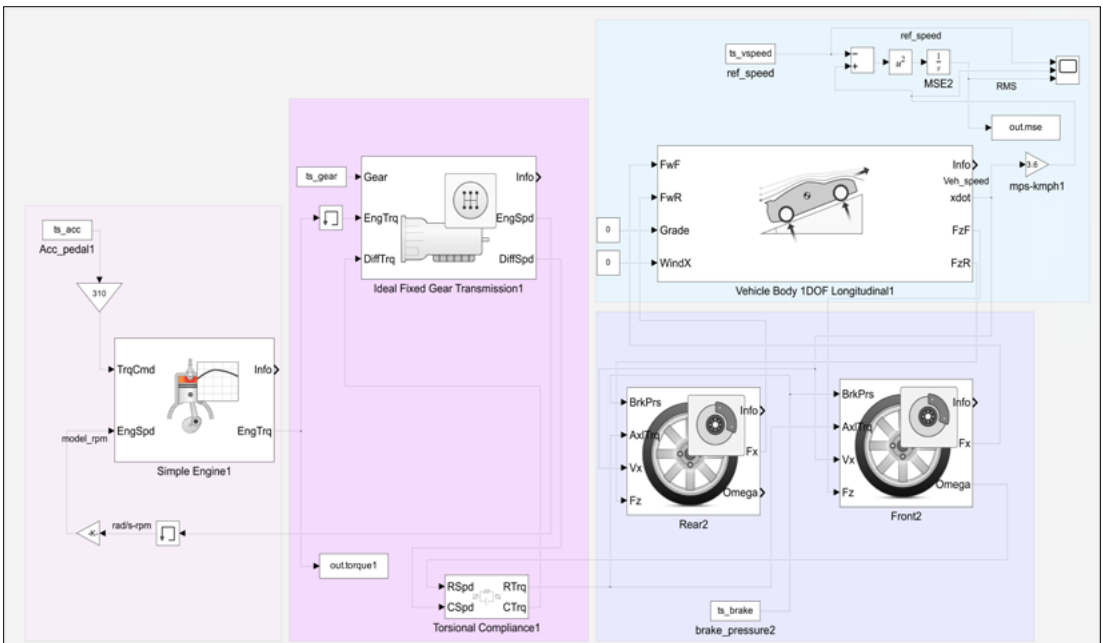


Fig.3. The longitudinal vehicle dynamic model in MATLAB-Simulink.

value of the deviation can be observed on a scope. To parameterize the model, the vehicle's mass and the distance of the axles from the center of mass had to be specified. For simplicity, the road gradient and wind speed were set to zero.

2.4. Data collection & analysis

During the research, measurements were carried out between August and October 2025 under varying road conditions, in both urban and highway traffic. During the tests, the sampling period was adjusted to determine the optimal setting. The recorded data proved sufficient for testing and validating the model, as well as for a basic analysis of the vehicle's dynamic behavior. The data collection process can be broken down into the following stages:

2.4.1. Configuration and OBD2 requests

Before starting the measurements, the CANedge2 device had to be configured to match the specific characteristics of the vehicle under test, as OBD-II requests and CAN network structures are model-specific. The configuration was performed in CSS Electronics' "OBD PID lookup tool" [10] online editor, where, after a test measurement, a list of supported PIDs could be viewed based on the bit structure of the response messages. For the selected signals (e.g., accelerator pedal position, brake pressure), using the online configuration tool provided by CSS Electronics, the bit mode (standard/extended), the frequency of the requests, and the response format were set, and then the configuration file was copied to an SD card, which was inserted into the device.

2.4.2. Data collection and decoding

During the measurements, the device was connected to the OBD2 port located under the steering wheel. Data collection starts automatically when the ignition is turned on and continues until it is turned off; the device indicates active recording via LEDs. The data is stored in MF4 format. To convert (decode) the raw CAN messages into physical parameters (Fig. 4) the open-source, Python-based asammdf software was used.

Decoding requires one or more appropriate DBC databases (files) that describe the meaning of the bi-terms and the scaling factors. In the early stages of the research, several databases were compared, as there were significant differences in units of measurement and structures. To ensure accurate results, it was ultimately decided to use multiple databases simultaneously.

2.4.3. Filtering and data analysis

Using Python code, straight sections were extracted from data recorded in real-world traffic, as these are necessary for the longitudinal model. During the filtering process, two main criteria were established:

- 1. The steering angle could not exceed 5° (straight-line motion).
- 2. The vehicle had to start from a stationary position (0 km/h).

The segments extracted were exported in .csv and .mat formats, then integrated into the MATLAB environment. The variables were converted into vectors (ensuring that each was consistently a row or column vector, as otherwise they could not have been used properly) . After that, they were converted to the "timeseries" format for loading into the Simulink model. An interpolation-based resampling was performed on the data along a common time vector. This ensured that all input parameters had the same time step, which allowed for faster and more stable model simulation runs. Finally, another MATLAB code was written to plot the simulation and model results on a single graph, making it easier to verify the results.

2.5. Preparation for optimization

The accuracy of vehicle dynamics models depends to a large extent on the correct selection of the parameters included in the model. The validation of vehicle dynamics models based on real measurements is a well-established topic in the literature and is considered essential for ensuring the reliability and applicability of simulation results. [11] During validation procedures,

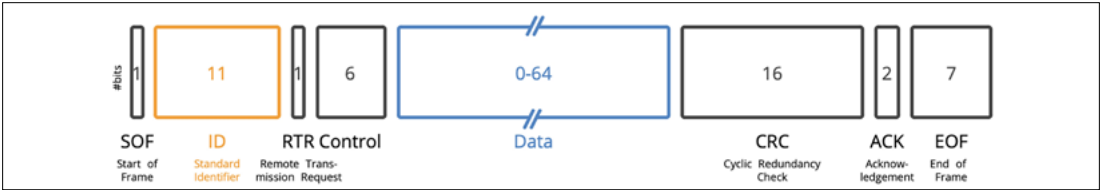


Fig. 4. The standard CAN frame. [10]

measured and simulated signals are typically compared under specified operating conditions, taking into account the model's assumptions, signal availability, and measurement uncertainty. [12, 13].

Although many parameters, such as the vehicle's mass or geometric data, can be directly determined from the vehicle's technical specifications, the values of certain parameters are only known approximately or depend significantly on the current operating conditions [11]. One such parameter is rolling resistance, which encompasses the effects resulting from the interaction between the tires and the road surface [9].

To refine the vehicle dynamics model, it is therefore necessary to calibrate these parameters based on measured data. Optimization methods are often used to determine the parameters, with the goal of ensuring that the vehicle behavior calculated by the model approximates the actual measurement results as closely as possible.

To determine the parameters of the vehicle dynamics model, it was necessary to perform measurements suitable for analyzing the vehicle's deceleration behavior. To do this, the vehicle was accelerated from a standstill in first gear, then allowed to decelerate without engaging the clutch. We repeated this several times, then performed the same procedure in second gear. To estimate the rolling resistance parameter, we selected the engine braking sections from the measurements. In these sections, the vehicle's speed decreases due to various resistive forces, while the drive-

train remains engaged because the clutch is not depressed.

In engine braking mode, the vehicle's deceleration is determined by the combined effect of several factors. These include rolling resistance, drivetrain losses, resistance from the engine brake, and, to a lesser extent, air resistance. According to previous research results, load-dependent losses affecting drivetrain efficiency vary significantly depending on speed and operating conditions. [14, 15, 16] In the present study, we focused primarily on the low-speed range, where the effect of air resistance is relatively small, so deceleration is primarily influenced by rolling resistance and effects from the engine brake.

During the measurements, the time-dependent changes in the vehicle's speed were examined within selected time intervals. As the first step in processing the measurement data, after plotting the data, time intervals were identified in which the speed-time curve exhibited a nearly linear decrease. These sections are suitable for estimating the vehicle's deceleration.

The selected measurement sections were processed in the MATLAB environment. First, the speed data were converted from km/h to m/s. Then, for each selected time interval, a linear fit was performed on the speed-time data using MATLAB's polyfit function.

The slope of the fitted line directly indicates the vehicle's deceleration in the given measurement section. The MATLAB code determined the slope of the fitted line separately for each selected interval. The results were also presented graphically.

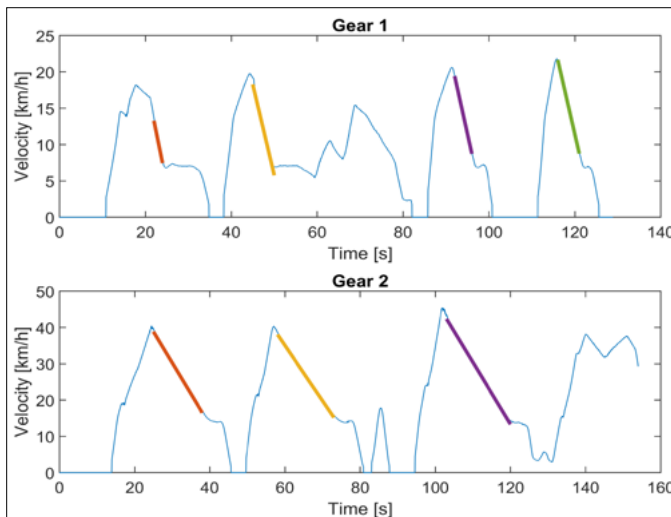


Fig. 5. Straight lines fitted to the deceleration sections in first (top figure) and second (bottom figure) gears

cally, showing the measured velocity-time curve alongside the fitted lines (Fig. 5).

During the test, four engine-braking measurement sections were selected in first gear and three in second gear. A separate deceleration value was obtained for each section. Since varying measurement conditions, such as road conditions, can cause minor differences between the individual deceleration values, the obtained values were averaged.

The average gradients obtained in first and second gears were determined separately. These average deceleration values represent the vehicle's behavior under the tested engine braking conditions and serve as the basis for parameter tuning of the vehicle dynamics model.

An optimization procedure will be used to determine the model parameters. During the optimization, two parameters will be identified:

- ERp, which compensates for the resistance effect from the engine brake
- RRp, which accounts for rolling resistance; this is the “Rolling resistance scaling factor, lam_My” parameter of the wheel block

To determine these parameters, the MATLAB Optimization Toolbox will be used. The goal of the optimization is to determine a combination of parameters such that the vehicle deceleration calculated by the model best matches the reference slope derived from the measurement data.

During the optimization process, an objective function is defined, which in this case represents the difference between the simulated and measured deceleration. The optimization algorithm searches for the combination of values that minimizes this error by iteratively adjusting the parameters.

As preparation for the optimization, lower and upper bounds were set for the parameters after conducting a few test simulations. Both parameters must be included in the objective function at this stage because they cannot be optimized independently of each other, as both influence deceleration. In the current measurement configuration, the vehicle's deceleration is significantly influenced by the effect of the engine brake; therefore, in the first step, a wider search range will be provided for the ERp parameter. In contrast, a narrower range will be selected for the RRp parameter, as more precise identification of rolling resistance requires further measurements.

In subsequent tests, we also intend to collect measurement data while the vehicle is coasting with the clutch disengaged, thereby eliminating

the effects of the drivetrain and engine braking. In this case, the vehicle's deceleration is primarily determined by rolling resistance and air resistance, which allows for a more accurate determination of the RRp parameter

3. Results

After developing the longitudinal vehicle dynamics model and the measurement method, the recorded CAN bus data was processed. The goal of the measurement system and the data processing procedure was to ensure that the vehicle model, created based on data derived from the vehicle's actual operation, represents reality as accurately as possible. To refine the model, the vehicle's deceleration behavior was examined under operating conditions suitable for the subsequent calibration of the model parameters.

During the processing of the measurement data, several engine braking sections were identified in the data recorded in first and second gears. In these sections, the change in vehicle speed over time was approximated using a linear function.

The slopes determined using the MATLAB polyfit function indicated the vehicle's deceleration in each measurement section. Based on the graphical representation of the fits, it was determined that the speed-time function exhibited linear behavior with good approximation in the selected sections, thus the linear fit proved to be a suitable method for estimating deceleration.

The slope was determined for four measurement sections in first gear and three in second gear. Minor deviations can be observed between the values obtained in the individual sections, which may result from measurement noise and various environmental effects.

By averaging the obtained gradients (Table 2) the average deceleration values characteristic of the first and second gear were determined, which will be used as reference values. These values represent the effect of the resistances causing

Table 2. Fitted slopes and their averages

	Slopes in first gear [m/s ²]	Slopes in second gear [m/s ²]
1	-0.8107	-0.4785
2	-0.6965	-0.4241
3	-0.7446	-0.4749
4	-0.7185	-
Avarege	-0.7426	-0.4592

the vehicle's deceleration in the examined engine braking operating condition.

The determined reference slope will serve as input data for parameter tuning of the vehicle dynamics model in the following.

4. Conclusion

The aim of this study was to present the measurement and processing methods required to determine the engine braking and rolling resistance parameters of a vehicle dynamics model. By processing CAN bus data from a real vehicle, it was possible to identify engine braking measurement sections suitable for analyzing the vehicle's deceleration behavior.

By performing a linear fit on the speed-time data, it became possible to determine the vehicle's deceleration in each measurement segment. By averaging the resulting slopes, reference deceleration values were determined that characterize the vehicle's behavior in the examined engine braking condition.

The determined reference slopes serve as the basis for identifying the parameters of the vehicle dynamics model using optimization methods. During parameter fitting, two main parameters will be determined: ERp, representing the resistance from the engine brake, and RRp, representing rolling resistance.

This work focused primarily on preparing for the optimization process and developing the necessary measurement and data processing steps. The defined reference values allow for the use of optimization methods in the next step to adjust the resistance parameters of the vehicle dynamics model, specifically, as a first step, to align the effects of engine braking and rolling resistance.

Further measurements are warranted in future work, for example under conditions where the vehicle is coasting with the clutch disengaged. Such measurement conditions allow for a more precise isolation of the rolling resistance effect, thereby supporting the subsequent more accurate identification of model parameters.

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DEVELOPMENT AND TESTING OF ADAPTIVE CRUISE CONTROL SYSTEMS FOR DIFFERENT POWERTRAINS

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Abstract

Due to the diversification of powertrains in the automotive industry, maximizing energy efficiency has become a core priority for driver assistance systems, alongside safety and comfort. My research aimed to develop a universal, energy-optimized adaptive cruise control (ACC) system operating optimally across internal combustion, hybrid, and purely electric vehicles. The scientific contribution of this research is a comprehensive simulation and validation framework that objectively demonstrates, via standardized metrics, the proposed control strategy's measurable energy savings in heterogeneous, simulated traffic conditions.

Keywords: *Adaptive Cruise Control (ACC), energy efficiency, powertrain technologies, simulation environment.*

1. Introduction

The automotive industry is currently undergoing one of its most significant transformations. This transformation is driven by two closely intertwined trends: the development of alternative powertrains to replace internal combustion engines (ICE), and the increase in vehicle autonomy. Tighter emissions standards are leading to the gradual decline of internal combustion engines and the rise of hybrid and fully electric (Electric Vehicle—EV) powertrains; in addition, the demand for safety and driving comfort is driving the widespread adoption of Advanced Driver Assistance Systems (ADAS). In industrial practice, the development of cruise control systems (CC) is carried out in accordance with strict standards and safety regulations. Most ACC systems currently on the market treat the powertrain as a "black box": the controller's output is a request for acceleration or deceleration, which the lower-level engine controller translates into a torque demand [1]. This approach enables modularity but also imposes efficiency limitations. A review of the literature reveals a significant gap in the study of the interaction between drivetrains and ACC systems. Most publications either focus on a

single specific powertrain (primarily EV or parallel hybrid) or examine only the optimization of energy management strategies under a fixed speed profile [2, 3]. However, there is a lack of a systematic approach that would examine the effect of a single ACC algorithm with fixed parameters across the entire powertrain spectrum. In particular, little attention is paid to more complex hybrid architectures, whose control is not a trivial task during ACC's dynamic interventions. Another methodological challenge is the comparability of results: it is difficult to objectively compare the fuel consumption reduction (l/100 km) of a diesel-powered vehicle with the energy savings (kWh/100 km) of an electric vehicle, especially when traffic conditions also vary. There is no uniform, dimensionless metric that would quantify the effectiveness of the intervention regardless of the type of energy source. This paper, in line with these approaches, examines a proprietary ACC system that I developed and tested on various vehicle types and powertrains in multiple traffic scenarios. The primary objective of the simulations was to analyze fuel and electric energy consumption. The results were compared and evaluated using a framework I developed in

order to gain a comprehensive understanding of the ACC's performance and applicability. The results of this thesis highlight how the same control logic can operate with varying degrees of efficiency depending on the type of powertrain, thereby providing guidance for the development of future powertrain-independent controllers.

2. Theoretical foundations, tools used, and methodology

The modern automotive industry, like other industrial sectors, is evolving and taking shape day by day. The era of vehicles powered solely by internal combustion engines appears to be coming to an end, as hybrid and electric powertrains are gaining an ever-greater foothold in the market [4]. The question of why this is happening calls for a complex answer, but in simple terms, there are environmental, commercial, and political reasons [5, 6, 7]. Below, I will discuss alternative powertrains, advanced driver-assistance systems, and energy consumption.

2.1. Types of drivetrains

2.1.1. Internal combustion engine powertrain

The most common type of powertrain today is the internal combustion engine powertrain [8]. While engine designs may vary depending on the fuel type, the structure of the powertrain is nearly identical, so we can discuss internal combustion engine powertrains in a general sense.

2.1.2. Parallel hybrid powertrain

One of the most common types of hybrid vehicles among passenger cars is the parallel hybrid electric vehicle - PHEV– *It should not be confused with the abbreviation for the term "Plug-in Hybrid Electric Vehicle."* [9]. The PHEV is particularly popular for urban and suburban use [10], as the electric motor handles most of the propulsion at low speeds, the vehicle consumes less fuel, and thus transportation costs are lower.

2.1.3. Series hybrid powertrain

The series hybrid powertrain is less common in motor vehicles due to its unique design and characteristics [11]. It is primarily used in small city cars and buses [12, 13]. This is because the internal combustion engine does not drive the wheels directly, but only drives a generator, which either converts the generated energy into power for the wheels or stores it in a battery.

2.1.4. Axle-split hybrid powertrain

A vehicle equipped with an axle-split drivetrain (Axle-Split Hybrid Vehicle – ASHEV) has a more complex design, as the two separate axles are driven by two different motors, operating mechanically independently of one another [14]. An electronic control unit coordinates the operation of the two drivetrains. The vehicle can operate the two motors separately (front-wheel or rear-wheel drive) or simultaneously (all-wheel drive).

2.1.5. Power-split hybrid powertrain

Of the systems listed in this paper, the least conventional powertrain is the power-split hybrid (Power-Split Hybrid Electric Vehicle – PSHEV), which is enjoying tremendous success today [15]. The system combines the architectures of series and parallel hybrids, with its distinctive feature being planetary gear-based torque distribution [16].

2.1.6. Electric powertrain

An electric vehicle, as its name suggests, has a fully electric powertrain [17]. This is an increasingly popular solution for public transportation [18], with the advantages that a very high percentage of the energy used can be converted into useful work [19], zero local emissions, and excellent torque delivery thanks to the flexible arrangement of the motor(s) [20, 21].

2.2. Control engineering solutions for driver assistance systems

Nowadays, most cars come equipped with a variety of driver-assistance systems, many of which are now mandatory [22].

2.2.1. Driver assistance systems

Examples of driver-assistance systems include the anti-lock braking system (ABS) [23] and lane-keeping assist (LKA) [24]. A system that can be used both in and outside of cities is adaptive cruise control [25]. With this feature activated, once the desired speed is reached, the driver does not need to worry about speed control, as the vehicle maintains the set speed. An advanced version of the CC system is adaptive cruise control [26], which differs from conventional cruise control in that it not only maintains the set speed but also maintains a safe distance from the vehicle ahead. ACC offers comfortable driving experience even at high speeds, as the driver does not need to react to minor changes in traffic, and in the city, driving in traffic jams can become more

bearable. The ACC system has certain safety and comfort restrictions. For example, it is strictly required that the vehicle maintains a three-second following distance [27], the system must determine the appropriate following speed while taking this restriction into account. In addition, for the comfort of passengers, it is mandatory to define a maximum allowable rate of acceleration and deceleration [28].

2.2.2. LQ control

LQ control is one of the fundamental methods of modern control theory, used to solve optimal control problems. The goal of this method is to stabilize a linear system around a specified reference value while minimizing the quadratically weighted cost of the states and control signals. Optimal control is thus based on linear feedback of the state vector, which guarantees system stability and cost minimization. The resulting control law ensures that the system converges toward the steady state for any initial condition. The advantages of the LQ controller include simplicity, guaranteed stability, and the fact that the method is well-suited for a wide range of linear systems [29]. The LQ controller can take two forms: offline and online LQ [30]. A characteristic of the offline LQ controller is that the feedback matrix is calculated in advance. This reduces the computational load on the controller; however, if the system parameters change, the offline configuration is less flexible. In contrast, the online LQ controller calculates the feedback matrix in real time. This is computationally intensive, but the system is more flexible and robust.

2.3. Software used

During testing, the virtual environment enables the safe, reproducible, and cost-effective evaluation of complex traffic situations and control algorithms. The simulations were run in IPG CarMaker software. This is an advanced vehicle dynamics simulation software primarily used for automotive development and research. The program enables realistic modeling of the entire passenger vehicle, its subsystems, and the driving environment. With CarMaker, engineers can create virtual prototypes, allowing various concepts to be tested in simulations even in the early stages of the development process. The software supports detailed analysis of vehicle dynamics, the powertrain, the suspension, and ADAS systems. CarMaker has an open architecture, making it easy to integrate with other engineering tools

and environments. Of particular importance is its interoperability with Simulink, which allows users to test their own control algorithms directly within the vehicle model [31]. Controllers written in Simulink can be run directly within the CarMaker simulation environment, thus supporting both hardware-in-the-loop (HIL) and software-in-the-loop (SIL) testing. Thanks to this, developers can also incorporate real control units into the simulation [32].

2.4. Mathematical tools

Three parameters (vehicle type, drivetrain, and traffic situation), are examined here, and six measurements are available for each combination. This provides ample opportunity for the effective application of statistical methods. A fundamental step in analyzing the data is determining the mean value, median, and range [33].

The box plot is one of the fundamental graphical tools of descriptive statistics, providing a visual representation of the distribution of a data set. The central element of the figure is the “box,” which indicates the range between the first and third quartiles. The line within the box represents the median, which is the typical value. The minimum and maximum values are indicated below and above the box, while the points outside these are outliers. The advantage of the box plot is that it provides information simultaneously on central tendency, dispersion, and any outliers [34].

A radial chart is a form of graphical representation that displays the values of multiple variables on axes radiating from a common center. Each axis represents a different dimension, and connecting the values forms a polygon. This polygon visually illustrates how balanced or distorted the given profile is. The advantage of the radial chart is that it allows for the comparison of multiple aspects simultaneously. The shape and area of the polygon can provide information about overall performance: a larger, more regular area indicates balanced and high-level results, while a smaller or distorted shape reflects weaker or uneven performance. For this reason, the radial chart is particularly useful for comparing complex systems where multiple dimensions must be considered simultaneously [35].

Calculating the area of a polygon using the Shoelace (Gaussian) formula is based on the principle that the area can be obtained as the sum of the cross-products of the polygon's polar coordinates, and then the absolute value of this sum is halved. Thus, given a number n of angles and the coordi-

nates (x, y) of the vertices, the area can be calculated according to Equation (1), which is a dimensionless quantity created solely for the purpose of comparison:

$$T = \frac{1}{2} \left| \sum_{i=1}^n (x_i y_{i+1} - x_{i+1} y_i) \right|, \tag{1}$$

where: $x_{n+1}=x_1$ and $y_{n+1}=y_1$.

2.5. Methodology

In this thesis, I examined the fuel consumption of six different types of vehicles with six different powertrains in four types of traffic situations, with the ACC system both on and off.
Simulation parameters were selected based on the data in Table 1., 2. and 3.

Table 1. Table listing the vehicles used in the simulations.

Vehicle type	Vehicle model
Hatchback	Honda Fit
Sedan	BMW 5
Van	Mercedes Vito
Pickup	Toyota Tacoma
SUV	Volvo XC90
Kombi	Renault Megane

Table 2. List of drivetrains used in the simulations.

Powertrain type
ICE
PHEV
SEHV
ASHEV
PSHEV
EV

Table 3. Description of traffic scenarios used in the simulations.

Traffic scenario
Following on a flat highway
Following on a flat rural road
Speed reduction zone
Following on a highway with varying terrain

To assess the fuel and electricity consumption required to power vehicles during a given simulation, the units of measurement for consumption must first be standardized. The unit of measurement for fuel consumption is l/100 km, while the unit of measurement for electricity consumption is kWh/100 km. A conversion factor can be established between these two units, which expresses fuel consumption in kWh/100 km as well. [36, 37]

3. Implementation

3.1. The Simulink ACC System

When the CarMaker project is created, the Simulink model is generated automatically. This enables SIL operation.
Vehicle parameters read from the previous simulation step are received via one data bus and then transmitted from the model to the next step via another bus. Between these two, the ACC system was created, which reads the incoming current speed as well as the accelerator and brake pedal positions. In addition to these, the system’s inputs also include the simulated sensor (which provides the distance and speed relative to the vehicle ahead) and the preset reference speed.
The first main component of the ACC system is the activation unit. If the vehicle’s speed is significantly below the set value, it is not advisable to activate the function, as the controller would take a very long time to reach the reference speed.
The next component is the reference speed preset unit. This is determined in two steps. First, the system checks whether the sensor detects a vehicle ahead. If so, the desired speed adopts the speed of the vehicle ahead, provided it does not exceed the preset speed. If there is no vehicle in front of the sensor, the desired speed becomes the preset speed. It calculates an error from the difference between the desired speed and the current speed, i.e., the amount of acceleration or deceleration required. In the second step, the system examines the calculated speed difference. If this value falls outside the minimum or maximum limits, the reference speed is set to the current speed plus or minus the given threshold value.
The LQ controller calculates the acceleration required to reach the reference speed. Its input is the difference between the set speed and the actual speed, and its output is an acceleration value. An offline LQ controller was used because the computational and time requirements for the simulations would have been too high with an on-

line controller. Thus, the controller weights were determined through heuristic pre-testing.

The final component is the pedal position actuator subsystem. Its main function is to divide the received pedal position value into two ranges. The positive range determines the accelerator pedal position, while the negative range determines the degree of braking. In addition, the subsystem includes a switch that transmits the pedal positions received at the input when the ACC is off, as well as a subsystem component designed for fuel consumption optimization, which, when following another vehicle and under certain speed differences, does not intervene with any pedal position. This thereby avoids rapid acceleration and deceleration occurring within a short period of time.

3.2. Evaluation of consumption data

With the ACC on and off, three simulations were run for each combination of vehicle type and drivetrain configuration. Fuel consumption values obtained from the simulations with identical parameters were averaged, also examining how long it took the vehicle to complete the simulation. There was never a significant difference in simulation times, so subsequent analyses disregarded

Table 4. Reference table used to determine the k_e value.

Range of percentage difference	k_e	Range of percentage difference	k_e
$(-\infty, -14]$	1	$(2, 6]$	6
$(-14, -10]$	2	$(6, 10]$	7
$(-10, -6]$	3	$(10, 14]$	8
$(-6, -2]$	4	$(14, +\infty)$	9
$(-2, 2]$	5		

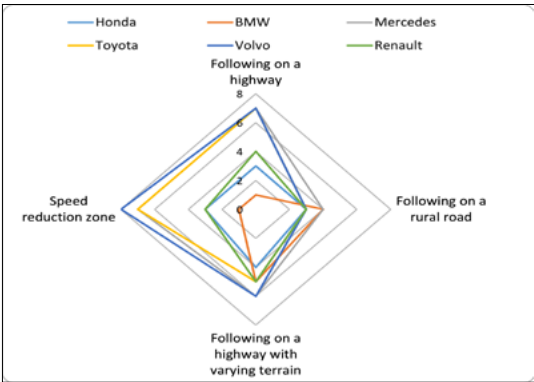


Fig. 1. ICE radial chart based on different vehicle types and traffic conditions.

that aspect. From the average fuel consumption of simulations with identical parameters, a percentage difference was determined between simulations run with ACC on and off. The magnitude of this difference determines the defined quality factor (k_e), which takes values between 1 and 9 as shown in Table 4. The accuracy factor allows for a uniform comparison of the ACC’s effectiveness across simulations with different parameters.

4. Results

Radial charts can be created for the six different powertrain types (ICE – I, PHEV – P, SHEV – S, ASHEV – AS, PSHEV – PS, EV – E). The areas of the charts indicate how the performance of the different powertrain types compare to one another. I examined the differences between the powertrains in four traffic scenarios using six vehicle types (Honda – H, BMW – B, Mercedes – M, Toyota – T, Volvo – V, Renault – R); the results are presented in Table 5. A typical radial chart is shown in Fig. 1 which presents a comparison of internal combustion engine simulations.

The performance of the various powertrains is shown in Fig. 2. The box plot shows seven outli-

Table 5. Areas of the radial charts from simulations compared based on different powertrain types

	I	P	S	AS	PS	E
H	21	70	81	45	153	91
B	15	70	136	84	93	84
M	71	82	127	90	102	78
T	60	90	117	96	108	97
V	71	84	153	82	96	97
R	27	66	144	82	135	84

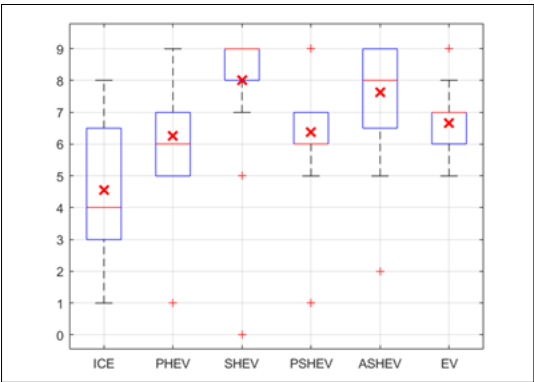


Fig. 2. Results compared based on drivetrains, presented using a box plot.

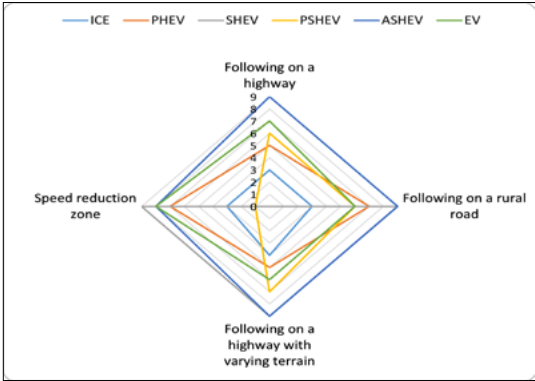


Fig. 3. Radial chart of a hatchback based on different vehicle types and traffic conditions.

Table 6. Areas of the radiation diagrams from simulations compared across different vehicle types

	<i>H</i>	<i>B</i>	<i>M</i>	<i>T</i>	<i>V</i>	<i>R</i>
<i>I</i>	21	15	71	60	71	27
<i>P</i>	70	70	82	90	94	66
<i>S</i>	81	136	127	117	153	144
<i>AS</i>	45	84	90	96	82	82
<i>PS</i>	153	93	102	108	96	135
<i>E</i>	91	84	78	97	97	84

ers. In one of these cases, the vehicle was unable to complete the simulation because its battery ran out. Apart from one powertrain type, all of them have an average rating above 5, meaning energy consumption is more favorable than with the ACC turned off.

Just as in the previous examples, the area comparison method using a radial chart can also be applied to compare different vehicle types (Honda – *H*, BMW – *B*, Mercedes – *M*, Toyota – *T*, Volvo – *V*, Renault – *R*). Assessment was made of the differences between vehicle types across four traffic scenarios and six powertrain types (ICE – *I*, PHEV – *P*, SHEV – *S*, ASHEV – *AS*, PSHEV – *PS*, EV – *E*), with the results presented in Table 6. The ray diagram for the hatchback vehicle is shown in Fig. 3.

The performance of the various powertrains is shown in Fig. 4. The average fuel efficiency of all vehicle types falls between 6 and 7, meaning that fuel consumption is, on average, 2–10% better when the ACC system is activated. This indicates that the ACC system performs consistently well regardless of the vehicle type.

The same procedure described above was followed when comparing the traffic situations. The

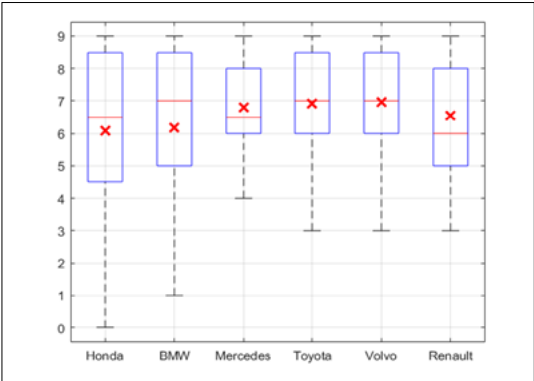


Fig. 4. Results compared by vehicle type, presented using a box plot.

Table 7. Areas of the radial charts from simulations compared based on different traffic scenarios.

	1.	2.	3.	4.
<i>I</i>	64	29	69	64
<i>P</i>	64	115	91	139
<i>S</i>	90	187	180	210
<i>AS</i>	88	103	104	130
<i>PS</i>	148	173	141	143
<i>E</i>	99	98	110	159

four scenarios were examined (following on a highway – 1, following on a rural road – 2, following on a highway with varying terrain – 3, speed reduction zone – 4) for six vehicle types, each with six powertrain types (ICE – *I*, PHEV – *P*, SHEV – *S*, ASHEV – *AS*, PSHEV – *PS*, EV – *E*). The results are presented in Table 7. The ray diagram for the traffic situation labeled “following on a country road” is shown in Fig. 5.

The performance results achieved in various traffic situations are shown in Fig. 6. In all traffic situations, an increase of at least 2% is observed, meaning that in most cases, the performance is good. In Scenario 4, the performance index is exceptionally high, while in Scenario 1, it is the lowest. In Scenario 2 and 3, the values are very close to each other. From this variation, it can be concluded that the ACC system does not operate consistently across traffic situations.

5. Conclusions

For every vehicle type, drivetrain type, and traffic situation, the largest possible total coverage area values—and those that are as close together

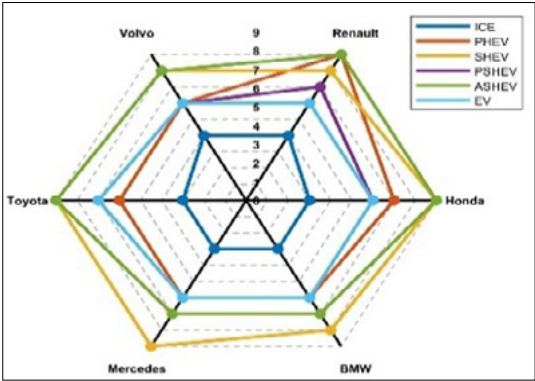


Fig. 5. A radial chart of a traffic scenario called "Following on a Highway," based on different powertrain types and vehicle types

as possible—indicate a universally successful ACC design.

For all three parameters examined, I calculated the sum of the maximum possible areas, then examined how the achieved total areas in the three cases compare to the given maximum, providing a final completeness (T_v). For every vehicle type, drivetrain type, and traffic situation, the largest possible total coverage area values—and those that are as close together as possible—indicate a universally successful ACC design.

For all three parameters examined, I calculated the sum of the maximum possible areas, then examined how the achieved total areas in the three cases compare to the given maximum, providing a final completeness Table 8. Each completeness index is above 50%, which, interpreted as an improvement in energy efficiency, represents an increase of approximately 4.6%. Therefore, it can be stated that the planned ACC system is successful, but there is still ample room for improvement.

There are several avenues for further development. On the one hand, the ACC can be fine-tuned for one or more specific parameters. On the other hand, the ACC system itself can be further enhanced, such as by transforming it into a fully autonomous longitudinal driving system (effective response to situations involving rapid acceleration and deceleration, start/stop function, etc.), or by implementing it into a lateral model (accounting for lateral acceleration). The LQ controller can also be further developed by introducing additional input parameters, such as pedal position difference or acceleration difference. Another direction for further development is increasing the complexity of the performance metric, such as examining emissions or the cost of fuel production.

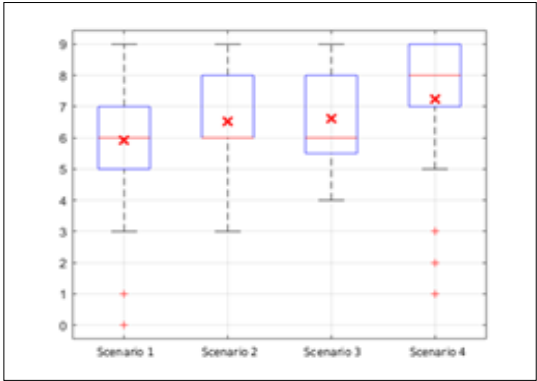


Fig. 6. Results compared based on traffic scenarios, presented using a box plot.

Table 8. T_v values for the three examined parameters

Parameter under test	T_v (%)
Vehicle type	54.66
Drivetrain type	54.67
Traffic situation	55.64

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GEOMETRICAL ANALYSIS OF A 4-DOF PARALLEL ROBOT

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Abstract

The thesis presents the development of the geometric and kinematic model of a 4-DOF parallel robot. The mechanism consists of two symmetric closed kinematic chains and provides three translational and one rotational degree of freedom through four actuated joints. The model was established using the Denavit–Hartenberg parametrization method, enabling the determination of the closed-form formulation of the forward kinematics. The inverse kinematic model was derived geometrically by exploiting the structural symmetry of the mechanism. The mathematical model was implemented in MATLAB, including a graphical user interface and a simple trajectory-tracking function. The developed system provides a basis for further workspace and dynamic analyses.

Keywords: *parallel robot, kinematic modelling, Denavit–Hartenberg parameterization, inverse kinematics, MATLAB application.*

1. Introduction

Parallel kinematic robots have become a prominent research area in robotics in recent decades due to their high stiffness, favourable payload-to-weight ratio, and high positioning accuracy [1]. In contrast to serial robots – which are more widespread in industrial applications [2] – in parallel structures, the end-effector is connected to the base via multiple parallel kinematic chains. This structure reduces the moving mass and improves dynamic properties [3].

One of the most well-known examples of parallel manipulators is the Stewart platform, described by Stewart for flight simulation applications [4]. Compared to full six-degree-of-freedom (6-DOF) systems, it is sufficient to use reduced-degree-of-freedom configurations in many industrial and research applications. This is confirmed by the International Federation of Robotics, based on a reference from the Balluff company [2], which states that the second most common type of robot in the industry is the four-degree-of-freedom SCARA. In the case of four-degree-of-freedom (4-DOF) mechanisms, typically three translations and one rotation are realized. Such systems of-

fer a favourable compromise between structural simplicity and functionality [3].

The basis for designing parallel robots is an accurate geometric and kinematic model. During kinematic analysis, we distinguish between direct (forward) and inverse kinematic modelling. In the case of parallel manipulators, inverse kinematics can often be determined in a closed form, whereas direct kinematics usually requires the solution of a system of nonlinear equations [1].

The Denavit–Hartenberg parameterization is a widely used method for the systematic geometric description of kinematic chains [5]. In this work, the Denavit–Hartenberg parameters of the investigated four-degree-of-freedom parallel robot were determined and then closed-form inverse kinematic equations were derived based on geometric relationships.

The model was implemented in the MATLAB environment, which provides an efficient tool for matrix operations, symbolic calculations, and spatial visualization [6]. The developed simulation application allows the spatial visualization of the robot's configuration using both the direct and inverse kinematic models.

The aim of the thesis is to determine and simulate the geometric model of the investigated four-degree-of-freedom parallel robot by creating a MATLAB-based application.

2. Proposed topology

The topology of the robot has four degrees of freedom, and accordingly, it has four active joints: two translational and two rotational joints. The mechanism is composed of two interconnected kinematic chains, which together contain ten—five per chain—passive joints. The structural layout of the system is illustrated in Fig. 1.

The first step in determining the kinematic model is defining the world coordinate system, which provides the fixed reference frame for the entire mechanical system. Within this global reference system, the position and orientation of the robot's base are fixed, and the local coordinate systems assigned to each joint are defined relative to it [3]. The description of robot mechanisms in this manner is based on the generally accepted formalism of rigid body kinematics [7].

The world coordinate system was determined as illustrated in Fig. 2. The direction of the $\vec{y}_0$ axis was chosen to match the direction of motion of the linear (translational) joints, while the $\vec{z}_0$ axis points vertically upwards. The $\vec{x}_0$ axis was defined to satisfy the requirements of a right-handed coordinate system [7].

The placement of the origin of the coordinate system takes into consideration geometric symmetry and computational simplicity: the y axis was placed in the centerline of the two linear guide rails, while the z coordinate of the origin is aligned with the theoretically highest point reachable by the robot's end-effector. This choice facilitates the formulation of kinematic equations and the interpretation of the workspace [3].

2.1. Direct kinematics

The most widely used method in the technical literature for determining direct kinematics is the Denavit–Hartenberg parameterization, which provides a systematic and structured procedure for modelling serial kinematic chains [5]. The method was introduced by Jacques Denavit and Richard S. Hartenberg and has since become a fundamental tool in robotics kinematics.

As a first step in formulating the model, a local coordinate system is assigned to each joint in accordance with the Denavit–Hartenberg rules [5]. Based on the topological analysis of the structure, it can be observed that certain pairs of passive

joints—between which no relative degree of freedom appears—can be treated as a single equivalent joint from a modelling perspective. This consolidation reduces the number of model parameters and simplifies the analytical description without affecting the kinematic behaviour [3].

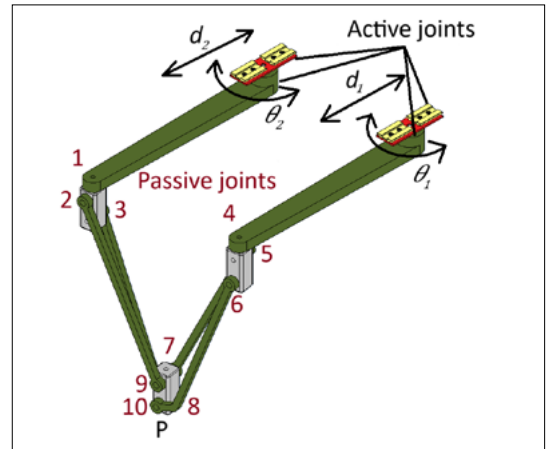


Fig. 1. Robot arm topology.

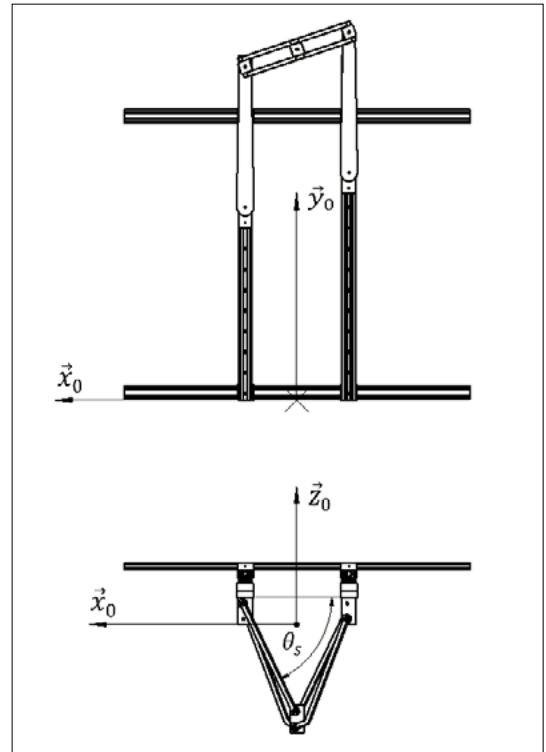


Fig. 2. Position and orientation of the world coordinate system.

The two kinematic chains will hereinafter be distinguished by the indices j and b , depending on whether they are located on the right or left side when looking in the positive direction of the world coordinate system's $\vec{y}_0$ axis. The application of such notation conventions facilitates the discussion of symmetric mechanisms.

The spatial relationship between the coordinate systems assigned to adjacent joints can be described by homogeneous transformation matrices, which uniformly contain the components of rigid body translation and rotation [7]. The complete direct kinematic mapping is determined by the successive product of the partial transformations. The specific position and orientation of the coordinate systems are illustrated in Fig. 3, along with the translational Denavit-Hartenberg parameters.

Since the origin of the world coordinate system and the axes of the first—linear—joints are not located at the same height, introducing an auxiliary coordinate system is necessary for the consistent determination of the Denavit–Hartenberg parameters [5, 7]. This intermediate system ensures that the parameterization meets the formal requirements of the method, and the transformation chain can be written in a uniform format.

The Denavit–Hartenberg parameters of the left kinematic chain are given in Table 1, while the parameters of the right chain are in Table 2.

The tables provide the four classical Denavit–Hartenberg parameters assigned to the i -th coordinate system [5]:

- α_{i-1} is the angle between the z_{i-1} and z_i axes measured around the x_{i-1} axis;
- a_{i-1} is the distance between the origins of the $\{i-1\}$ and $\{i\}$ systems along the x_{i-1} axis;
- θ_i is the angle between the x_{i-1} and x_i axes around the z_i axis;
- d_i is the offset between the x_{i-1} and x_i axes in the direction of the z_i axis.

These parameters uniquely determine the homogeneous transformation matrices between adjacent coordinate systems, and thereby the direct mapping of the entire kinematic chain [3, 7].

In the tables, θ_1 and θ_2 denote the angles of the active, controlled rotational joints, while d_1 and d_2 denote the magnitudes of the displacements of the active translational joints. To determine the coordinate systems, the rotation angles of the passive joints were also introduced with the notation θ_p and θ_s . The parameter θ_p is also equivalent to the rotation of the end-effector around the z_0

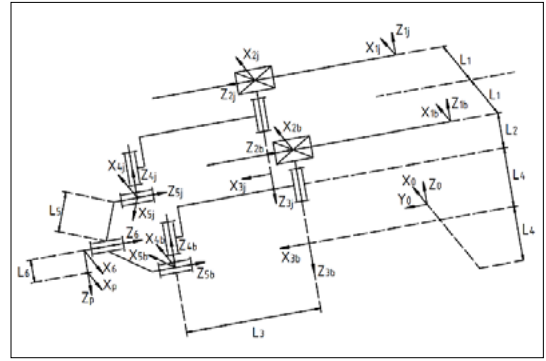


Fig. 3. Representation of the robot's Denavit-Hartenberg parameters.

Table 1. Denavit-Hartenberg parameters of the left kinematic chain

DH	α_{i-1}	a_{i-1}	θ_i	d_i
1.	0	$-L_1$	0	$L_2 + 2L_4$
2.	$-\pi/2$	0	0	d_1
3.	$-\pi/2$	0	$-\theta_1$	$L_2 + L_4$
4.	π	L_3	$-\theta_1 + \theta_p$	0
5.	$\pi/2$	0	$-\theta_s$	0
6.	0	L_5	$\theta_s + \pi$	0
TCP	$-\pi/2$	0	0	L_6

Table 2. Denavit-Hartenberg parameters of the right kinematic chain

DH	α_{i-1}	a_{i-1}	θ_i	d_i
1.	0	L_1	0	$L_2 + 2L_4$
2.	$-\pi/2$	0	0	d_2
3.	$-\pi/2$	0	$-\theta_2$	$L_2 + L_4$
4.	π	L_3	$-\theta_2 + \theta_p$	0
5.	$\pi/2$	0	$\theta_s + \pi$	0
6.	0	L_5	$-\theta_s$	0
TCP	$-\pi/2$	0	0	L_6

tengely körüli elfordulásával is ekvivalens, így a rendszer negyedik szabadságfokát reprezentálja.

A passzív csuklósögek nem független változók, hanem a zárt kinematikai lánc geometriai kényszereiből adódóan az aktív csuklókoordináták függvényeként határozhatók meg axis, thus representing the fourth degree of freedom of the end-effector.

The passive joint angles are not independent variables but can be determined as a function of the active joint coordinates due to the geometric

constraints of the closed kinematic chain [1, 4]. Their values were calculated based on the geometric relationships given in equations (1)-(4), which can be derived from trigonometric relations written in the planar projection of the chain.

$$\theta_p = \arctan\left(\frac{D_{jb_4}^{y_0}}{D_{jb_4}^{x_0}}\right) \quad (1)$$

$$\theta_s = \arctan\left(\frac{\sqrt{4L_5^2 - D_{jb_4}^{x_0} - D_{jb_4}^{y_0}}}{\sqrt{D_{jb_4}^{x_0} + D_{jb_4}^{y_0}}}\right) \quad (2)$$

$$D_{jb_4}^{x_0} = 2L_1 + L_3(\cos(\theta_2) - \cos(\theta_1)) \quad (3)$$

$$D_{jb_4}^{y_0} = d_2 - d_1 + L_3(\sin(\theta_2) - \sin(\theta_1)) \quad (4)$$

The above parameters and constraint equations together enable the complete determination of the direct kinematic mapping of the system as the product of homogeneous transformations. The results of the products are illustrated in equations (5)-(7), where $\vec{r}$ determines the position of the end-effector, while the R matrix determines its orientation in the world coordinate system.

$$\vec{r} = \begin{pmatrix} L_1 + L_3 \cos(\theta_2) - L_5 \cos(\theta_p) \cos(\theta_s) \\ d_2 + L_3 \sin(\theta_2) - L_5 \sin(\theta_p) \cos(\theta_s) \\ L_4 - L_6 - L_5 \sin(\theta_s) \end{pmatrix} \quad (5)$$

$$R = \begin{pmatrix} \cos(\theta_p) & -\sin(\theta_p) & 0 \\ -\sin(\theta_p) & \cos(\theta_p) & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad (6)$$

$$Th_0^p = \begin{pmatrix} R_{3 \times 3} & \vec{r}_{3 \times 1} \\ \vec{0}_{1 \times 3} & 1 \end{pmatrix} \quad (7)$$

2.2. Inverse kinematics

The inverse geometric model aims to determine the inverse of the direct mapping, meaning the position and orientation of the end-effector are given, from which the necessary joint variables must be calculated. The inverse model generally represents a system of nonlinear equations, which can yield multiple solutions, and singularities may occur in certain configurations. The model was determined taking into account the topological features of the structure.

To create the inverse kinematic model, the positions of the coordinate systems illustrated in Fig. 3 were calculated in the world coordinate system. The first system is the 6th, which only has an offset along the z axis relative to P, i.e., the end-effector's system. The height along the z axis of the left and right 5th coordinate systems is known (L_4), while to determine their x and y

coordinates, we had to calculate half the distance between the right and left 5th systems. Knowing that the end-effector will always be in line with this midpoint, we thus know one of the catheti ($z_5 - z_6$) and the hypotenuse (L_5) as well. The origins of the 4th systems coincide with the origins of the 5th ones, so they do not need to be calculated.

$$D_{5P}^{x_4} = \sqrt{L_5^2 - (L_6 - L_4 + z_p)^2} \quad (8)$$

$$Ob_5 = \begin{pmatrix} x_p + \cos(\theta_p + \pi) D_{5P}^{x_4} \\ y_p + \sin(\theta_p + \pi) D_{5P}^{x_4} \\ L_4 \end{pmatrix} \quad (9)$$

$$Oj_5 = \begin{pmatrix} x_p + \cos(\theta_p) D_{5P}^{x_4} \\ y_p + \sin(\theta_p) D_{5P}^{x_4} \\ L_4 \end{pmatrix} \quad (10)$$

To calculate the 3rd coordinate systems, we define a circle each using geometric equations such that the 5th systems are the center points of the circles and their radius is of size L_3 . These circles are intersected by the lines defined by the linear joints ($x = \pm L_1$), and these intersection points determine the position of the origin of the 3rd coordinate systems. The position of the origin in the world coordinate system is illustrated by equations.

$$d_1 = y_{b_3} = y_{b_5} - \sqrt{L_3^2 - (-L_1 - x_{b_5})^2} \quad (11)$$

$$d_2 = y_{j_3} = y_{j_5} - \sqrt{L_3^2 - (L_1 - x_{j_5})^2} \quad (12)$$

$$Ob_3 = \begin{pmatrix} -L_1 \\ y_{b_3} \\ L_4 \end{pmatrix} \quad (13)$$

$$Oj_3 = \begin{pmatrix} L_1 \\ y_{j_3} \\ L_4 \end{pmatrix} \quad (14)$$

To determine the joint parameters, the position of the left and right 5th and 3rd systems is sufficient, whose y coordinate corresponds to the linear joint parameters d_1 and d_2 . The calculation of the rotational joint parameters θ_1 and θ_2 is illustrated by equations (15) and (16).

$$\theta_1 = \arctan\left(\frac{y_{b_5} - y_{b_3}}{x_{b_5} - x_{b_3}}\right) \quad (15)$$

$$\theta_2 = \arctan\left(\frac{y_{j_5} - y_{j_3}}{x_{j_5} - x_{j_3}}\right) \quad (16)$$

Determining the position of the further coordinate systems can be achieved with simple translations. Calculating these is only necessary for the graphical representation of the model.

3. Matlab application

To formulate the models and perform the necessary mathematical operations, we used the Matlab programming environment, which is capable of executing matrix-based calculations efficiently [6]. The handling of homogeneous transformation matrices, as well as the symbolic processing of nonlinear equations, significantly facilitated the derivation of the kinematic relationships. The results of the relationships are depicted by the built-in 3-dimensional graphical display (plot3). The models and their representation were implemented in a Matlab application, whose graphical user interface (GUI) is shown in Fig. 4.

The panel marked with number 1 contains the graphical representation of the kinematic models. The control interfaces marked 2 and 3 serve to set the input parameters for the inverse and direct models, respectively. The button labeled "Direkt" in Fig. 4 provides the option to switch between direct and inverse kinematic modes; in the event of a mode switch, the button's label dynamically changes accordingly, in this case to "Inverz".

The interface has also been supplemented with a basic trajectory tracking algorithm, which can be started by pressing the "Kör pálya" (Circular path) button. During the operation of the function, the system generates the points of a circular path and then tracks them successively with the joint variables calculated using the inverse kinematic model. The motion of the robot is displayed in graphical form on panel 1.

4. Conclusions

The aim of the thesis was the determination of the geometric and kinematic model of a four-degree-of-freedom parallel robot, as well as its MATLAB-based simulation implementation. The investigated mechanism consists of two symmetric kinematic chains with four active joints, which provide the end-effector with three translational and one rotational degrees of freedom.

During modelling, we determined the direct kinematic mapping by appropriately choosing the world coordinate system and applying the Denavit–Hartenberg parameterization. The inverse kinematic model was derived geometrically, enabling the analytical determination of the active

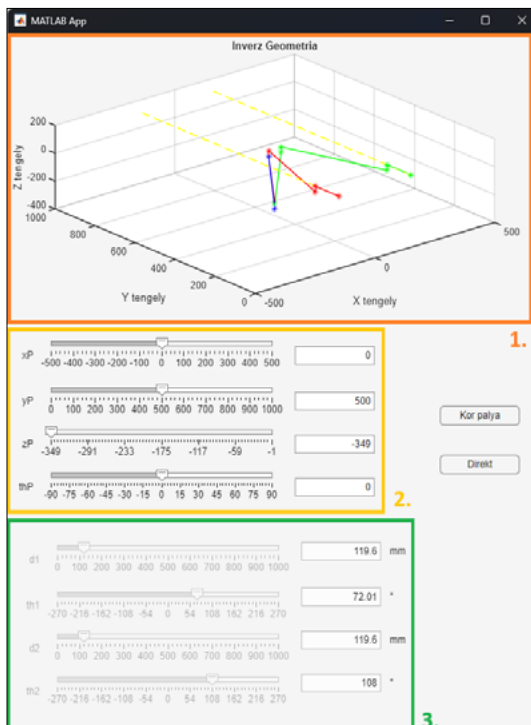


Fig. 4. Application's user interface.

joint parameters based on the prescribed end-point position and orientation.

Building on the mathematical model, an application with a graphical user interface was created, suitable for examining direct and inverse kinematics, as well as for simulating simple trajectory tracking tasks.

The developed model provides a suitable basis for further workspace, singularity, and dynamic investigations.

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LIGHTS OUT – LOGIC GAME

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Abstract

Lights Out is a logic puzzle game that was distributed in various versions by a company called Tiger Electronics between 1995 and 1998. Later, the production was taken over by a larger company, Hasbro, and the last version was released about two decades ago. The mathematical foundations of the game have been studied by several researchers. We aimed to extend the game by exploring the possibilities of manual solving, and to generalize and expand its mathematical model. To this end, we first developed a computer-based version, which made it easier to implement and test the mathematical background of the game in practice. Our future goal is to build a physical prototype constructed from 3D-printed components and controlled by a microcontroller, in order to test the gameplay experience of this new version.

Keywords: *Lights Out, logic game, system of linear equations, finite field $GF(n)$.*

1. Introduction

Lights Out is an electronic logic game, first released under this name by the American company Tiger Electronics in 1995 (Fig. 1). The game consists of a 5×5 grid of push buttons arranged in a square matrix, each of which can be either lit or unlit. When a button is pressed, its light changes state: if it was on, it turns off, and vice versa. However, pressing a button also changes the state of its neighbours arranged in a cross pattern: the buttons above, below, and to the left and right of the pressed button. At the beginning of the game, some lights are on, and the goal is to turn off all the lit buttons.

In later editions, the game was further developed. This led to the 4×4 Mini Lights Out, which introduced a toroidal (edge-free) layout, where the end of a row continues at the beginning of the same row, and the bottom of a column continues at the top of the same column. This can be imagined as playing the game on the surface of a ring (torus), where one can move continuously in both directions

In Lights Out 2000, released by Hasbro, a variant was introduced in which the lights have three

states: lit buttons are green, and between the off and green states there is an intermediate, red-lit state.

Later, a 6×6 version, called Lights Out Deluxe, was released, in which the effect of a button press

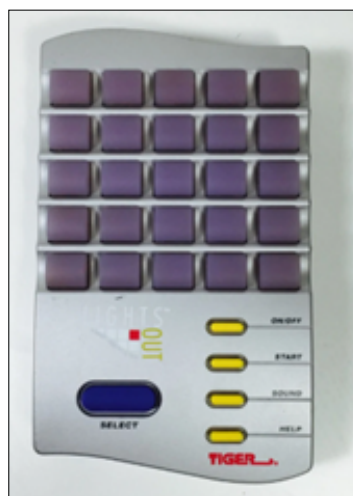


Fig. 1. The Lights Out released in 1995.

was extended to an X-shaped pattern: the four diagonally adjacent neighbours of the pressed button also change their state.

The game did not appear without precedent: Gábor Dávid, László Mérő, and Ferenc Szatmári developed a game essentially identical to the 1995 Lights Out around the time the Rubik's Cube was introduced. It was patented in 1982, and a year later it began to be manufactured in Hong Kong by a company called Vulcan Electronics under the name XL 25 (Fig. 2; the image is sourced from the Internet). Due to the technical conditions at the time, production in Hungary was not possible, but the game was also distributed there. This version of the game worked not only with the cross-shaped effect pattern but also included a “knight’s move” variant.

In the accompanying figures, the red cell represents the pressed button, and the yellow cells indicate the affected neighbours, shown in the three mentioned arrangements (Fig. 3).

Lights Out also has an even earlier predecessor, which was one of the first microcontroller-based games: Merlin, released in 1978 by the American company Parker Brothers. Among other games, it featured a Lights Out-like game that could be played on a 3×3 grid. This photograph (Fig. 4) is also sourced from the Internet.

2. The Objective of the Study

While studying the operational principle of the game, the idea arose to expand the playable variants. In theory, the pattern of lights affected by button presses, the number of states, and the size of the board can be varied arbitrarily, meaning that an infinite number of versions could be created. One of our objectives was to examine the possibilities for manual solutions when the game is extended.

Several researchers have studied the mathematical foundations of the game. After reviewing their work, we decided to extend and generalize the mathematical model for solving the game by machine.

Since it would be technically difficult to implement larger layouts as handheld games, the largest size studied for manual play remained 6×6 , although we introduced new variations in the patterns of the lights. Moreover, the player can create any pattern within a 3×3 section, which will then propagate through the rest of the game.



Fig. 2. The XL 25 released in 1982,

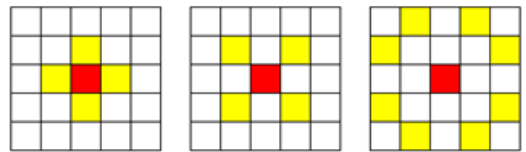


Fig. 3. The lights toggled by a button press



Fig. 4. The Merlin released in 1978.

3. Implementation

Developing and testing the game software on a PC is simpler than implementing it directly on a microcontroller. This led to the creation of a program whose user interface is shown in Fig. 5. In addition to the functions of commercially available games, the program allows a given state to be saved, so that the player can return to it with a single button press to restart the game from that point. It provides greater flexibility in set-

ting up the board layouts to be played, is suitable for calculating and displaying optimal (shortest) solutions, and can also identify solvable configurations. The latter proved to be an important tool in developing solution procedures.

The physical implementation of the game is still in progress. It will be based on an ESP32 micro-controller. The control elements displayed on the user interface of the software version will be replaced by push buttons. The lit buttons will be 3D-printed, with WS2812B RGB LEDs embedded inside. The game settings will be displayed on a small LCD screen.

4. Studied Cases

We focused on three basic types of symmetric patterns affected by button presses: the classic cross (+), the lesser-known X (×), and our custom-developed square (□). All three patterns can also be hollow (#), which is another of our innovations: in this case, the pressed button itself does not change state, so the center of the pattern is missing (Fig. 6).

At the same time, any version can be toroidal (no border, ∞), which means that when buttons on the edge rows, columns, or corners are pressed, the part of the pattern that would extend beyond the button grid appears on the opposite side. In Fig. 7 these are shown as red-marked cells, exemplifying the cross-shaped arrangement of the lights.

In addition, we revived the variant with three-state lights, extending its principle to lights with more states, as well as the “knight’s move” variant. As an experimental configuration, introduced mainly to gain a more detailed understanding of the mathematical properties of the game and to test the program, we also examined the placement of lights in asymmetric patterns, for example, in a triangular arrangement.

The button grid (the board) can be either square, when the number of rows and columns is the same, or rectangular. For example, in a 5×6 layout, the 30 buttons are arranged in 5 rows and 6 columns, while in the 6×5 version, the same number of buttons is arranged in 6 rows and 5 columns; these are versions rotated 90 degrees relative to each other. However, if we stick to the usual top-to-bottom reading order, the sequence of moves required to solve them will differ.

The game also has a “reverse” mode, in which the goal is the opposite: to turn on all the lights. In this context, one can make the following observation: in the literature on solving Lights Out,

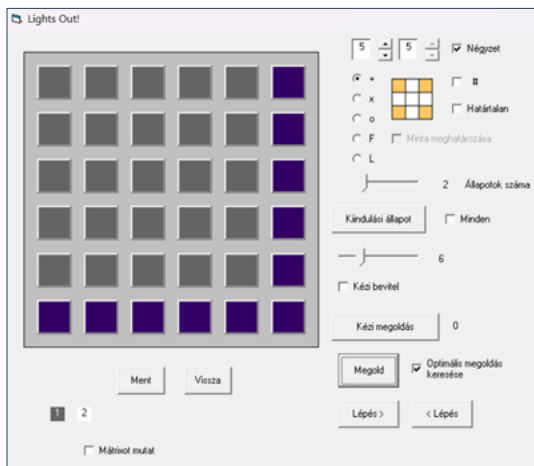


Fig. 5. The user interface of the computer version of the game.



Fig. 6. Patterns of lights affected by a single button press.

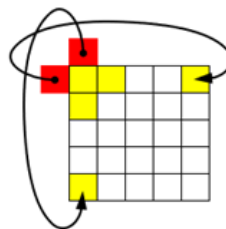


Fig. 7. The extent of the cross-shaped pattern of lights affected by a button press in the toroidal version.

it is often stated that the starting state in which all lights are on is always solvable. From this, it is concluded that from any state that can be solved by turning off all the lights, it is possible to turn all the lights on. This observation was originally made for the cross-shaped light arrangement. Based on our investigations, in the solutions listed for the effects of button presses, this statement does not always hold for the hollow versions. In other words, if a state is solvable in terms of turning off the lights, it is not necessarily possible to turn all the lights on from that state.

This observation is also important for generating solvable starting states. If we want the game to be winnable, then in the original version, where

the goal is to turn off all the lights, the starting state can be created by pressing a few buttons on a completely dark board, which will light up some of the lights.

In the reverse mode, where the goal is to turn on all the lights, the same procedure is applied to a fully lit board, where pressing a few buttons will turn some lights off. Both states are guaranteed to be solvable because pressing the same buttons again will restore the board to either the completely dark or completely lit state.

In the version running on the microcontroller, the program randomly decides which buttons to press to generate the solvable starting state, while the number of presses can be set by the player.

The number of possible starting states depends on the number of buttons and the number of states of the lights: if there are g buttons, then for n -state lights, the number of possible starting configurations is ng . In the studied cases with two-state lights, this number ranges from 2 (for a 1×1 layout) to 2^{36} (for a 6×6 layout); the latter is a very large number: 68,719,476,736.

In many cases, there is no solution for every possible starting state, meaning that there may exist configurations that cannot be solved. This should be kept in mind when manually entering starting states.

5. Possibilities for Manual Solution

With the Rubik's Cube, we can observe that if it has been scrambled with only two or three turns, it is relatively easy to identify these few moves and restore the cube to its solved state. The same applies to Lights Out: the effects of two or three button presses can still be traced back, but additional presses mix the lights so much that it is likely impossible to manually undo them.

For larger boards, the number of solvable starting states is too large to devise separate rules for manually solving each one. Similar to the Rubik's Cube, the solution can only be approached in smaller steps.

The solution depends on the size and pattern of the board, and the typical strategy involves creating a light arrangement that can later be handled with simple rules. We examined or developed manual solution methods for a total of 62 variants. In this article, we present four highlighted cases.

Beyond these 62 variants, the player also has the option to play on rectangular boards or to freely configure the lights in a 3×3 section. In these

cases, developing the solution rules is left to the player.

6. Manual Solution of the Classic Case

The classical manual solution follows the well-known “light chasing” method. In the first step, the lights are pushed down to the bottom row. In the second step, depending on the pattern formed in the bottom row, certain buttons in the upper rows are pressed, and the newly lit lights are again pushed down to the bottom row. In both steps, the procedure is carried out row by row, moving from top to bottom.

Generalizing the procedure, in the first step we press buttons in the second row under the lights that are lit in the top row. In the example shown in Fig. 8 the second and fourth buttons in the second row, marked with red X's, need to be pressed.

This rule can be relaxed: for instance, if the first two lights in the top row are on, pressing the button in the top-right corner will turn off both lights. Similarly, if three adjacent lights in the top row are on, pressing the middle one will turn off all three.

After turning off the lights in the first row, the second and third rows also change (Fig. 9). Next, we turn off the lights in the second row by pressing the buttons directly below them. The buttons in the second row cannot be pressed, because that would also affect the state of the lights in the row above, i.e., the already turned-off first row.

We continue row by row, moving downward. In the end, only the fifth row may have remaining lit lights (Fig. 10), although with a bit of luck, it is also possible to turn off all the lights in the first step.

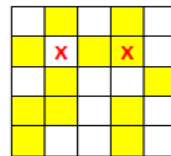


Fig. 8. A starting state.

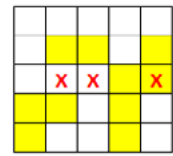


Fig. 9. The lights after pressing buttons in the second row.

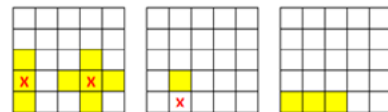


Fig. 10. The situation after the first step of light chasing.

In the 5×5 version, not every combination of lights is solvable. In solvable starting states, the lights in the bottom row can appear only in the arrangements listed in Fig. 11. Ignoring symmetric repetitions, there are five such states, or seven if symmetries are included. If the lights in the bottom row appear in any other configuration, the game has no solution.

The second step of light chasing is adjusted to the bottom row: to solve the game, it may be necessary to press the marked buttons in the top row, and then, using the light-chasing procedure, continue from the second row downward to the bottom row again. If everything is done correctly, all lights can be turned off. No buttons other than the marked ones in the top row should be pressed.

These rules can be established by starting from a state in which no lights are on, pressing a button in the top row, and then observing the pattern of lights that appears in the bottom row after applying the light-chasing procedure (Fig. 12). In this way, solutions for five out of the seven possible cases are immediately obtained.

However, if the two outer lights in the bottom row are on, pressing a single button in the top row is not sufficient to solve it. But if we press the first button (which toggles lights 2, 3, and 5 in the bottom row) and then the second button (which toggles lights 1, 2, and 3), the lights 2 and 3 remain unchanged due to the two consecutive back-and-forth toggles, and only the outermost lights 1 and 5 change. Thus, for the sixth case, the first and second buttons in the top row must be pressed. The seventh case is solved in a similar manner.

7. 6×6, Hollow Square, Toroidal (□#∞)

The hollow square, shown as the last pattern in Fig. 6 requires a significantly different solution method compared to the previous case (and the other studied cases) because, using the light-chasing method, two lights may remain unsolvable at the ends of rows due to the toroidal layout and the pattern of the lights. As a result, these lights cannot be pushed down into the lower rows. After the first step, we can observe various combinations of lights in the two rightmost columns and the two bottom rows.

If we examine the solvable states, we find that the lights appear in pairs, with a dark (unlit) button between the two lit buttons. One such pair can be seen in Fig. 13, along with the button presses required to turn them off. This requires

a relatively large number of presses—10 buttons in this case

Identifying the pairs can be tricky: if there are lights in three or more rows, they may also appear vertically. In Fig. 14 the red and blue pairs are arranged vertically. By breaking down the state after the first step into elementary pairs, the lights can be turned off relatively easily in the second step of light chasing, accepting the risk of repeated, unnecessary button presses. In the example, the five pairs would require fifty button presses. This can be simplified by eliminating repeated presses. While this would be difficult to do mentally, planning the solution on paper beforehand makes it much more manageable.

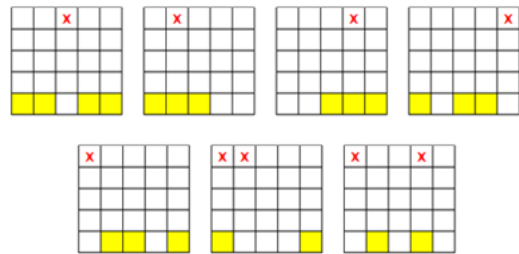


Fig. 11. The possible solvable states in the bottom row, and the button presses required in the top row to solve them.

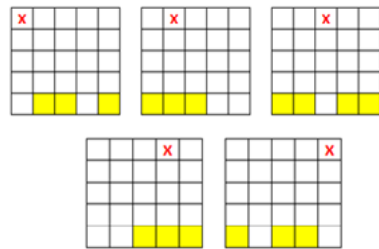


Fig. 12. Determining the button presses required to turn off the lights in the bottom row

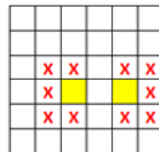


Fig. 13. A pair of lights and the button presses required to turn them off.

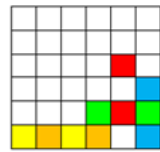


Fig. 14. Breaking down into pairs.

8. 5 × 5 with Knight’s Move

This is one of the configurations of the XL 25, which later versions of Lights Out did not adopt. The likely reason is the difficulty of solving it. The positions of the lights affected by a single button press are sufficiently complex to make it difficult even to recognize situations solvable with just one or two presses, since the effect of a press extends over a larger area, up to two rows or columns away from the pressed button. As a result, when using light chasing to push the lights downward, some lights may remain lit in the bottom two rows, and in some rows, not all lights can be turned off at once. Because any starting state is solvable in this variant, the number of possible combinations of lights after the first step is very large, making it impractical to develop solution methods based solely on the observed pattern. The feasible approach is to turn off the remaining lights one by one, which requires a lengthy procedure based on more complex schemes.

In Fig. 15 we can see the steps required to turn off a single light. These cannot be determined by the classic trial-and-error method. The figure shows the six basic cases, and for the other situations, these patterns must be rotated or mirrored. Since, as a result of pushing the lights downward according to the classical procedure, many lights may remain on (up to 13), and turning them off individually requires at least 9 and up to 16 button presses, it is more practical to first create a less orderly starting state with fewer lit lights. For example, pressing the lit buttons in the outermost rows and columns will turn them off, providing a chance to reduce the number of lit lights to four or five by repeating this process. These remaining lights can then be turned off using the six procedures shown in Fig. 15.

9. 5 × 5 with Three-State Lights

This feature appeared in the “Lights Out 2000” version, where pressing a button causes the lights to cycle as follows: from off (denoted 0) to red (1) on the first press, then to green (2) on the second press, and the third press turns the light off again. Thus, the three states follow a cyclic sequence 0→1→2→0... rather than toggling back and forth. To turn off a light in the intermediate state, two button presses are required. The effect of pressing a button still follows the classic “+” pattern, affecting the neighboring lights.

The solution procedure is not very different from the classic version: in the first step of light chasing, the lights are pushed down to the bottom row, where off, red, and green lights can all appear. Since some starting states are unsolvable, these lights in the bottom row can appear only in the eight arrangements shown in Fig. 16. It can be observed that these arrangements consist of same-color pairs, with their superposition rules: $r + r = g$, $g + g = r$, $r + g = 0$.

In the second step of light chasing, starting from these eight arrangements, all the lights must be turned off. By applying the method of tracking the effects of button presses in the top row, we arrive at the solution rules shown in the figure. In the figures, a red X indicates a single press, while a green X indicates a double press.

10. The Mathematical Solution

Three elements are needed for the calculations. The first of these is the $[K]_{m \times m}$ connection matrix, which has as many rows and columns as there are buttons in the studied layout (m = number of rows × number of columns). Each row of this matrix corresponds to a light, and the entries in

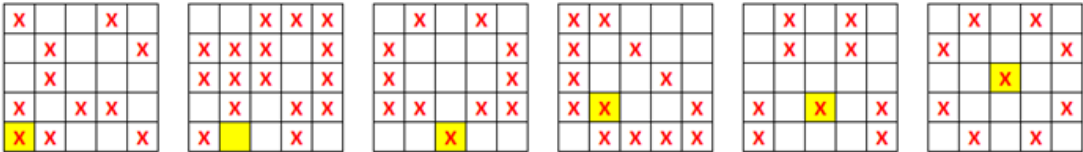


Fig. 15. Button presses required to turn off a given light.

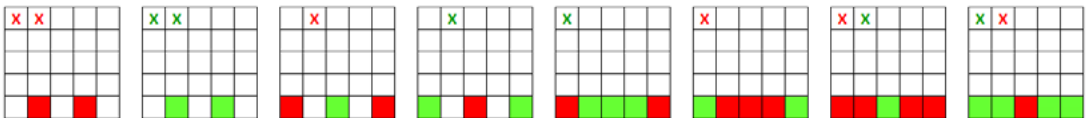


Fig. 16. Three-state lights at the end of the first step.

a row indicate which buttons affect the state of that light. Thus, the connection matrix is a square matrix containing only 0s and 1s. In the studied cases, with the exception of the triangular pattern, the effect of button presses is the same in both directions—we could say it is isotropic—so the placement of lit lights is symmetric both horizontally and vertically. As a result, the connection matrix is symmetric, meaning that if button i changes the state of button j , then button j also changes the state of button i .

If this symmetry is broken, as in the example of the triangular arrangement of lights (right side of Fig. 17), the connection matrix also loses its symmetry.

The second element needed for the mathematical solution is the state vector $\{A\}_m$ which stores the states of the lights. Each element of the state vector represents the number of steps needed to turn off a light. If the button state is x and the number of light states is nA , then the corresponding element of the vector is $nA - x$, assuming the light is not already off (if it is off, the element remains 0).

The third necessary element is also a vector, $\{G\}_m$, which indicates the buttons to be pressed to turn off the lights (i.e., how many times each button must be pressed for the solution).

These three quantities are related by the linear system $[K] \cdot \{G\} = \{A\}$. Its physical meaning is as follows: if we multiply the i -th row of the connection matrix by the button presses vector, the term $K_{ij} \cdot G_j$ gives how many steps the j -th light's state changes. The row-vector product, i.e., the sum of all $K_{ij} \cdot G_j$ terms, gives the total change in the state of the j -th light after pressing the buttons.

By solving this system, we aim to find the buttons to press given a known starting state. While this setup may seem familiar, it has a special feature: all three components can only take integer values between 0 and $nA - 1$. Therefore, the calculations must be performed over the set of numbers $\{0, 1, \dots, nA - 1\}$.

In the case of two-state lights, we are working over the two-element Galois field $GF(2)$, where

arithmetic is performed modulo 2. In $GF(2)$, every number has both an additive and a multiplicative inverse, so no arithmetic issues arise when solving the linear system using the Gauss–Jordan elimination.

An important point for Lights Out: adding 1 to a number gives the next element of the set, and if you add 1 to the last element, you wrap around to the first element (resulting in 0).

The same principle applies to three-state lights, where the solution is sought over $GF(3)$. From this, one might extrapolate that the general solution should be formulated over $GF(nA)$. However, for four-state lights, this does not hold. $GF(4)$ does exist, but its elements are not integers; they are $\{0, 1, \alpha, \alpha + 1\}$, where α and $\alpha + 1$ are the roots of the polynomial $x^2 + x + 1$ (these are formal elements, not numbers). At first glance, it might seem natural to treat α as “2” and $\alpha + 1$ as “3”, but in $GF(4)$ $0 + 1 = 1$, $1 + 1 = 0$, “2” + 1 = “3”, “3” + 1 = “2”. Thus, this does not reproduce the cyclic progression of the states. The same problem occurs whenever nA is the power of a prime.

From this, we conclude that for solving Lights Out, the key is not Galois-field arithmetic, but calculations modulo nA . This has a drawback: if nA is not prime, not every number has a multiplicative inverse. For example, in the four-state case $3^{-1} = 1$, but 2^{-1} does not exist modulo 4. Consequently, in Gauss–Jordan elimination, if a 2 appears on the diagonal, normalization cannot be performed, and attempting back-substitution can corrupt other rows (e.g., a row already normalized might need to be multiplied by 2, turning the diagonal 1 into 2).

When studying further cases, it must be noted that if nA is not a prime or a prime power, then it is not possible to form a Galois field with it. Therefore, for $nA = 6$, a different method must be devised. We could try calculating modulo 6, but the drawback is that 2, 3, and 4 do not have multiplicative inverses, which leads to a situation even more complicated than with four-state lights.

However, there is the Chinese Remainder Theorem (CRT), which can be applied to pairwise relatively prime numbers (since $6 = 2 \cdot 3$ and $\gcd(2, 3) = 1$, our case fits perfectly). According to this theorem, if $x \bmod m_1 = a_1$, $x \bmod m_2 = a_2$, etc., where $m_1, m_2, \dots$ are relatively prime, then $x = a_1 \cdot M_1 \cdot y_1 + a_2 \cdot M_2 \cdot y_2 + \dots$, where $M_i = M/m_i$, $M = m_1 \cdot m_2 \cdot \dots$, $M_i \cdot y_i = 1$, modulo m_i .

To apply this theorem, we solve the system twice, once modulo 2 and once modulo 3. Let the two solutions be $\{G_2\}$ and $\{G_3\}$. The solu-

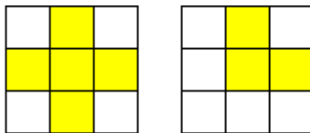


Fig. 17. Symmetric and non-symmetric arrangements of the lights.

tion modulo 6 is then given by the combination $\{G_6\} = 3 \cdot \{G_2\} + 4 \cdot \{G_3\}$.

We can generalize the observations as follows:

- if nA is prime, then we compute modulo nA , which is equivalent to working over $GF(nA)$;
- if nA is a prime power, we still compute modulo nA , but $GF(nA)$ cannot be used; consequently, the Gauss–Jordan procedure must be suitably modified;
- if nA is a composite number, then it must be decomposed into relatively prime factors. For each component we solve the system separately according to the previous two points, and the solutions are then combined using the Chinese Remainder Theorem.

Based on this, among the cases we studied the 2-, 3- and 5-state versions are straightforward to handle; $4=2^2$ is a prime power and can lead to situations that must be treated separately modulo 4; $6=2 \cdot 3$ requires solving twice (mod 2 and mod 3) and then combining the results (via the Chinese Remainder Theorem).

If we continue the sequence: 7 is prime, 8 and 9 are prime powers, $10=2 \cdot 5$ is a product of two primes, 11 is prime, $12=3 \cdot 4$ is a product of relatively prime factors, and so on.

The system of equations is solved by the Gauss–Jordan method. Proceeding from top to bottom, we try to normalize the diagonal entry. If the diagonal contains a zero or a non-invertible number (the latter can occur for four-state lights, where that number may be 2), we first try to swap rows to bring a 1 into the diagonal position, or if no 1 is available, an invertible number.

When row swaps do not solve the issue, we perform full pivoting (i.e. we also swap columns), while keeping track of the new order of the variables. If we run out of 1s and invertible numbers, we move a nonzero entry onto the diagonal.

When not every starting configuration is solvable, the last rows will contain only zeros (including on the diagonal). If such a row has a nonzero right-hand side, the starting configuration is unsolvable.

Fig. 18 shows the extended matrix of the linear system reduced in this manner, for the case of four-state lights. We can observe that in the first eight rows, the main diagonal contains ones, which means that the reduction and back-substitution have already been performed (in the first eight columns, only zeros appear outside the main diagonal).

In the next two rows, the main diagonal contains twos, so these rows cannot be normalized

and therefore cannot be reduced or back-substituted. These two rows are solved by trial and error, searching for the first possible solution. The first eight variables are taken as zero. For the remaining eight, we try all possible combinations, which in this case totals $48=65536$. This seems like a large number, but a computer-based method can quickly find the required solution. We first search for a possible solution for the first row, and once found, we check whether it also satisfies the second row. If not, we continue the search. In the example shown in the figure, one possible solution is the vector whose tenth element is 1 and all other elements are 0. Once a solution is found, the free term in row 9 is set to 0 and in row 10 to 1, the twos on the main diagonal are replaced with ones, and all other elements in these rows are zeroed.

The obtained solution is then back-substituted above and below these two rows: for example, the free term of the i -th row is updated by multiplying the corresponding element of the solution vector b_x with K_{ix} and moving this product to the right-hand side, giving a new value of $b_i - b_x \cdot K_{ix}$.

In Fig. 18 the six bottom rows contain only zeros (including the free terms), so the elements of the solution vector corresponding to these rows can be taken as zero.

In this way, the linear system, and therefore the initial state, is brought to one possible solution.

	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6
1	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1
2	0	1	0	0	0	0	0	0	0	3	0	2	3	2	3	2
3	0	0	1	0	0	0	0	0	0	0	3	0	0	3	0	3
4	0	0	0	1	0	0	0	0	0	0	3	3	2	3	2	3
5	0	0	0	0	1	0	0	0	0	3	0	3	3	0	2	0
6	0	0	0	0	0	1	0	0	1	0	1	0	0	1	0	0
7	0	0	0	0	0	0	1	0	0	3	0	3	2	0	3	0
8	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	1
9	0	0	0	0	0	0	0	0	2	0	2	0	0	2	0	2
0	0	0	0	0	0	0	0	0	0	2	0	2	2	0	2	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 18. Partially reduced form of the augmented matrix of the system of linear equations.

11. The Optimal Solution

The optimal solution requires pressing the fewest possible buttons. Even in simpler cases, finding it without any aids is quite difficult, and in more complex cases it is essentially impossible; it can only be achieved mathematically.

The mathematical background of this problem is related to solving an underdetermined linear system, where there are more unknowns than independent equations. Using Gauss-Jordan elimination, we obtained a possible particular solution $\{G_p\}$ of this system in which all freely selectable variables were set to zero. Due to the underdetermined nature of the system, multiple solutions exist. These can be expressed by solving the homogeneous linear system $[K] \cdot \{G\} = \{0\}$. If $\{G_h\}$ is a solution to this system, then $\{G_p\} + \{G_h\}$ represents a general solution to the linear system. Furthermore, any linear combination $\{G_p\} + \sum c_i \cdot \{G_{h_i}\}$ is also a solution. The set of solutions of the homogeneous system is called the “null space.”

If the variables were defined over an infinite set, such as the set of integers, the null space would have infinitely many elements (assuming the linear system is solvable). In our case, however, the variables can only take integer values from 0 to $nA - 1$, so the null space contains only a finite number of elements: if the reduced matrix of the linear system has n all-zero rows, then the number of possible arrangements for the freely selectable unknowns is nA^n .

If this number is not too large, the optimal solution can be found by searching the entire null space. For this, we generate basis vectors. Each basis vector has all entries equal to zero, except for one corresponding to a row in the null space, which takes a value between 1 and $nA - 1$. Using all possible combinations of these basis vectors, we solve the homogeneous linear system (only back-substitution is needed in the already reduced form), and for each combination, we count the number of button presses in the solution vector. The optimal solution is the one (or ones) where this number is minimal.

If this number is too large, searching the entire null space would be extremely costly. In some infinite 6×6 layouts, the number of zero rows was 20. In these cases, for six-state lights, the number of possible solutions would be 6^{20} , which is an extremely large number. In such situations, only a trial-and-error-based approach can be applied: we used a 10-step Greedy search, which in most cases led to the truly optimal or near-optimal

solution. The algorithm applied checks the basis vectors one by one, and if the result improves, it incorporates that vector into the solution. Since this creates a new state, the search is restarted nine more times, excluding the already incorporated basis vectors. The solution obtained at the end of the tenth step is considered the best achievable.

12. The Optimal Solution with a Manual Procedure

Based on the previous chapter, it becomes clear that manually finding the optimal solution is practically impossible due to the large number of operations required. However, if one insists on achieving the glory of reaching the optimal solution by human calculation, there is still a method for simpler cases. This is possible when the null space contains only a few elements.

The solution relies on the “zero effect” patterns of button presses, which are the non-trivial solutions of the homogeneous linear system. These can be determined in advance using a computer. In other words, the computer still does the heavy lifting, while the manual calculations rely on these reusable partial results.

Such a pattern (known as a *Quiet pattern* or *zero pattern*) is a sequence of button presses that ultimately does not change the state of the lights. If this sequence is applied to a fully extinguished board, the board remains completely off at the end.

In the classic version of Lights Out, there are three such patterns. As shown in Fig. 19, the second pattern is a rotated version of the first, and the third pattern is a combination of the first two.

The procedure for finding the optimal solution can be followed in Fig. 20. The first two squares depict the button presses made during the two steps of the light-chasing method.

The third figure is generated by combining these two squares: when the two squares are overlaid, overlapping X's cancel each other out and are removed. We then count the remaining button presses; let this number be n_0 .

The fourth square shows one of the quiet patterns, while the fifth depicts the result of overlaying this quiet pattern with the button presses from the light-chasing steps. We count the number of button presses in the fifth figure (n_1) and then repeat this calculation with the other two quiet patterns as well (n_2 and n_3).

The optimal solution is thus the one for which the n_i value is the smallest. In our example, this is shown in Fig. 20; the first two “quiet patterns” lead to a higher number of button presses (Fig. 21).

13. Conclusions

During the development of Lights Out, two main ideas emerged: increasing the number of light states and allowing arbitrary light patterns. This required expanding and generalizing the mathematical model of the game. Earlier publications related to solving the game treated the $GF(n)$ Galois field as the mathematical basis, but such a field only exists for prime numbers or powers of primes.

For prime numbers, this mathematical model and the solving algorithm can be applied straightforwardly. However, for prime powers, addition does not cycle through all possible states, so it does not guarantee the cyclic progression of states. From this, we concluded that the key point is not the existence or use of a Galois field, but rather performing arithmetic modulo n .

For prime powers and other composite numbers, calculations modulo n introduce additional challenges: not all numbers in the set of states have multiplicative inverses. As a result, in the linear system connecting light states to button presses, not all rows can be normalized using Gauss-Jordan elimination. Therefore, the part of the system where the diagonal contains non-invertible numbers must be solved by trial-and-error.

For composite numbers that can be expressed as a product of relatively prime factors, the Chinese Remainder Theorem provides a simpler solution, as it splits the problem into smaller subproblems, reducing the number of non-invertible rows. For example, with six-state lights, the system is solved twice: once modulo 2 and once modulo 3, and the final solution is obtained by combining the two partial results. In this way, the problem of non-invertible rows disappears.

The optimal solution of the game is often sought, particularly in layouts where not every starting configuration is solvable. This corresponds to an under-determined linear system, meaning multiple solutions exist. The task is then to choose the solution that requires the fewest button presses. If the number of free rows (zero rows) is small, the optimal solution can be found by searching the full solution space. Otherwise, heuristic, trial-based search algorithms (e.g., a Greedy ap-

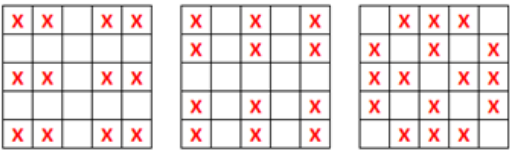


Fig. 19. „Quiet patterns”

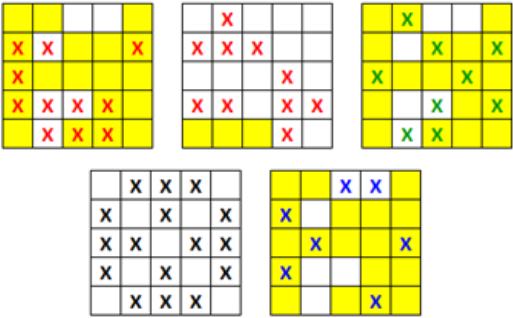


Fig. 20. The procedure for manually searching for the optimal solution.

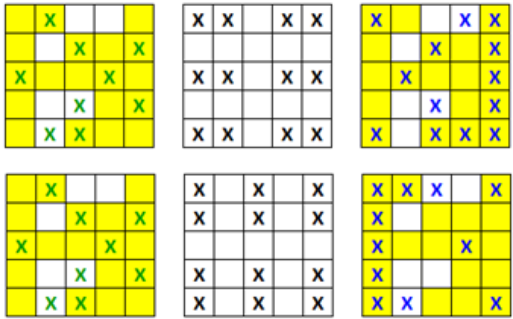


Fig. 21. The other two possibilities.

proach) can be applied to obtain a good solution, though it may not be guaranteed to be fully optimal.

References

Publications specifically dedicated to the history of Lights Out are scarce. Jaap Scherphuis is one of the most well-known international experts, collectors, and documenters of twisty puzzles (Rubik’s Cube and related mechanical logic games). He is primarily recognized for Jaap’s Puzzle Page (jaapsch.net), which is one of the largest, most accurate, and comprehensive online databases for mechanical and electronic logic games. On this site, a brief overview can be found on the origin, development, and precursors of Lights Out.

In terms of Hungarian relevance, the XL 25 version is mostly mentioned in blogs rather than formal publications.

For the mathematical foundations of solving Lights Out, the following works can be consulted:

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https://people.sc.fsu.edu/~jburkardt/classes/imps_2017/11_28/2690705.pdf

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https://doi.org/10.1007/978-3-642-40273-9_13



THE DESIGN OF A HYDRAULIC PROFILE OPENING TOOL

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Abstract

The topic of this publication is the design of a hydraulically operated manual profile opening tool that enables the precise and repeatable opening of extruded aluminum profiles used in bus bellow manufacturing. The necessity of the development was justified by the difficult handling and inaccurate operation of the currently used equipment. The paper presents the different structural designs and operating principles examined during the design process and provides a detailed justification for the application of hydraulic actuation. The main structural elements of the equipment are introduced, as well as the structure and operating principle of the hydraulic system. During the design process, special attention was given to ergonomic aspects, ease of operation, and workplace safety. The structural strength verification was carried out exclusively using the finite element method, which confirmed the adequate stiffness and operational reliability of the construction. Compared to the previously used equipment, the presented solution enables higher accuracy, better repeatability, and a more efficient manufacturing process, while reducing the number of errors and the proportion of nonproductive time. The longterm objective of the development is to ensure the flexible applicability of the tool for different profile sizes.

Keywords: *hand tool design, cold forming, finite element analysis.*

1. Introduction

Articulated buses, trolleybuses, and rail vehicles used in public transportation rely on bellows systems that play a crucial role in ensuring passage between vehicle units. The manufacturing of these bellows fundamentally consists of two main parts: the preparation of the fabric and the machining of aluminum profiles [1].

The present project focuses on the development of a profile opening device used in the field of aluminum bending. During aluminum bending, extruded profile bars are processed to produce various structural components, such as bellows frames, handrails, and roof structures. In the manufacturing process, the profiles are cut to size, bent, and subjected to preparatory operations required for assembly, such as drilling holes and creating joints.

One important step in the production process is establishing the connection between the profiles and the fabric. During this step, the aluminum profiles are first crimped (Fig. 1), and then hammered (Fig. 2) onto the pre-sewn fabric waves. The problem arises at the stitching points of the fabric pieces, where three layers of fabric overlap, significantly increasing the thickness. This increased thickness no longer fits within the original cross-section of the profile; therefore, at these points it is necessary to open the profile (Fig. 3), to ensure proper insertion of the fabric.

Currently, the company uses an opening device operated by a pneumatic cylinder with a piston diameter of 100 mm. There are two versions of this system: a single-cylinder design and a tandem-cylinder design (Fig. 4), the latter being used for thicker profiles. During operation, a wedge-



Fig. 1. Sample of a profile crimped onto fabric.

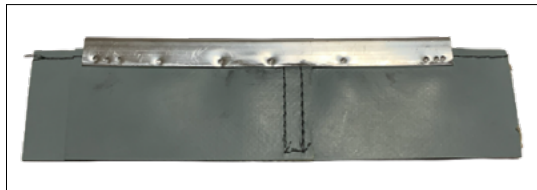


Fig. 2. Sample of a profile hammered onto fabric.



Fig. 3. Sample of an opened profile.

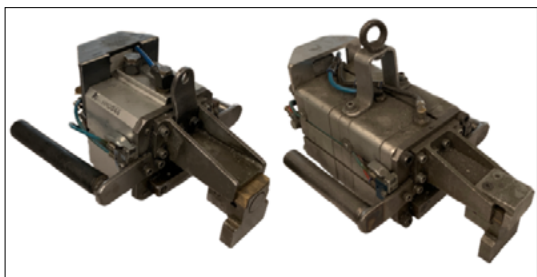


Fig. 4. Opening devices used by Hübner-H.

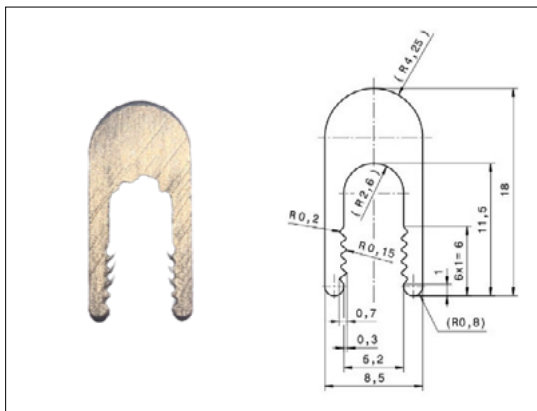


Fig. 5. Cross-section of the 8,5 mm x 18 mm profile.

shaped jaw is pressed into the interior of the profile, opening it into a V-shape.

During the project, a profile with a cross-section of $8,5 \times 18$ mm (Fig. 5) was examined, which, based on manufacturing experience, causes the most difficulties during the opening process. Due to its thick base cross-section, the profile can only be opened using a tandem-cylinder device. Although the required opening can be achieved, several practical issues arise that justify the need for further design development of the equipment.

2. Description of the current opening technology

During the opening process, the cross-section of the profile is deformed into a V-shape, allowing the insertion of fabric with increased thickness.

Despite the simplicity of the operating principle, several issues arise during the application of the technology. It is a common occurrence that the operator opens the profile to a greater extent than necessary, which makes subsequent assembly operations more difficult. In such cases, the crimping machine and the crimping hammer no longer fit properly, and therefore additional adjustment is required.

Another problem is that the device does not create the opening at the base section of the profile, which means that the fabric cannot always be inserted properly. To correct this, workers manually trim the edges of the profile using hand tools, which is time-consuming and increases the risk of scrap formation.

In the case of thicker profiles, the required opening often cannot be achieved in a single operation; therefore, the process must be carried out in multiple steps. This increases cycle time and operator workload. Due to the significant weight of the tool (Fig. 6) handling is particularly difficult, especially in cases where opening must be performed along the entire perimeter.

During operation, the opening jaws require continuous lubrication, which is currently provided by manual oiling. This not only slows down the process but also contaminates the profile, which negatively affects subsequent bonding operations. As a result, excess lubricant must be removed after the opening process.

Based on the issues described above, it can be concluded that while the current technology is functional, it requires further development in several respects, particularly in terms of accuracy, ergonomics, and process efficiency.



Fig. 6. Tandem opening machine on a scale.

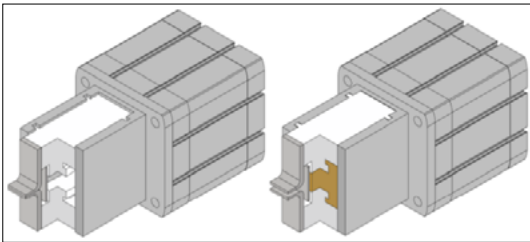


Fig. 7. Schematic of the parallel opening device.

3. Development task and requirements

The problems presented earlier clearly justify the development of a new profile opening device. The currently used equipment does not provide stable operation, the opening force is limited, and its handling is inadequate from ergonomic and productivity perspectives. The goal of the development is therefore to design a device that is easy to operate, reliable, and stable, enabling precise and repeatable opening of profiles, reducing the possibility of errors, and minimizing non-productive time during manufacturing. In addition, the design should ensure ergonomic and safe working conditions for operators, while increasing the efficiency and quality of the production process.

The primary function of the proposed device is to open profiles with the required force under stable fixation, while a pneumatic cylinder provides the force transmission. Operator safety and protection against overload are also key requirements; therefore, the system is started using a two-hand control. The opening jaw gradually expands the profile and then retracts after the operation, allowing easy removal of the workpiece.

The device must be capable of continuous operation in a three-shift system, approximately twenty hours per day. One opening cycle lasts about two seconds, and approximately 500 openings must be performed per shift. The surfaces of the opening jaws are exposed to significant loads; therefore, they should be made of high-strength steel or hardened material, with appropriate surface treatment if necessary to reduce wear. Lubrication between the jaw and the profile reduces friction; alternatively, a low-friction coating may also be applied, and any lubricant used must be easily removable so that it does not interfere with subsequent manufacturing processes.

The mass of the device must be designed so that it remains easy to handle and mobile, while still providing the required opening force. The structure should be easy to assemble and maintain, with lubricable and replaceable moving elements. The opening jaw and its counterpart should be replaceable quickly. Manufacturability is also important, allowing production through conventional machining or 3D printing, while material selection should ensure an optimal balance of strength, weight, and cost.

Overall, the objective of the development task is to create a reliable, precise, ergonomic, and economically manufacturable profile opening device that improves production efficiency in the long term, reduces the number of errors, and enhances working conditions for operators.

4. Concepts and outline of possible solutions

At the beginning of the development of the profile opening device, several design alternatives were examined. The first concept was a parallel opening mechanism (Fig. 7) with pneumatic actuation and a mechanical transmission. Due to the narrow internal cross-section of the profile, the thickness of the opening jaws could only be 2.5 mm, which made the required opening force unfeasible from a materials engineering perspective. Although it could theoretically have worked, practical implementation was not possible; therefore, this concept was deemed unsuitable for application.

Subsequently, an asymmetric parallel opening device (Fig. 8) was also investigated, which would have allowed the use of thicker jaws of up to 5 mm. According to calculations, this solution would have been feasible; however, during the expansion of the profile, displacement could

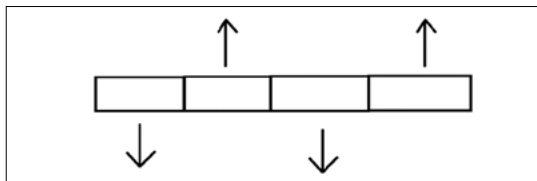


Fig. 8. Second parallel opening concept.

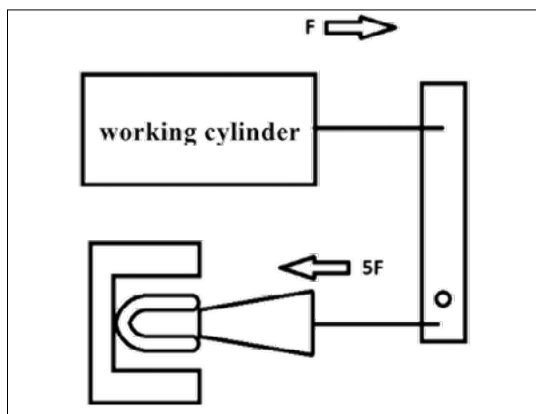


Fig. 9. Lever-mechanism opening device.

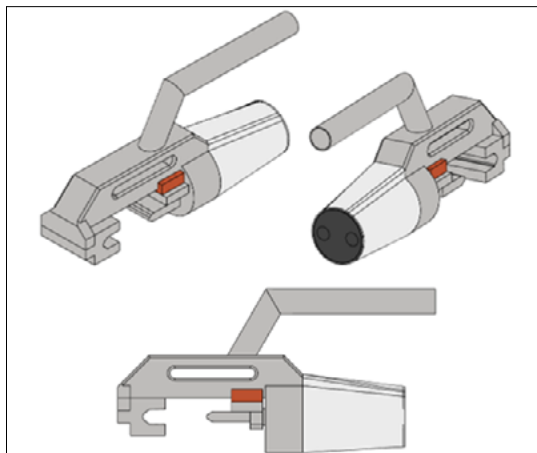


Fig. 10. Hydraulic wedge opening schematic.

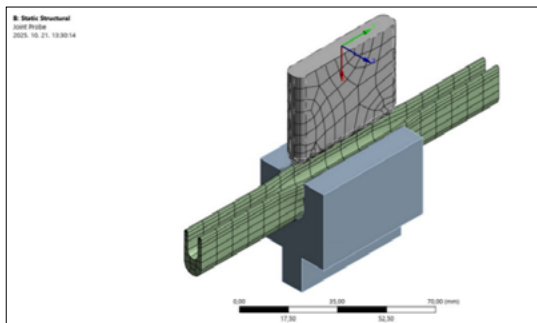


Fig. 11. Simulated opening test.

occur, and a rear support would have been required. This would have increased the weight and complexity of the device. As a result, this solution also did not meet the requirements of simple, safe, and repeatable operation.

The third concept was a pneumatic opening mechanism with a lever-type force transmission (Fig. 9) which would have provided the opening force using a smaller cylinder. Although this solution would have been functional, the complexity of the structure and the need for a longer-stroke cylinder did not result in a significant weight reduction. Therefore, this concept was also not selected.

Finally, the hydraulic wedge-opening design (Fig. 10) proved to be the most suitable solution. The hydraulic system provides high pressure with a relatively small cylinder, while the opening jaw and the cylinder are aligned on the same axis, reducing deflection. With the help of a counter-support, the opening process is controlled and repeatable. The system is compact, stable, and precise, and it enables the handling of different profile sizes using the same device. Therefore, the following chapters focus on the development of this design.

5. Tests and evaluation

The required profile opening force was first determined using the ANSYS finite element analysis software. The purpose of the simulation was to establish the force required to open the examined aluminum profile, as well as to investigate the stress distribution and deformation occurring during the opening process. The 3D model of the profile was imported into the ANSYS environment, after which a static structural analysis was performed (Fig. 11).

In the analysis, the material of the profile was modelled using the properties of Aluminum 6060 T66, taking into account the elastic modulus, Poisson's ratio, yield strength, tensile strength, and elongation at break. Boundary conditions included fixing the counter-support, while the motion of the opening jaw was defined as a sliding joint. A frictional contact was assigned between the profile and the opening insert. In the simulation, only the deformation of the profile was evaluated, while the other components were considered rigid bodies.

Using a meshed model and motion divided into 60 segments, the required opening force was determined based on the resistance occurring dur-

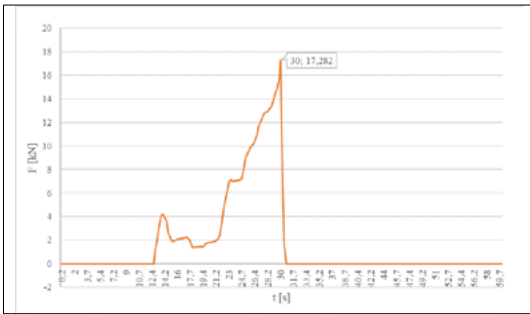


Fig. 12. Force-time (F - t) graph of the acting opening force.

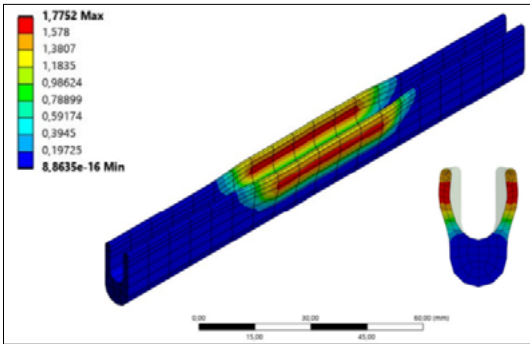


Fig. 13. Deformation of the profile.

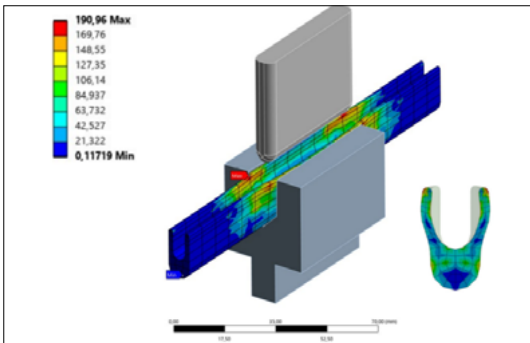


Fig. 14. Stress distribution in the profile after plastic deformation.

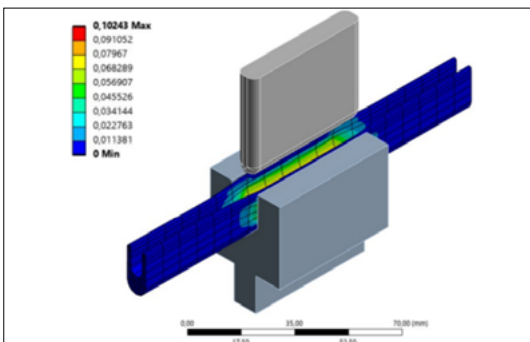


Fig. 15. Magnitude of plastic strain in the profile.

ing wedge advancement. The resulting force was 17.28 kN (Fig. 12). This value is higher than the opening force of the previous device, since the new design allows for a more obtuse wedge angle due to the counter-support, which increases the internal cross-sectional expansion of the profile and therefore results in higher resistance.

During plastic deformation, the maximum permanent deformation in the profile was 1.78 mm (Fig. 13), while the resulting von Mises stress was 190.96 MPa (Fig. 14), which did not exceed the material's tensile strength. In the plastic range, the proportional relationship between stress and strain no longer applies; therefore, failure was evaluated based on equivalent plastic strain. According to the results, the maximum plastic strain was 10% (Fig. 15), which remained below the material limit of 15%, indicating that the profile does not fracture during cold forming.

In addition to the simulation, the opening principle was also tested under real conditions. By modifying the existing opening machine and reducing the width of the jaws, the profile opened without any issues, with permanent deformation and no fracture. Several wedge angles were tested, and the 70° configuration proved to be the most stable and provided the best repeatability.

During the tests, it was also verified whether the profile produced using the new principle could be properly fitted to the fabric. The trials showed that the sewn fabric could be easily inserted into the unmodified profile without manual trimming; thus, the operating principle of the developed device is also effective in practical application.

6. Design of the construction

Based on the simulation results, which indicated an opening force of approximately 17.3 kN, a lightweight and easy-to-assemble cylinder capable of providing at least 20 kN of force was selected: the ROEMHELD B1.309-1343165 model (Fig. 16). The main selection criteria were the installation dimensions, stroke length, and ease of handling.

Based on the selected cylinder, the schematic design of the opening device was prepared (Fig. 17), where the primary considerations were the ability to handle the largest profile dimensions, ease of assembly and maintainability [2].

The sizing of the machine frame and the counter-support was optimized using the generative design module of ANSYS Discovery (Fig. 18), reducing the mass by half without a significant de-

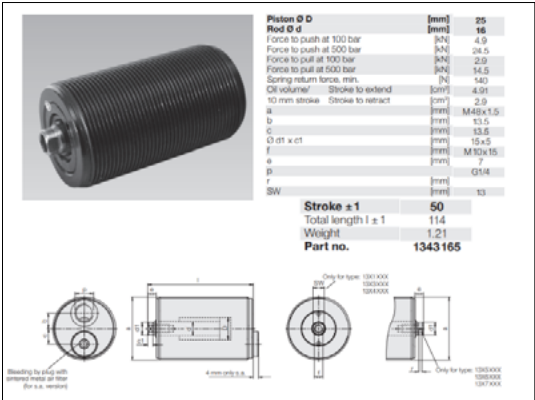


Fig. 16. ROEMHELD B1.309-1343165 hydraulic cylinder [Source: <https://ws.roemheld.de/en/products/threaded-body-universal-cylinder~ps-nY7PGzvOQX>]

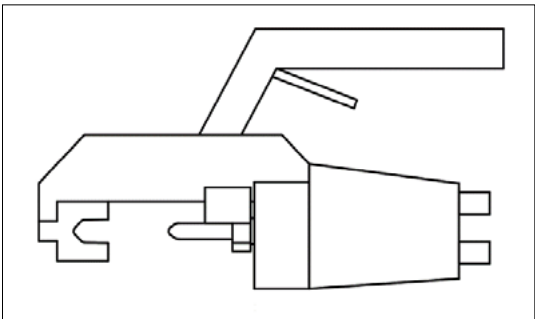


Fig. 17. Schematic of the opening device.

crease in stiffness. Although the model generated by the software could also be manufactured using metal powder 3D printing, a simplified design was chosen due to cost-effectiveness and ease of machinability [3].

The counter-support (Fig. 19) was designed to be detachable, and the protection of the profile surface was ensured by a 3D-printed plastic insert. Inside the insert, a wear-indicating layer is also incorporated, which supports preventive maintenance. The clamping of the 70° wedge-shaped opening insert (Fig. 20) allows for quick replacement when working with different profiles, secured by three M8 set screws, while the fixation of the cylinder is ensured by a DIN 1804 locknut. Parallel alignment and smooth motion are provided by a bronze plain bearing, reducing friction and increasing precision [4].

The handle designed in accordance with ergonomic standards (Fig. 21) ensures that the cylinder operates only when both the button and the trigger are pressed simultaneously; releasing

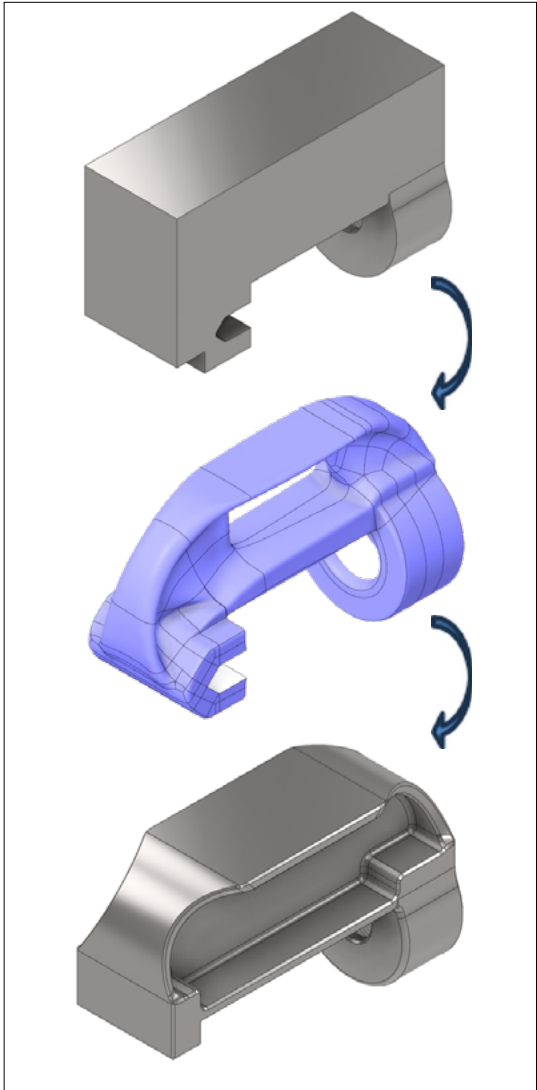


Fig. 18. Topology optimization of the machine frame.

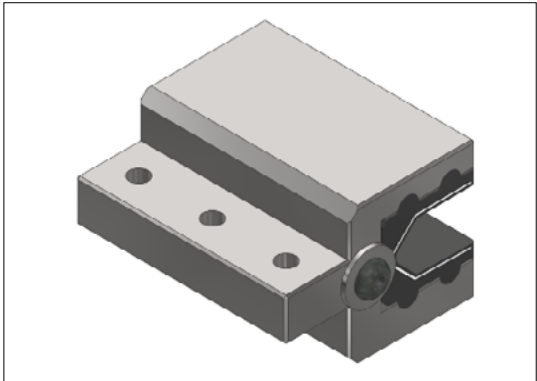


Fig. 19. Design of the counter-support.

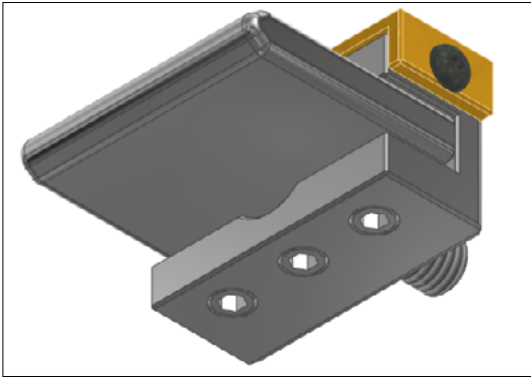


Fig. 20. Clamping design of the opening insert.



Fig. 21. Ergonomic handle.

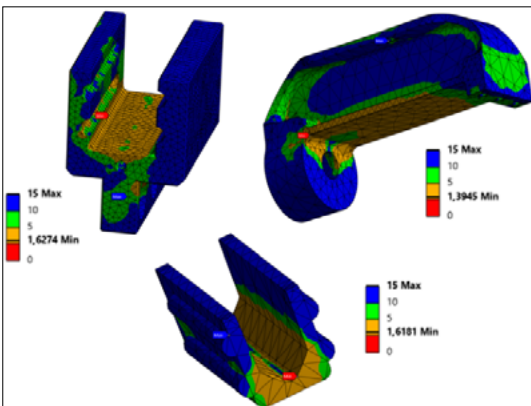


Fig. 22. Safety factors of the machine frame components

either of them causes the system to return to its initial position. As a result, the design is compact, stable, ergonomic, and universally applicable to all profile types [5, 6].

7. Strength analysis and material selection

The strength verification of the critical structural components of the machine was carried out in ANSYS [7]. The aim of the analysis was to evaluate the behaviour of the most highly loaded parts, as well as the suitability of the selected materials. During the simulation, the directly interacting components were analyzed together, allowing for a fast computation focused on critical regions while accurately representing real loading conditions.

In the case of the machine frame and the counter-support, the cylinder mounting was fixed, and the structure was loaded with the maximum opening force of 20 kN. Based on the resulting von Mises stresses, S355JR structural steel was selected for the steel components of the frame and the counter-support. This material is cost-effective, easy to machine, readily weldable, and meets the required strength criteria. For corrosion protection, a black oxide coating was applied [8], while POM (polyoxymethylene) was chosen for the plastic insert due to its good wear resistance and chemical resistance.

Based on the mechanical properties of the selected materials, the safety factors were verified, showing adequate values for both the frame and the counter-support (Fig. 22).

The opening insert and its clamping component were also analysed under an opening force of 20 kN. S355JR structural steel was assigned to the steel elements of the clamp and the frame, while 42CrMo4 alloy steel was selected for the opening insert, which provides high wear resistance and toughness when quenched and tempered. The surface of the opening insert was coated with a DLC (diamond-like carbon) coating to reduce wear and minimise the coefficient of friction [9]. The plain bearing material is CuSn7Pb15 bronze, which provides good lubrication performance under dry and contaminated conditions [10].

Since the cylinder manufacturer did not specify the material of the piston rod, it was modelled using quenched and tempered C45 steel as an industrial standard assumption. Based on the simulations, the safety factors of the components are adequate: both the opening insert and the clamping

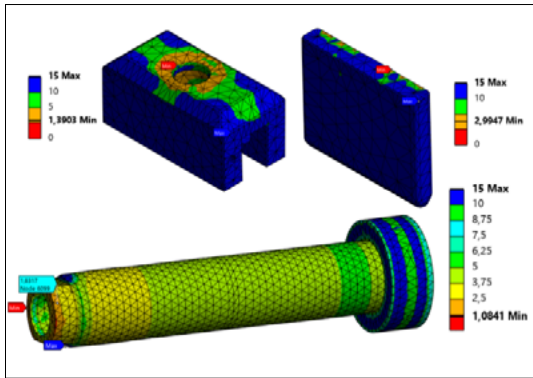


Fig. 23. Safety factors of the opening insert and its clamping system.



Fig. 24. Prototype of the developed opening device.

element operate safely under load. Local stress concentrations occurred due to sharp geometric transitions; however, in real applications these could be significantly reduced by introducing fillets (Fig. 23).

Overall, the simulations and material selection confirmed that the main components of the machine operate safely under the designed opening force and fulfil the required functionality.

8. Conclusions

As a result of the research and design work, a hydraulically actuated manual profile opening tool was developed (Fig. 24), which is suitable for the precise and repeatable opening of extruded aluminum profiles.

The use of hydraulic actuation enables the required force to be provided while keeping the device compact and easy to handle. Finite element analyses confirmed that the structural strength and stiffness of the system meet the design requirements.

Compared to previously used equipment, the developed device improves manufacturing accuracy and reduces the number of errors. Future development directions include adapting the tool to different profile sizes and further optimizing the manufacturing process.

Acknowledgements

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PRESENTATION OF THE WATCH+ CAREER ORIENTATION PROGRAM AND OPPORTUNITIES FOR FURTHER DEVELOPMENT

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Abstract

The underrepresentation of women in STEM fields remains a global problem today, necessitating the creation of numerous programs. In this thesis, in addition to analyzing statistical data, international and domestic initiatives are presented, with a particular focus on WATCH (Women at Tech), launched by the Agóra Tudományos Élményközpont. Within the alumni program of this initiative, WATCH+, the program is further developed by designing and leading an electronics project-building activity, utilizing the opportunities provided by the Electrical Engineer and Mechatronics Department at the University of Debrecen.

Keywords: *STEM, career orientation, electronics, WATCH program.*

1. Introduction

Achieving gender balance in scientific and technological fields is widely recognized as one of the most important social and professional challenges of our time. Although women currently make up the majority of students in higher education worldwide, their significant under-representation in STEM fields remains clearly evident. The disparities observed in engineering and technology careers are also reflected in differences in salaries and opportunities for career advancement: women tend to earn lower salaries on average and proportionally occupy fewer senior and leadership positions compared to their male counterparts.

Numerous studies have highlighted that career choice is influenced not only by individual interests and abilities but also by a wide range of social and cultural factors. Persistent stereotypes, the lack of visible and relatable role models, and limited exposure or experience in technical fields all play a significant role, contributing to the fact that fewer young women continue their studies in STEM disciplines compared to other fields.

One of the most effective tools for addressing this issue is career orientation, particularly through structured programs that provide participants with opportunities to gain practical experience in technical fields. Project-based activities, in particular, allow participants to engage directly with real-world challenges, helping them to develop a deeper understanding of engineering thinking, problem-solving processes, and applied technical skills.

One such initiative in Hungary is WATCH (Women at Tech), launched by the Agóra Tudományos Élményközpont. This program offers high school girls the opportunity to become acquainted with, among other subjects, the fundamentals of 3D design, programming, and electronics. During the program, participants implement their own projects under the guidance and support of experienced mentors, and these projects are presented at the end of the year during a dedicated closing event. The enhanced version of the program, WATCH+, provides former participants with the opportunity to further deepen and expand their knowledge and practical skills gained in previous sessions.

The aim of the present research is to present the RGB LED project developed within the framework of the WATCH+ program, during which participants were able to learn the fundamental principles of electronics through the design, construction, and practical implementation of a simple electrical circuit.

2.Gender Ratios and Trends in Higher Education

The issue of women’s participation in STEM fields has become an important and increasingly discussed topic in academic research in recent years. Although women have already formed the majority in higher education for several years, their significant underrepresentation in engineering and scientific fields can still clearly be observed.

In Europe, the proportion of women participating in higher education has steadily increased over recent years. Based on data collected from 25 countries between 2013 and 2018, the average enrolment ratio of women to men was 1.4:1, which clearly demonstrates that the presence of women in higher education is becoming increasingly significant and more prominent over time [1].

A similar tendency can also be observed in the United States, where women significantly outnumber men in terms of both college enrolment and graduation rates. At the national level, women accounted for 58% of all college students in 2020, compared with 56.6% six years earlier. For several decades, women have formed the majority among students, and the difference between the two groups has gradually continued to increase over time. The graduation rate is also higher for women: in 2022, the graduation rate for women (67.9%) exceeded that of men (61.3%) by more than 6 percentage points overall [2].

At the world’s leading universities, the most recent available data show varying gender ratios among students. Although in many cases the distribution of male and female students is nearly balanced, a slight predominance of men is still generally characteristic, and at technical universities a two-thirds majority of male students can also be observed, as illustrated in Fig. 1. [3].

Examining the distribution by fields of study provides a more nuanced and detailed picture of gender representation in higher education. Based on the 2023 statistics of the European Union, it becomes clearly visible that significant differences

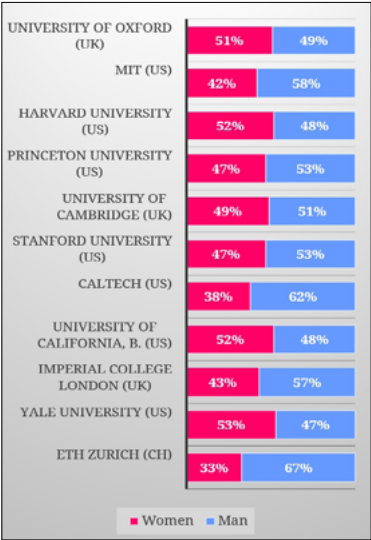


Fig. 1. Gender distribution at the world’s leading universities in the 2024/25 academic year, based on [3].

exist between the various academic disciplines. According to Table 1 while the number of female students exceeds that of male students in teacher education, the arts, humanities, and health-related fields, the opposite trend can be observed in engineering programs, where the proportion of male students is more than two and a half times higher than that of female students [4].

Table 1. Gender distribution of students by field of study (EU, 2023), based on [4].

Education	Women	Man
Pedagogy/Education	1 105 278	295 356
Arts and humanities	1 369 897	736 422
Social sciences, journalism and information	1 229 786	630 496
Business, administration and law	2 265 148	1 873 770
Natural sciences, mathematics and statistics	656 053	617 325
Information and communication technologies	209 193	818 794
Engineering, manufacturing and construction	765 538	1 996 793
Agriculture, forestry, fisheries and veterinary	194 076	209 709
Health and welfare	1 967 170	748 623
Services	421 437	478 427

Not only in higher education, but also in the labor market, significant disparities can be observed. According to a 2021 European Union report, only 19% of workers in the technology sec-

tor are women, while approximately one-third of STEM graduates are female. Moreover, in these fields, men earn on average about 19% more than their female colleagues. Little progress has been made in this regard, as these proportions have not changed significantly in recent years. Among entry-level positions, women make up 29.4%, but this proportion drops drastically at senior management levels to between 12.4% and 17.8%. According to the 2023 Global Gender Gap Report by the World Economic Forum, achieving full gender equality would take approximately 132 years [5].

3. Review of International Research

In this chapter, various international studies examining women's participation in STEM fields are reviewed. These studies approach the issue from different perspectives: some focus on cultural and educational factors, while others examine the workplace environment or psychological influences.

The study by Shapiro and Sax reviews the factors that influence women's choice of STEM majors and their persistence in these programs. The authors highlight the importance of early experiences, self-confidence, supportive environments, and mentorship. The research emphasizes that institutions need to actively investigate and address the factors leading to gender disparities within their own environments [6].

Blackburn analyzes the literature from 2007 to 2017, focusing on the role of women in STEM fields. The main topics include recruitment, retention, barriers, and faculty experiences. The study highlights the impact of stereotypes, biases, and institutional culture on women's academic and professional advancement, while also emphasizing the importance of identity and a sense of belonging [7].

García-Holgado and colleagues, within the W-STEM project, examine the low participation of women in STEM in Latin America, where cultural norms and social biases further exacerbate gender inequalities. Although the proportion of female students in higher education is generally high, they remain a significant minority in STEM fields. Their goal is to develop tools and programs that showcase female role models and provide motivation [8].

The study by Beede and his colleagues analyzes gender differences in the U.S. STEM workforce. Although women make up nearly half of the workforce, they occupy only a quarter of STEM

positions. Women working in STEM fields earn on average 33% more than women in non-STEM occupations, reducing the wage gap. The authors argue that the lack of female role models, stereotypes, and inflexible work environments hinder women's participation, highlighting the need for stronger support and inclusion [9].

Cimpian and his colleagues examine gender ratios in STEM majors in the United States, noting that men remain significantly overrepresented, especially among lower-performing students. Their findings suggest that high-achieving women can be effectively encouraged through role models and targeted programs, while deeper causes of gender differences—such as cultural norms and stereotypes—primarily reinforce men's overrepresentation in these fields [10].

Research by Bloodhart and his colleagues found that female students outperform their male peers in both natural and life sciences undergraduate programs, yet they are still perceived as less talented. This distorted perception within the university environment reinforces gender stereotypes, reduces women's self-confidence, and contributes to dropout. The authors emphasize that recognizing women's achievements is crucial for retaining them in STEM pathways [11].

Kahn and Ginther examine why women remain underrepresented in math-intensive STEM fields. They highlight the role of environmental and social factors: gender stereotypes, cultural expectations, and patterns of interest are formed in childhood and continue to influence women throughout schooling and into the labor market. Their analysis suggests that these factors together explain gender disparities in STEM, where approaches based on preferences and psychological differences are particularly significant [12].

Diekmann and his colleagues investigate why women continue to be underrepresented in STEM careers despite decreasing performance gaps between genders. They argue that women's motivation is often influenced by social and family factors, as well as stereotypes specific to STEM careers. The study provides practical recommendations for promoting women's engagement and retention, including fostering supportive workplace cultures and flexible working conditions [13].

Avolio and his colleagues, based on a comprehensive analysis of 470 studies, examine the factors influencing women's participation and advancement in scientific careers. They identify five groups of factors: individual, family, social, educational, and labor market-economic influ-

ences. They point out that these factors interact with each other, requiring a systemic approach to addressing the problem [14].

Morganson and his colleagues examine women's underrepresentation in STEM through the lens of social coping. Their results indicate that women rely more frequently on social support, which strengthens their commitment to their field and reduces dropout. In contrast, among men, social coping was less strongly associated with performance. The study suggests that supportive community connections are key to retaining women in STEM career [15].

4. Programs Supporting Women in STEM Careers

4.1. OxWEST

OxWEST (Oxford Women in Engineering, Science, and Technology) is one of the largest student organizations at the University of Oxford, dedicated to supporting women in pursuing careers in science, technology, engineering, and mathematics. The organization hosts workshops, community events, and mentorship programs, providing students with opportunities to connect with sponsors and professional networks. In addition, they hold annual conferences aimed at showcasing talented young women and supporting them in launching engineering careers [16].

4.2. WTP

The MIT Women's Technology Program (WTP) is a four-week, residential summer course for high school girls who are interested in mathematics and science but have not yet had engineering experience. The program aims to provide insight into the world of engineering through hands-on classes, laboratory exercises, and team projects, thereby encouraging participants to pursue further education in STEM fields [17].

4.3. WiSTEM

WiSTEM (Women in Science, Technology, Engineering, and Mathematics) seeks to support women studying at Harvard University in STEM fields through mentorship. The program connects undergraduate students with women pursuing postgraduate studies, who provide professional guidance and inspiration. Its long-term goal was to strengthen an inclusive community and promote broader representation of women in STEM careers; however, the program was archived on July 10, 2025 [18].

4.4. Girls' Day

Girls' Day is a nationwide STEM-oriented career orientation day in Hungary, organized by the Nők a Tudományban Egyesület (Association of Women in Science) for upper secondary and high school girls. On this day, numerous companies, universities, and research institutes across the country host interactive programs, allowing girls to explore the world of science through direct contact with practicing professionals [19].

4.5. The WATCH Program

The WATCH (Women at Tech) program was launched in 2021 by the Agóra Tudományos Élmenyközpont in Debrecen, with strategic support from Emerson | NI. Over the years, it has become one of Hungary's most successful career orientation programs specifically targeting high school girls.

The aim of the WATCH program is to introduce high school girls to the diversity of engineering and technology careers in an engaging and experiential way. The initiative is based on a year-long, practice-oriented project in which participants work in small teams of 3–5 students with the support of mentors.

The program begins with a foundational training phase, where for ten weeks, participants meet twice weekly to learn the basics of 3D modeling, programming, robotics, and electrotechnics, while also developing presentation and communication skills. This knowledge is then applied in the development of their own projects, which are showcased to the public, including at the end-of-year WATCH closing event at the Agóra Tudományos Élmenyközpont, as well as at the Campus Festival and Researchers' Night [20].

Career orientation is an integral part of the program: participants have the opportunity to meet female engineers in person and visit universities and industrial companies. The initiative is supported strategically by EMERSON | NI, and every year, more volunteers join as mentors—not only from Emerson | NI, but also from Sensirion Hungary Ltd. and Diehl Aviation Hungary Ltd. [20].

Since 2023, the program has expanded under the name WATCH+, providing former participants with the opportunity to deepen their knowledge through additional project work. Due to high demand, from 2026 the program has also been opened to boys under the new name Welcome All to Tech, while maintaining its original objec-

tives—promoting and supporting young people's interest in STEM careers [20].

As a mechatronics engineering student at the University of Debrecen and an ambassador for the program, I strive to contribute to the further professional development of WATCH through the opportunities provided by the department. Our goal is to open the path to technology and engineering careers for even more young people in the future, while preserving the program's inspiring and supportive community character.

5. Development of an Electronics Project for the WATCH+ Program

As part of the university-level expansion of the WATCH+ program, a workshop was designed in which participants could create an RGB LED-based electronic device with adjustable color temperature using potentiometers, capable of glowing in the dark. At the end of the session, participants were able to take their completed devices home as a keepsake. The purpose of the project was to give girls hands-on experience with the key steps of the engineering development process, from design to production. During the workshop, participants could design and customize a simple LED circuit using KiCad software, and the completed PCBs were manufactured using the LPKF ProtoLaser H4 laser PCB milling machine located at the Department of Electrical Engineering and Mechatronics at the University of Debrecen.

A key consideration in developing the workshop was to allow participants to creatively shape the final appearance of the device. Therefore, the program provided the opportunity to design custom-shaped PCBs. The base shapes were created in AutoCAD and then imported into KiCad, where the circuit wiring was completed. Fig. 2 shows the first prototype, featuring a heart-shaped PCB design.

Several different shapes were designed to inspire the participants. The PCBs can also be personalized with motifs and inscriptions, enhancing the project's motivational and experiential nature. The completed designs can be viewed in the program's 3D preview, allowing participants to see the expected appearance of their devices before manufacturing. The final visual designs are shown in Fig. 3.

5.1. Component Sizing

The circuit is built around an RGB LED, with the required series resistors calculated based on the LED's forward voltage and desired current

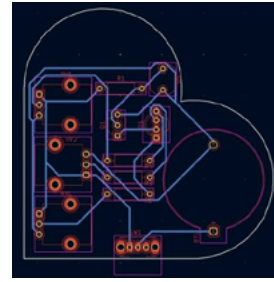


Fig. 2. PCB after Wiring Completion.

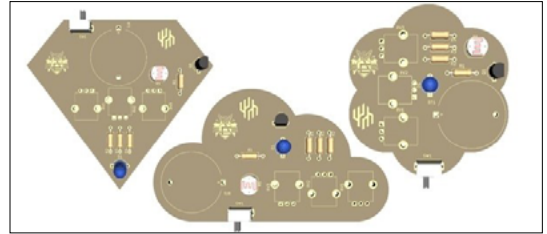


Fig. 3. Visual Designs in Diamond, Cloud, and Flower Shapes.

to ensure proper operation. To guarantee stable performance, the circuit is powered by two series-connected button cells, providing a 6 V supply. Potentiometers control the RGB LED's color temperature, while a photoresistor and transistor form a control circuit for operation in the dark, set so the switching threshold occurs at 10 lux. Ease of manual soldering was also considered, so through-hole components were selected

5.2. Prototype Fabrication

Based on the finalized circuit design, the project prototype was assembled to verify circuit functionality and to test the manufacturing and assembly processes. The PCB was fabricated using the aforementioned LPKF ProtoLaser H4 laser PCB milling machine. After precisely milling the heart-shaped contour, the edges of the board were cleaned, and the surface was dust-free and prepared for component placement.

The necessary components were manually soldered onto the board. After completing the soldering, the back of the PCB was cleaned and treated with a transparent protective lacquer to prevent corrosion and contamination.

The completed circuit functioned as expected: in a bright environment, the LED remained off due to the photoresistor, while in darkness it turned on, as shown in Fig. 4. and 5. Using the three potentiometers, the RGB LED colors can be adjusted continuously over a wide range. The prototype

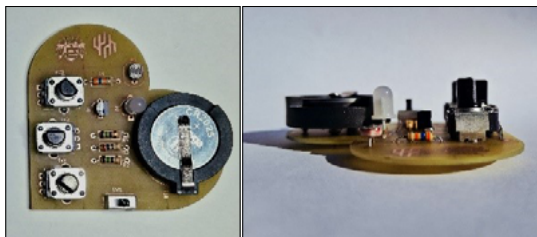


Fig. 4. *The Device in a Bright Environment, LED Off.*

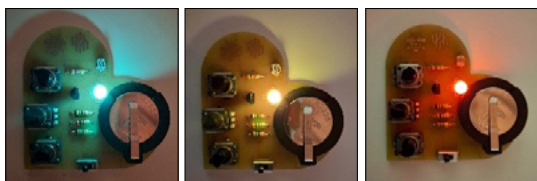


Fig. 5. *The Device in Darkness, with Three Different Color Temperature Settings.*

demonstrated stable operation and was aesthetically suitable for further educational use.

The trial production confirmed that the designed circuit and PCB layout were suitable, and the selected components fit well within the construction. Based on these experiences, the design proved suitable for both series production and the project assembly to be carried out with the participants.

5.3. Project Assembly Implementation

The project assembly took place on November 18, 2025, at the Department of Electrical Engineering and Mechatronics at the University of Debrecen. During the session, high school girls participating in the WATCH+ program were able to assemble their own PCBs based on the previously presented designs and circuits.

Throughout the workshop, students worked in small groups under the guidance of both faculty and student mentors, ensuring that everyone received personalized assistance. At the end of the project assembly, participants were able to take home their own uniquely designed circuits, which can serve as both a keepsake and a motivational tool on their path toward technical careers (Fig. 6).

6. Conclusions

During this research, a new educational project-building opportunity was developed within the framework of the WATCH+ program, aimed at providing participants with hands-on experi-

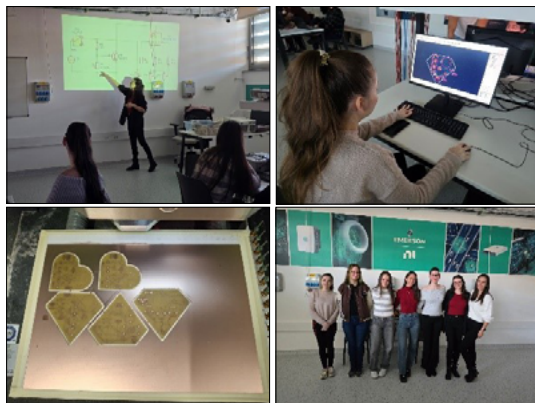


Fig. 6. *Project Assembly.*

ence in the fundamentals of mechatronics and electronics. The development focused on a simple and visually illustrative electronic system that demonstrates the relationship between light sensing and LED control. A key consideration in the concept design was that the project should convey STEM-related core concepts in an engaging way and support the development of technical thinking and creative skills.

The project assembly session was held on November 18, 2025, at the department as part of the WATCH+ program. Following the announcement, all available spots were quickly filled, and the necessary educational materials and tools were prepared in advance. During the session, the girls learned the basics of electronics in a practical manner while building their own functioning circuits. The goal of the workshop was to provide a tangible experience of the engineering creation process and thereby strengthen their interest in STEM careers.

The session was successfully conducted according to plan, and the participants' feedback was extremely positive. Even if only a few of them choose an engineering career as a result of this experience, it can already be considered a significant outcome, as the WATCH and WATCH+ programs will help bring more female engineers into industry in the future.

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STUDY OF THE COLUMN STOVE LOCATED IN THE BOLYAI MUSEUM

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Abstract

Bolyai Farkas is best known as a mathematician, yet his interests also extended to the design and construction of stoves and furnaces. The main goal of his research was to develop a heating system that could operate economically. As a result, the stoves later known as Bolyai stoves were created, spreading throughout Transylvania in the early nineteenth century, particularly in the region of Târgu Mureș. These stoves were not only technological innovations but also improved everyday comfort and energy efficiency. Two original examples of the stoves designed by Bolyai can still be seen today in the collection of the Teleki-Bolyai Library in Târgu Mureș. In our study, we examined the green tile stove, identified its type, and conducted thermal analysis.

Keywords: *tile stove, column stove, efficiency, Farkas Bolyai.*

1. Introduction

The material relics preserved from the lifetimes of the two Bolyai and exhibited in the Bolyai Museum, located in the Teleki-Bolyai Library building in Târgu Mureș, evoke an imaginary study room. In one corner of this reconstructed interior stand two distinctive heating devices of unusual construction. One of these is externally clad in green-glazed ceramic tiles and is widely known as the “green column stove.” [1]. It was constructed either by Farkas Bolyai himself or by a local potter from Târgu Mureș following his designs.

The stove's original location is unknown; it may have been transferred to the Bolyai Museum either from a room of the former Reformed College or from a private owner.

In the manuscript entitled *Treatise on Stoves*, Bolyai referred to heating devices generically as stove, distinguishing between types through the use of specific qualifying adjectives. As the term *kahle* evolved into *tile* in everyday Hungarian usage, the earlier expression was gradually replaced by the term *tilled stove* [1, 2].

The external structural configuration of the green tiled stove is illustrated in Fig. 1.

The internal structure of the tiled stove is unfortunately missing, although this may have constituted its principal innovation. In our study, we aim to reconstruct, model, and analyze its internal configuration.



Fig. 1. The column stove of the Bolyai Museum.

The design and operation of modern heating systems are closely linked to mathematical modeling and a series of experimental measurements [3, 4]. The combined application of these principles and tools enables the development of energy-efficient and optimized systems [5, 6], as well as the technical characterization and evaluation of existing heating appliances.

2. Examination of the Column Stove Located in the Bolyai Museum

In the present case, we are able to verify and examine the stove designed by Farkas Bolyai [6].

Methodology of the investigation:

- determination of the stove type and measurement of the dimensions of its components;
- reconstruction of the stove's internal structure and preparation of its technical drawings;
- thermal analysis of the stove: examination of the firebox; calculation and evaluation of the flue gas path length; determination of the stove's efficiency; calculation of the stove's heating performance.

2.1. Determination of the Stove Type

The green column stove located in the Bolyai Museum is a solid-fuel heating appliance suitable for local space heating. It was constructed on site from individual elements and shaped tiles, and it released heat into the room in which its external surface is located. It is suitable for firing with split firewood. During operation, it is capable of storing the heat generated within it.

Its firing period and heat delivery period differ significantly. The stored heat was transferred predominantly by radiation. The heat-storing structural mass absorbed heat directly from the hot flue gases through internal heat transfer processes. [6]

The lower part of the tiled stove has a square base measuring $2,5 \times 2,5$ tiles, while the upper part has a width of 2×2 tiles, also with a square base. This corresponds to a relatively small cross-sectional area. The lower section of the stove forms the firebox. There are no flue passages adjacent to the firebox; it is a so-called blind firebox. The height of the stove consists of seven rows of tiles.

Accordingly, it can be classified as a column stove. In terms of its design, it is a column stove with a central cornice and an open niche (Fig. 1) [6].

The dimensions of the tiles used in the construction of the stove are 205×235 mm. The stove is clad with 62 tiles, of which 52 constitute

the heating surface, corresponding to an area of $2,5 \text{ m}^2$.

The firebox door measures 240×115 mm, while the lower ventilation and cleaning door measures 150×130 mm.

2.2. Internal Structure of the Stove

The flue system was presumably constructed with horizontal passages, as suggested by the two cleaning openings located on the left side of the stove (Fig. 1).

Based on professional stove-building practice and experience, we reconstructed the interior by designing five rows of horizontal, counter-flow flue passages.

In Bolyai's time, efficient heat emission was a primary objective; therefore, he also incorporated and designed air-circulation ducts in his stoves. This duct, routed upward through the center of the flue passages, allowed air to be heated and then flow into the room [1, 6]. Although there is no physical evidence of a centrally positioned air-circulation duct in the museum artifact, such a feature could have been integrated into this stove. Accordingly, following Bolyai's presumed concept, we have included it in our reconstruction (Fig. 2).

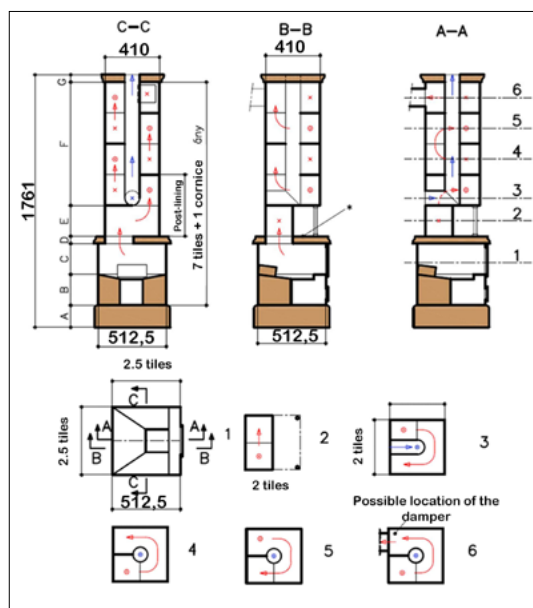


Fig. 2. Technical drawing of the column stove.

A – base; B – ash chamber (air plenum); C – firebox; D – central cornice; E – open niche; F – location of the horizontal flue passages, stove body; G – upper cornice.

2.3. Thermal Analysis of the Column Stove

During the heating-up and cooling-down periods of the appliance, transient (non-stationary) processes take place. These are neglected in the present analysis, as the nominal heat output is delivered under steady-state operating conditions. Accordingly, the nominal performance was determined assuming steady-state conditions [6].

The performance parameters were calculated in accordance with the MSZ EN 15544 standard.

2.3.1. Examination of the Firebox and Determination of the Fuel Quantity

In order to determine the technical parameters of the stove, the width, depth, and height of the firebox were first measured.

Firebox dimensions: $45 \times 45 \times 30$ cm.

Based on these dimensions, the maximum quantity of firewood that can be loaded into the firebox can be determined:

$$m = \frac{2 A_t + K \cdot h}{900} \quad [\text{kg}], \quad (1)$$

where: A_t is the area of the firebox, $[\text{cm}^2]$;

K is the circumference of the firebox, $[\text{cm}]$;

h is the height of the firebox $[\text{cm}]$.

Calculated value: 10.5 kg.

The initial amount of firewood that can be loaded is half of the calculated value $m = 5$ kg.

Subsequent loading: $m = 2,5$ kg.

2.3.2. Calculation and Evaluation of the Flue Gas Path Length

According to the MSZ EN 15544 standard, a minimum flue gas path length is specified to ensure stove operation at an efficiency of 78%. Accordingly, the assumed flue gas temperature at the firebox outlet decreases from 550°C to 240°C by the end of the minimum required flue path length.

For a single-shell stove without an air gap and with a series flue configuration, the minimum flue gas path length can be calculated using the following empirical relationship [6]:

$$L_{j\min} = 1,3 \sqrt{m} \quad [\text{m}], \quad (2)$$

where: m is the mass of firewood that can be loaded into the firebox $[\text{kg}]$.

The calculated value is: $L_{j\min} = 2,91$ m, ha $m = 5$ kg.

Based on the reconstructed layout and our construction experience, the lengths of the flue pas-

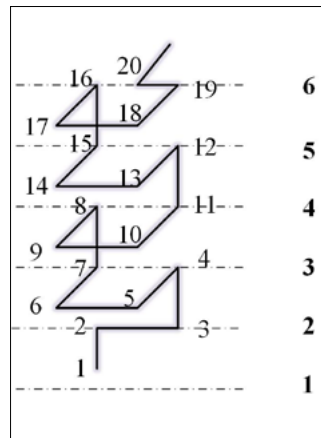


Fig. 3. Presumed flue gas path of the column stove.

Table 1. Determining the length flue gas path

Flue gas path parts	Values [m]
Vertical	$5 \cdot 0.230 = 1.15$
Horizontal	$4 \cdot 0.6 + 0.2 + 0.2/2 = 2.7$
Total, L_j	3.85

sages were estimated and drawn. The configuration of the flue system is shown in Fig. 3.

The calculation of the flue gas flow path length was performed based on Table 1.

According to the reconstructed design, the total flue gas path length is 3.85 m.

The estimated path length exceeds the required minimum flue gas path length.

2.3.3. Calculation of the Stove Efficiency

To calculate the efficiency of the stove, it is necessary to determine the temperature decrease along the flue gas path. This can be calculated using the following relationship [6]:

$$t_k = 550 e^{-\frac{0,83 L_j}{L_{j\min}}} \quad [^\circ\text{C}], \quad (3)$$

where: L_j is the calculated flue gas path length $[\text{m}]$.

The temperature of the exiting flue gas is 183°C .

The variation of the flue gas temperature is illustrated in Fig. 4.

The stove efficiency can be calculated using the following empirical formula, [6, 7]:

$$\eta = 101,09 - 0,0941 t_k - 6,275 \cdot 10^{-6} t_k^2 - 3,173 \cdot 10^{-9} t_k^3 \quad [\%], \quad (4)$$

where: t_k is the temperature of the flue gas leaving the stove flue system $[\text{C}]$.

The calculated efficiency is: $\eta = 84\%$.

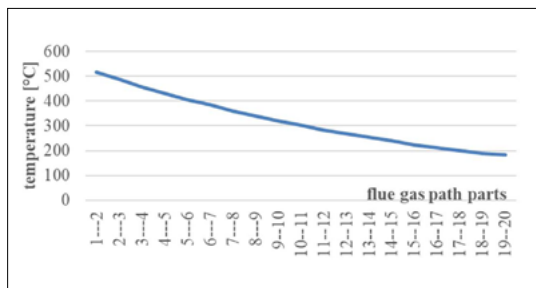


Fig. 4. Flue gas temperature variation along the flue gas path.

2.3.4. Calculation of the Heating Capacity of the Column Stove

For the determination of the nominal heat output of tiled stoves, the MSZ EN 15544 standard provides the following relationship:

$$P_n = 3,25 \cdot m_{be} / t_{fűtés} \text{ [kW]}, \quad (5)$$

where: m_{be} is the mass of firewood to be loaded into the stove [kg], and $t_{heating}$ is the nominal heating duration [h].

Calculated value, assuming a nominal heating period of 8 hours: $P = 2.03 \text{ kW}$.

3. Conclusions

It can be stated that the investigated column stove has good efficiency; however, the flue gas exit temperature is below the recommended 240°C , which may have resulted in tar condensation within the chimney.

Based on its nominal heat output, it would have been sufficient for heating a smaller room.

In Bolyai's time, the specification of performance data was not considered essential. If a stove oper-

ated properly and was capable of providing the expected indoor temperature, it was regarded as satisfactory even without detailed knowledge of its technical characteristics [1]. In our opinion, the "green column stove" is exceptionally elegant; it would be worthwhile to consider redesigning and constructing its internal structure in accordance with contemporary requirements.

Acknowledgements

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DEVELOPMENT OF A DIGITAL TWIN USING BUILDING INFORMATION MODELING AND IOT SENSOR NETWORK INTEGRATION

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Abstract

The construction industry has been undergoing significant transformation in recent years, largely driven by the rapid advancement and widespread adoption of Building Information Modeling (BIM) and Internet of Things (IoT) technologies. BIM encompasses intelligent 3D modeling methods and management processes that enable the comprehensive planning, documentation, and management of buildings throughout their entire lifecycle. IoT technologies, through the deployment of sensor networks, allow for real-time monitoring, data collection, and analysis of buildings and their environments. A high-level integration of Building Information Modeling (BIM) and Internet of Things (IoT) technologies can be achieved through the implementation of a Digital Twin framework.

Keywords: digital twin, Building Information Modelling (BIM), Internet of Things (IoT), ESP32, MQTT.

1. Introduction

The integration of BIM and IoT creates an opportunity to utilize real-time data during the design, construction, and operation of buildings for model-based decision-making and to track building operations in real-time. This can increase the efficiency, safety, and sustainability of buildings, while making the costs associated with construction, operation, and facility management more predictable, transparent, and calculable. The combined application of the two technologies, Digital Twin, opens new possibilities in the field of facility management.

1.1. Objectives

The main objective of the research, development, and innovation project is to combine the advantages of BIM (primarily "Closed BIM" in the current phase of the project) and IoT technologies based on a construction industry approach, and

to substantiate its justification and usability, considering the possibilities of the Digital Twin.

In many cases, the goal is the full-lifecycle application of "Closed BIM" systems [1, 2, 3], but its actual implementation is currently subject to compromises [4]. Problems may also arise regarding the long-term storage and accessibility of files [5]. Furthermore, interconnection and monitoring with IoT devices in these closed environments raise even more questions and technical difficulties to be overcome [6, 7, 8]. However, despite these challenges, the application possibilities can be diverse, especially alongside the use of modern technologies [9].

Therefore, this project focuses on developing an integrated methodology and system. Unlike many available solutions and current research, this approach utilizes the BIM model for applications extending far beyond monitoring and visualization. The approach is based on merging and managing

BIM model elements created with Autodesk Revit software and real-time data from IoT sensors within the framework of a central digital twin model. The goal is to develop and test a solution concept that enables the logical connection of real objects and digital models, thereby providing real-time information about the operation and condition of buildings within native models.

1.2 MQTT Standard and protocol

It is important to highlight a key point of the project, which is the application of the correct data transmission and communication method. The foundation for this is the MQTT (Message Queuing Telemetry Transport) protocol. MQTT is a publish-subscribe messaging protocol based on a client-server architecture, explicitly designed for low-resource and constrained network environments. Due to its minimal data footprint and easy implementation, it is particularly suitable for machine-to-machine (M2M) communication and application within IoT systems [10].

The protocol is built upon a transport layer (typically TCP/IP) that provides a reliable, ordered, and bidirectional connection. Furthermore, it is independent of the content of the transmitted messages, thus it can be flexibly applied for transmitting various data types. The publish-subscribe communication model enables the easy coupling of units and supports the development of highly scalable systems. Minimizing network traffic was also considered a high priority during the design of the protocol [10].

In IoT-based facility management systems, the MQTT protocol offers a particularly advantageous communication solution, as numerous different sensors and actuators need to be integrated into a single system. In such systems, continuous data collection typically occurs in the form of temperature, humidity, air quality, energy consumption, or presence values, the transmission of which is often realized over low-bandwidth, intermittently unstable networks. The MQTT protocol allows data transmission to function reliably even with minimal network and energy requirements [11, 12].

The publish-subscribe model is especially favorable from a facility management perspective because it allows for the functional separation of data sources (sensors) and data processors (e.g., supervisory systems, digital twins, BIM-based visualizations, automated control algorithms). This promotes system modularity, scalability, and long-term expandability, which is always a criti-

cal aspect in complex building management environments [13].

Overall, MQTT aligns well with the architectural requirements of smart buildings and complex sensor networks. It supports real-time data flow, reliable device-cloud-device communication, and the efficient servicing of operational decision-support systems.

2. Concept, design, structure

Considering the previous chapters, and our preliminary research and development results, the following main areas have been identified as current and future development target areas:

- Real-time data collection and monitoring: Collecting data from IoT sensors using ESP32 modules, followed by their integration into a native Autodesk Revit [14] (and later Graphisoft Archicad [15]) BIM model and a web-based environment.
- Control and management: Executing operations with automated or independent manual intervention based on incoming data.
- Maintenance predictions: Predicting maintenance needs, reducing costs, and preventing major failures through the analysis of collected data.
- Energy efficiency optimization: Utilizing the data to presumably improve the energy efficiency of the building.
- Improving security and asset protection: Enhancing building security through the analysis of IoT data.
- Use of IFC models: Utilizing BIM models in IFC format alongside the "Closed BIM" methodology approach.
- Implementing Artificial Intelligence (AI): Connecting large language models (LLMs) and custom tools.

In the long term, the goal is to expand the capabilities of the software and hardware environment, establish the highest possible level of software interoperability, and integrate these into a unified, modular framework. In the short term, the focus is on developing methodological principles, preparing the software environment and ensuring its stable operation, interconnecting hardware elements, and verifying the effectiveness of the entire concept.

2.1. Design and structure

Following the literature review and professional background research, one of the first steps in the process is formulating the principles of the hard-

ware architecture concept that serves the expected operation and correspondingly selecting and designing the necessary sensor group and receiving environment (Fig. 1).

During the development of the structure, a primary consideration was that sensors should not be placed independently at various points in the building's spaces, but rather that complex, modularly grouped nodes should be formed. This can also be identified as one of the main directions of the development, for the testing of which our research group's office space provided a suitable environment, where commissioning could be implemented via retroactive, non-destructive installation.

Accordingly, as shown in Fig. 1 a sensor group comprises several sensors and forms a so-called node (Fig. 2).

The central unit of the node is an ESP32-S3 [16], microcontroller, which manages the information arriving from and intended for transmission to the sensors, and which facilitates continuous data exchange with the MQTT broker. The sensors constituting the node are the following:

- internal temperature and humidity sensor,
- external temperature and humidity sensor,
- presence sensor,
- sound generator,
- microphone,
- light sensor,
- light intensity sensor,
- air quality sensor,
- gas sensor,
- smoke sensor,
- rain sensor,
- opening (door/window) sensor,
- infrared transmitter.

In addition to these, another key element of the hardware design is a central unit whose dedicated task is to process and standardize the data packets sent by the nodes to the MQTT broker and then transmit them to a central database. The processing component of the central unit, similar to the node, is an ESP32-S3 microcontroller, which does not have a direct sensor connection. The units are powered by a mains power source.

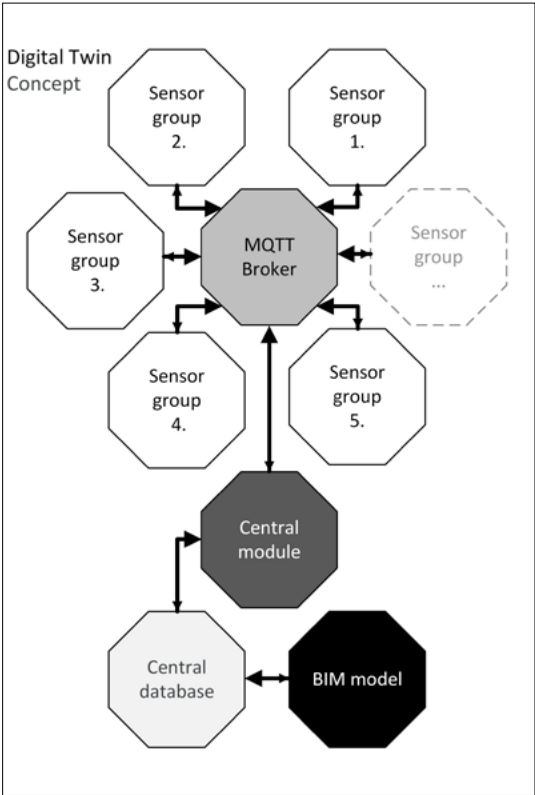


Fig. 1. The main structure of the communication and data flow system.

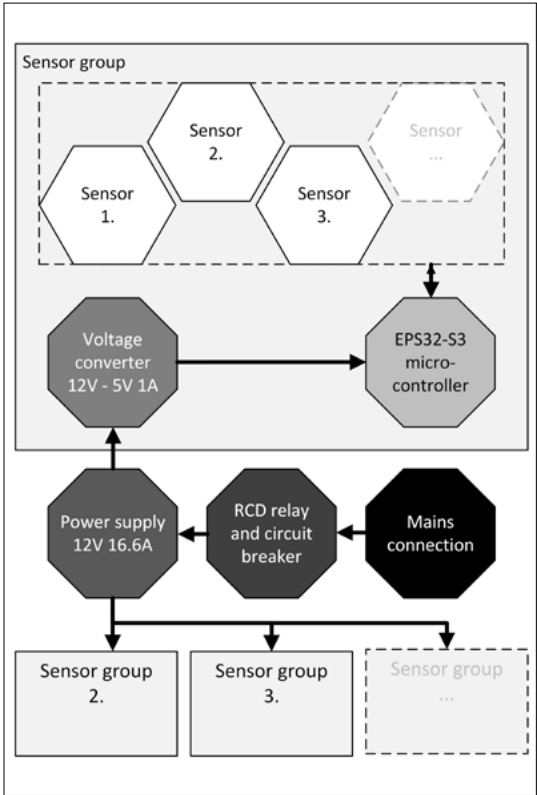


Fig. 2. Main logical principle of the structure.

3. Operating mechanism

The system implemented within the framework of the project is a multi-layered, event-driven, and digital twin centric facility management infrastructure that directly integrates the physical sensor network into a native BIM-based environment. During the system's design, paramount attention was paid to ensuring that individual components can operate independently without blocking each other, stably handle large volumes of data and information, establish a real-time feedback bidirectional connection between the native BIM and the physical infrastructure, and guarantee that every event remains traceable.

The microcontroller-based node located in the physical layer measures various environmental and operational parameters (Fig. 3).

Data collection is coupled with local pre-processing, as the measured values receive a timestamp on the node device, are converted into a structured JSON data format, and utilize a temporary buffering solution in the event of network outages.

Data publication occurs according to the MQTT publish-subscribe model, in which the nodes do not send data directly to the central unit but publish to thematic topics. Thus, the central communication element of the system is a broker-based infrastructure, which ensures the separation of messages by topic, the implementation of delivery according to permission levels, and TLS-based encrypted data transmission.

The central unit connected to the broker plays a dual role: on the one hand, as an MQTT subscriber, it collects and validates data arriving from relevant topics; on the other hand, it provides an interface to the the data storage layer. In the latter case, following verification, the data is transmitted to the central database via REST-based API calls (Fig. 4).

The central unit thus concurrently functions as a control node, as it transmits commands generated in the database as MQTT messages to the appropriate subsystem.

Data persistence is implemented in a relational database environment (as a PostgreSQL-based infrastructure), which provides time-based data storage, indexing by sensor and node identifiers, and the management of control capabilities. The associated permissions management enables the application of a multi-user, differentiated access model. Consequently, the database does not merely serve a storage function but also operates as

```
[12:01] T=26.30°C, RH=44.60%, Heath index =26.57°C
[FILTER] No significant change, not sending.
[TEMP-ADC] raw=0 V=0.000
[LAMP][REQ] lux updated
[TEMP] lux=0.0 (no significant change)
[DS18B20] T=8.2°C
[PM] No significant change, not sending.
[STATE] presence=NONE | door=CLOSED | ldr=DARK | lamp(obs=OFF, asm=ON,
MISMATCH) | mq4=OK(f=2337 b=2343)
[RAIN] No significant change, not sending. state=NONE
[MQ4] No significant change, not sending. state=OK filt=2332 base=2337
[PRESENCE] TRUE
[LAMP][REQ] presence change
[LAMP][EVAL] lux=0.0 (LOW) | ldr=DARK | pres=TRUE | lamp=ON | wantOn=TRUE
wantOff=false
[IR] NEC SEND: ON | reason=LAMP ON condition | code=0x00FFD827
[LAMP][ACTION] ON command sent -> assumed=ON
[LAMP][RETRY] ON attempt: 1/3 az window
[LDR] Change: dark -> light
[LAMP][RETRY] Reset: observed=ON (successful power-up)
[LAMP][OBS] LDR most: BRIGHT | observed=ON | assumed=ON
[LAMP][REQ] LDR change
[LAMP][RETRY] Reset ON retry: wantOn terminated
[LAMP][EVAL] lux=0.0 (LOW) | ldr=BRIGHT | pres=TRUE | lamp=ON |
wantOn=false wantOff=false
```

Fig. 3. Data log sample of node units.

```
[DATA] Starting POST...
[DATA] Sent JSON: {"node_id":"node_01","sensor":"presence","value":1}
[DATA] HTTP code: 201
[DATA] Successful insert
[DATA] Starting POST...
[DATA] Sent JSON:
{"node_id":"node_01","sensor":"light","value":1,"ts_utc":"2026-02-
22T12:01:35Z"}
[DATA] HTTP code: 201
[DATA] Successful insert
[DATA] Starting POST...
[DATA] Sent JSON:
{"node_id":"node_01","sensor":"co2_state","value":1,"unit":"lvl","ts_utc":"
2026-02-22T12:02:27Z"}
[DATA] HTTP code: 201
[DATA] Successful insert
[DATA] Starting POST...
[DATA] Sent JSON:
{"node_id":"node_01","sensor":"sound_event","value":10624,"ts_utc":"2026-
02-22T12:03:13Z"}
[DATA] HTTP code: 201
[DATA] Successful insert
[DATA] Starting POST...
[DATA] Sent JSON:
{"node_id":"node_01","sensor":"temperature","value":26.5,"unit":"C","ts_utc
":"2026-02-22T12:07:00Z"}
[CMD] PATCH 46b70940-51b7-465b-b576-933cae94025e -> sent code=200
resp:{"id":"46b70940-51b7-465b-b576-
```

Fig. 4. Data log sample of central units.

Panel

Status: logged in

Sensor View

Select Sensors

Logout

node_01

Select

sensor	value	unit	local time
co2	915	ppm	2026-02-13 17:32:00
co2_state	0	lvl	2026-02-13 17:35:55
door	0		2026-02-13 17:21:34
heat_index	28,0088	C	2026-02-13 17:30:00
humidity	41,9	%	2026-02-13 17:21:11
light	0		2026-02-13 17:43:44
light_lux	0,0806	lux	2026-02-13 17:21:16
mq4_gas_event	0		2026-02-13 17:23:59
outdoor_temperature	24,4375	C	2026-02-08 04:00:11
pm10	4,2	ug/m3	2026-02-13 17:21:20
pm25	1,7	ug/m3	2026-02-13 17:21:18
presence	1		2026-02-13 17:47:39
rain	0		2026-02-13 17:21:30
sound_event	239		2026-02-13 17:49:39
sound_level	5,3056	%	2025-12-18 15:16:48
temperature	28,3	C	2026-02-13 17:21:09

Fig. 5. Revit sensor data viewer Add-in.

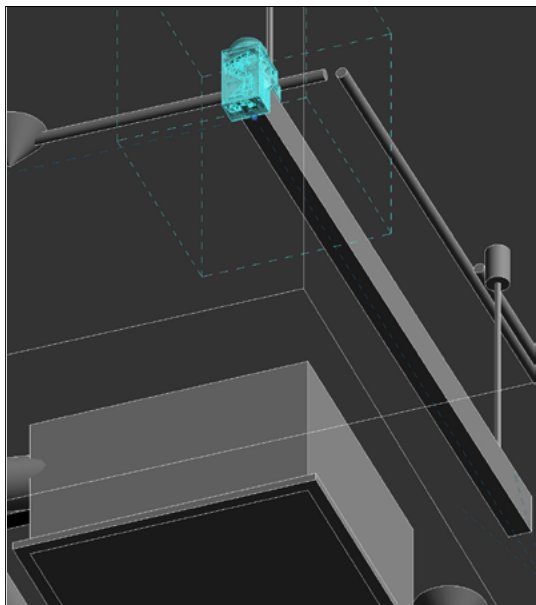


Fig. 6. BIM model with a node element.

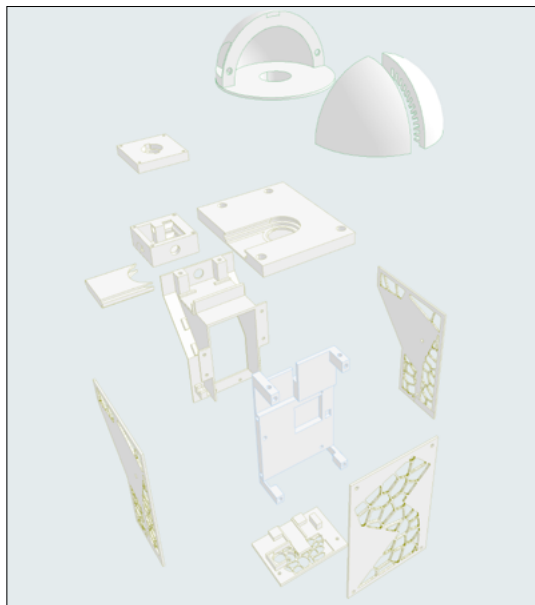


Fig. 7. Exploded 3D model of the designed device frame.

the state repository and instruction manager of the digital twin. From this, the upper layers, including the native BIM environment, extract information using structured queries.

At the highest level of the system lies the native BIM-based digital twin layer, which currently connects to the database via a custom, complex add-in developed on the Autodesk Revit platform (Fig. 5).

The objects in the model (Fig. 6) are connected to the physical sensor network using unique identifier parameters.

The add-in communicates via the API, queries the current sensor data, and then integrates it into the model at the parameter management and visualization level. As a result, the native BIM model transforms into a dynamic state representation. Within this framework, geometric entities will no longer simply be static design or construction objects, but digital entities possessing real-time operational data.

A defining characteristic of the system is the implementation of closed-loop control. The user can generate control instructions in the native BIM environment and, in the subsequent phase of development, through a connected web interface; these are recorded in the database as structured command records. The central unit transmits this information in the form of an MQTT message to the appropriate topic, which the affected nodes

also monitor as subscribers. Following execution, the system generates a status message and updated sensor data, which is re-entered into the data stream, ensuring the state change also appears in the digital twin. This mechanism ensures consistent, auditable, and real-time feedback between the physical infrastructure and the virtual model.

In summary, the architecture developed in the project should not be interpreted as a one-way, linear data processing chain, but rather as an event-driven, MQTT broker-based, bidirectional communication system featuring a regulated state repository. The integration of the physical sensor network, the message broker layer, the database, and the native BIM model-based digital twin results in a complex information ecosystem suitable for real-time monitoring, predictive analysis, and active intervention alike, laying the groundwork for a higher-level implementation of intelligent facility management.

4. Device frame

Since a complex sensor node is being created in the project and modularity is a primary consideration, a custom-designed frame is required (Fig. 7).

The prototype of the device frame was produced using a 3D printer. Given that robust protection against dropping or falling is not necessary in this

instance, a white, 1.75 mm diameter Polylactic Acid (PLA) printing filament was utilized (Fig. 8).

Currently, the prototype has been created specifically tailored to the characteristics of the concrete test environment, but the future goal also encompasses designing much more universally applicable versions. Regarding its internal structure, every sensor was placed on a custom-designed receiving surface and in a dedicated position. The implemented construction not only provides fundamental protection for the sensors but also ensures non-destructive, straightforward installation, accessibility, and maintainability (Fig. 9).

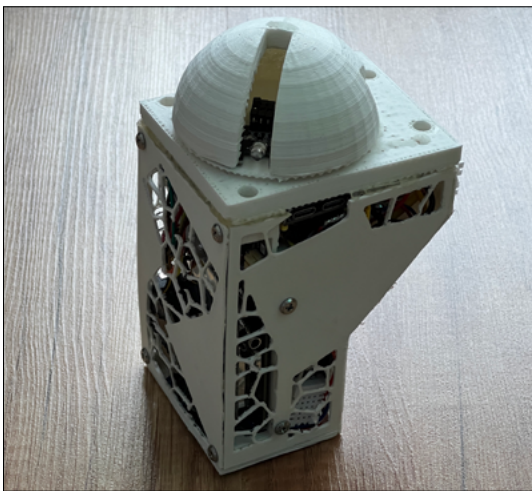


Fig. 8. Printed, assembled model of the prototype.



Fig. 9. The installed device.

5. Conclusions

A bemutatott rendszerarchitektúra egy integrált, kéThe presented system architecture represents the first working prototype of a digital twin-based facility management infrastructure implementing integrated, bidirectional communication. The system is capable of both real-time condition monitoring and control feedback, establishing the connection between the native digital model and the physical infrastructure. However, it must be emphasized that the research, development, and innovation process is currently still in its preliminary phase. The current implementation is of a proof-of-concept nature, focusing primarily on validating the structure and assembly, examining communication reliability, and verifying the operability of the native BIM-based integration.

Nevertheless, the potential inherent in the system is significant, particularly regarding scalability, automated decision support, and predictive operational models. Further development directions can be interpreted across multiple dimensions, and beyond the application and research vectors identified as target areas in chapter 2; the project carries additional innovation potential. Among those not yet mentioned, the first to be highlighted is the creation of modules with identical compositions but varied shapes that can be installed in alternate locations or positions, alongside the full implementation of web access and hosting the system on a dedicated server. A further strategic direction is increasing sensor density, expanding the system within a pilot environment, and elevating the IT security level. Additionally, the development can provide an excellent framework in the future for involving students in research group activities, as well as for preparing domestic and international grant projects.

Overall, it can be concluded that the system created within the framework of the project in its current state serves as the foundation of a scalable digital twin platform, which, with appropriate further development, is capable of the integrated implementation of intelligent facility management, data-driven decision support, and real-time infrastructure control. The present results provide the basis for the subsequent development phase, wherein the industrial validation, security reinforcement, and scientific deepening of the system will be simultaneously realized.

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DATA PROCESSING AND EVALUATION OF FRICTION FACTORS OBTAINED USING A STICK-SLIP LABORATORY MEASURING DEVICE

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Abstract

The aim of the study was to determine the frictional properties of different material pairs using a stick-slip laboratory measuring device. During the measurements the contact of aluminum, steel, tin, cooper, brass with a polymer conveyor belt was analyzed. By processing the experimental data, the static and kinetic friction coefficients were determined and compared with values recommended in the literature. For more accurate evaluation, correction procedures were applied in the determination of the friction coefficients.

Keywords: *stick-slip phenomenon, coefficient of friction, data processing, evaluation.*

1. Introduction

Friction is one of the fundamental physical phenomena in mechanical systems, which has a significant impact on the operation and service life of components.

At low displacement speeds of 0.18-180 mm/min, the movement of friction joints is followed by a stick-slip phenomenon.

The stick-slip phenomenon can be explained by the creation of adhesion and friction points [1, 2, 3, 4].

The stick-slip phenomenon plays a particularly important role in understanding the dynamic friction processes between moving surfaces [5, 6, 7].

This phenomenon results from the periodic alternation of adhesion and slippage, which can cause vibrations and uneven movement. The study of this phenomenon contributes to the optimization of the operation of various industrial equipment.

The laboratory stick-slip measuring device can be used to test different material pairs.

The measurements allow the static and sliding friction coefficients to be determined.

The results can be compared with data found in the literature, which helps to validate the measurement methods.

The tests contribute to a deeper understanding of friction processes and the development of tribological systems.

1.1. Equipment design

The equipment consists of a small Dörner conveyor belt driven by an electric motor.

The conveyor belt is made of PVC-coated fabric, 610 [mm] long and 155 [mm] wide, with a maximum load capacity of 36 kg.

A force sensor is attached to the frame of the conveyor belt, to which a spring is connected, and the test specimen is placed at the end of the spring.

The force sensor is connected to a measuring circuit and an Arduino card that performs the measurement. The force sensor module is attached to the frame of the conveyor belt.

The test specimen is a rectangular piece of wood weighing 313 grams, with a 0.5 mm thick metal plate attached to its bottom, which is in contact with the PVC conveyor belt.

The frame of the device is made of Bosch 45x45 aluminum profiles. The conveyor belt is located on this frame (Fig. 1).

Condition for adhesion (Fig. 2):

$$F_r \leq \mu_s \cdot N, \quad (1)$$

where: F_r - spring force;
 N - normal force;
 μ_s - static friction coefficient.

F_s static friction force relationship:

$$F_s = \mu_s \cdot N \quad (2)$$

The equation of slippage (Fig. 3):

$$F_{cs} - F_r = m \cdot a \quad (3)$$

$$F_{cs} = \mu_k \cdot N, \quad (4)$$

where: F_{cs} - sliding friction force,
 m - test body mass,
 μ_k - kinetic friction coefficient.

2. Determining the friction factor

During the measurement process, we continuously recorded changes in friction force, which allowed us to determine the force associated with the adhesion and slippage conditions. We determined the stick-slip adhesion and sliding friction coefficients of CuZn, Cu, Al, Sn, and FeC materials on the plastic surface

Conditions for periodic slippage:

$$\mu_s / \mu_k \geq 1 \quad (5).$$

To determine the static friction coefficient, we use the maximum force immediately before slippage (Table 1).

For the kinetic friction coefficient, we use the average force during slippage (Table 1, light shade).

We determined the static and kinetic friction coefficients using the measured maximum force values. We used equations (1...5) to calculate the friction factors.

Table 1. Values of measured forces

Measured force [N]				
CuZn	Cu	Al	Sn	FeC
0.01	0.22	0.07	0.13	0.3
0.64	1.8	0.13	1.02	0.41
2.49	3.21	0.13	2.69	0.12
3.45	3.85	0.06	3.51	0.08
3.94	4.47	1.42	4.11	0.1
4.43	5.09	3.06	4.73	0.93
4.92	5.71	3.86	5.35	2.42
5.5	6.33	4.4	5.95	3.07
6.1	6.94	4.96	6.54	3.6
6.71	7.53	5.46	7.14	4.11
7.32	7.85	5.87	7.75	4.35
7.94	7.28	6.1	8.35	4.37
8.55	6.06	6.21	8.94	4.11
9.17	5.07	6.22	9.14	3.62
9.8	4.97	6.22	8.26	3.31
9.67	5.5	6.18	6.62	3.43
2.49	6.12	6.16	5.21	3.8
0.25	6.73	6.14	4.89	4.1
1.57	7.33	6.09	5.37	4.25
3.04	7.95	6.04	5.99	4.22



Fig. 1. The planned equipment.

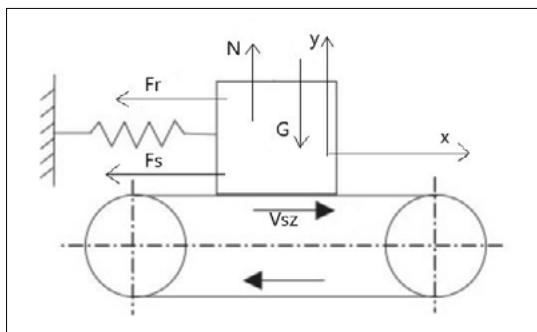


Fig. 2. The effect of forces in the case of adhesion.

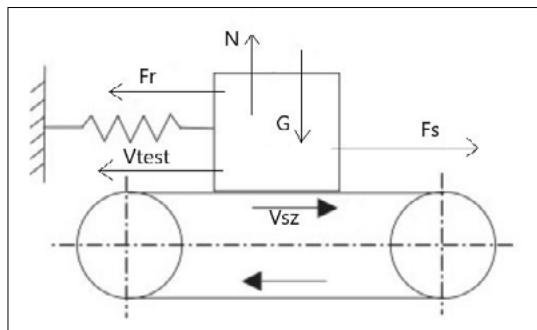


Fig. 3. The effect of forces in the event of slippage.

2.1. Experimental results

The condition for intermittent slippage are met [Table 2](#).

During the measurements, changes in force over time ([Fig. 4.](#), [5.](#), [6.](#), [7.](#), [8.](#)), can be observed at the contact points of different material pairs. Periodic force fluctuations can be observed in the graphs, indicating the presence of adhesion and slippage phenomena. For some materials, the force peaks and minima occur at different amplitudes, which indicates different friction properties. In the case of Sn, the force fluctuation is relatively uniform, while CuZn show larger amplitude fluctuations. For aluminum, the force change shows less fluctuation, indicating more stable sliding behavior. In the case of steel, the change in force is more uniform, with smaller amplitude fluctuations, indicating a more stable sliding process and less stick-slip effect. In the case of Cu, a gradual increase in force can be observed during the adhesion phase, followed by a sudden decrease during slippage, indicating greater friction fluctuations.

Table 2. Average values of friction factors

Material	CuZn	Cu	Al	Sn	FeC
mass [kg]	0.43	0.45	0.43	0.43	0.47
$\mu_{\text{static 1}}$	2.30	1.65	1.49	2.19	0.96
μ_{kinetik1}	0.97	1.21	1.43	1.45	0.80
$\mu_{\text{static 2}}$	1.86	1.96	1.42	1.92	0.93
μ_{kinetik2}	1.74	1.35	1.40	1.23	0.85
μ_{static3}	2.23	2.14	1.50	2.08	1.00
μ_{kinetik3}	0.67	1.35	1.40	2.02	0.84
$\mu_{\text{average adhesion}}$	2.13	1.92	1.47	2.06	0.96
$\mu_{\text{average slip}}$	1.13	1.30	1.41	1.57	0.83
ratio	1.89	1.47	1.05	1.32	1.16

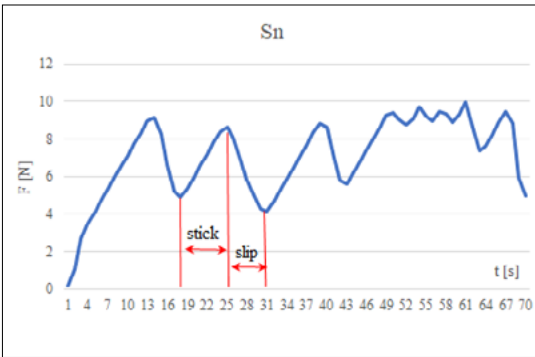


Fig. 4. Force change over time for Sn-PVC, without lubricant .

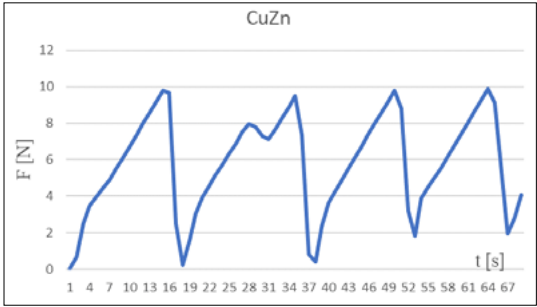


Fig. 5. For CuZn-PVC, the change in force over time, without lubricant.

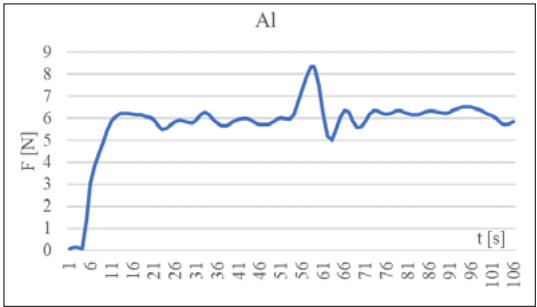


Fig. 6. Force variation over time for Al-PVC, without lubricant.

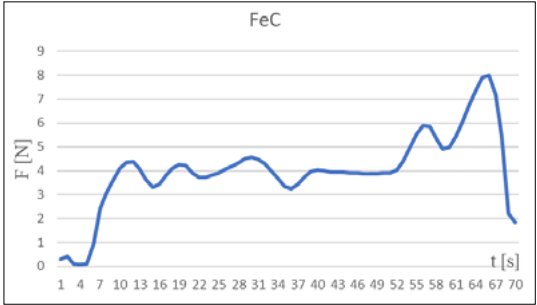


Fig. 7. FeC-PVC, the change in force over time, without lubricant.

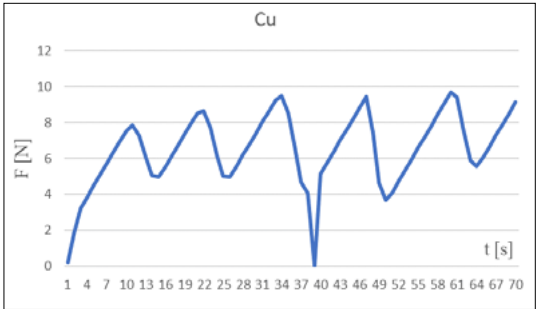


Fig. 8. Cu-PVC, the change in force over time, without lubricant.

Table 3. Comparison between measured and literature-based adhesion friction coefficients

	μ average	literary data	
CuZn	2.13	0.8	r
Cu	1.92	0.8	0.8161
Al	1.47	0.9	
Sn	2.06	0.7	
FeC	0.96	0.9	

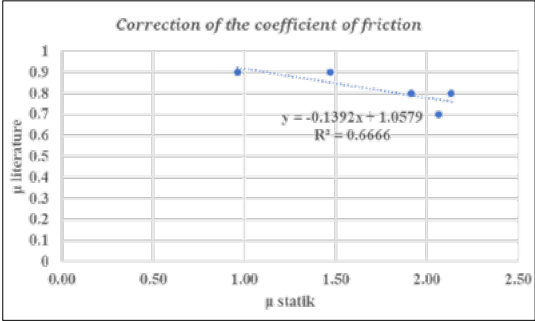


Fig. 9. Correction of the coefficient of friction.

2.2. Data processing

We compared the experimental results with the friction factor values recommended in the literature. In order to examine the differences, we created correction curves for both static and kinematic friction coefficients. Using linear regression analysis, we determined the relationship between the measured and literature values, (Fig. 9), (Fig. 10), which allowed us to refine the measurement results.

3. Conclusions

The equipment enabled us to observe significant differences in friction behavior between different material pairs. The tests confirmed that the equipment is suitable for analyzing stick-slip friction factors and processes.

Table 4. Comparison between measured and literature values for sliding friction coefficients

	μ average slip	literary data	
CuZn	1.13	0.6	r
CuZn	1.30	0.6	0.7708
Al	1.41	0.7	
Sn	1.57	0.5	
FeC	0.83	0.8	

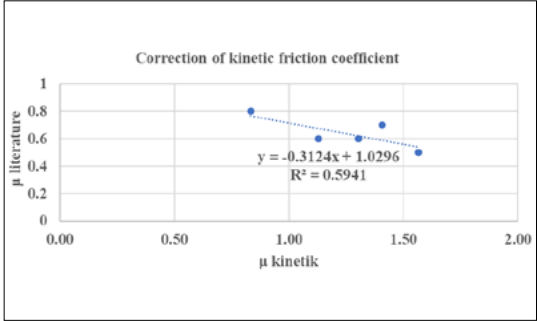


Fig.10. Correction of kinetic friction coefficient.

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AI-BASED ON-SITE CONSTRUCTION QUALITY CONTROL: EXPERIENCES IN TRAINING AI FOR CONSTRUCTION-SPECIFIC APPLICATIONS

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Abstract

This study investigates the applicability of artificial intelligence in the construction industry, specifically focusing on the automation of on-site quality control through the training and fine-tuning of a YOLO-based segmentation model. The research presents the process of creating custom, construction-specific datasets within a Docker-based CVAT environment, highlighting the significance of the Human-in-the-Loop (HITL) methodology. To minimize human annotation time and prevent faulty feedback loops, the workflow was optimized using a custom Python script. By integrating the Douglas-Peucker algorithm and IoU-based filtering, this solution automatically smooths the fragmentation of AI-predicted polygons and eliminates duplicates. The results demonstrate that combining algorithmic cleaning of raw detection data with expert supervision is essential for developing reliable, industrial-grade AI solutions in the construction sector.

Keywords: *computer vision, construction quality control, YOLO segmentation, Human-in-the-Loop (HITL).*

1. Introduction

The construction industry is globally one of the largest economic sectors; however, it lags behind other industries—such as manufacturing or automotive—in terms of digitalization and automation. Nevertheless, with the increasing complexity of modern construction projects and stricter quality and safety requirements, the integration of Industry 4.0 technologies has become inevitable. Artificial intelligence (AI), and particularly Computer Vision (CV) algorithms, have brought a breakthrough in monitoring on-site processes, improving occupational safety, and conducting quality control. Traditional, manual methods of on-site quality control are highly time- and resource-intensive, and they heavily depend on the subjective judgment and current decision of the inspecting professional.

Systems based on Machine Learning (ML) and Deep Learning (DL) are now capable of identifying deviations, defects, and safety risks in real-time from visual data (images, videos, point clouds) captured on-site. However, the efficiency and industrial applicability of these models - such as YOLO (You Only Look Once) object detection architectures - are directly proportional to the quality and size of the datasets used for their training. This is especially true for specific, highly complex tasks such as the quality control and segmentation of masonry structures. Construction data is often unstructured and noisy, and creating properly labelled training databases of sufficient size and quality remains a significant barrier to the practical implementation of AI.

The aim of this study is to investigate the applicability of AI in the construction industry, specifically focusing on automating on-site quality control

by training and fine-tuning a YOLO-based segmentation model. The research focuses on generating specialized datasets for masonry work. The workflow was implemented in a Docker-based CVAT (Computer Vision Annotation Tool) environment, with a strong emphasis on the Human-in-the-Loop (HITL) method. Since manual annotation is expensive and slow, this research presents an optimized, Python script-based solution that automatically smooths the fragmentation of AI-generated polygons and removes redundant duplicates by integrating the Douglas-Peucker algorithm [11] and Intersection over Union (IoU) based filtering. The article investigates and proves the hypothesis that combining the algorithmic cleaning of raw detection data with expert human supervision (HITL) is essential for developing reliable, industrial-grade AI quality control systems.

2. Literature review

The literature on the application of AI and computer vision in the construction industry has shown exponential growth over the past decade. The focus of research ranges from safety monitoring to automated condition assessment and integration with project management systems.

2.1. Integration of AI and BIM in the construction industry

A significant portion of AI applications in construction is linked to Building Information Modeling (BIM) frameworks. Pan and Zhang [2] pointed out in their comprehensive study that integrating BIM and AI is critical for automating future construction processes, where AI-based data processing complements the static geometric and semantic data of BIM. Similarly, Zheng et al. [3] examined the integration of deep neural networks and BIM for the next generation of building condition assessment, proving that processing visual data with AI greatly increases survey accuracy. In the specific, enclosed, and hazardous environment of underground construction (tunneling), Ninic et al [4] investigated the synergies of machine learning and computer vision with BIM, highlighting the importance of real-time monitoring. Using an innovative, game-like approach, Boton et al. [5] developed a hybrid application that enables on-demand monitoring of construction projects by combining BIM and machine learning, thereby improving information flow between project managers and on-site processes.

2.2. Adaptation and implementation challenges in the industry

Although the technological background is available, industrial adoption faces several issues. Elghaish et al [6] examined the current and future applicability of AI tools from an industry perspective, emphasizing that the lack of knowledge and missing data management protocols are the main barriers. Regarding preventive measures and occupational safety, Muñoz-La Rivera et al. [7] analysed the feasibility of adopting new technologies (including AI). Testing adoption influencers with a "light" deep learning approach, Abioye et al. [8] concluded that optimized models requiring less computational capacity could promote wider technology adoption among construction companies. Zhong et al. [9] also addressed this issue, investigating small-sample training frameworks for extracting information from construction accident reports, noting that intelligent data preparation and augmentation are essential in data-scarce environments.

2.3. Deep learning in defect and deficiency detection

The most common AI application for on-site quality control is defect detection. Li et al. [10] developed a rule-based deep learning method for evaluation-oriented facade defect detection, providing objective metrics for repair work. The focus is also increasingly shifting towards Off-Site Construction (OSC) elements: Kim et al. [11] used deep learning-based image recognition to detect cracks and inspect the quality of precast concrete elements, significantly reducing the need for human inspection. Besides quality, safety is also critical: Wang et al. [12] combined deep learning with Augmented Reality (AR) to identify scaffolding assembly deficiencies on-site.

2.4. Operating principle and evolution of the YOLO architecture

Among convolutional neural networks (CNNs), the YOLO (You Only Look Once) [13] architecture, introduced in 2016, represented a major milestone in object detection. Unlike traditional two-stage region proposal methods, YOLO treats object detection as a single integrated regression problem. The network evaluates the entire input image in one phase, dividing it into a grid, and simultaneously predicting bounding boxes and their corresponding class probabilities. Thanks to this "single-glance" principle, YOLO can operate

at outstanding speeds (even in real-time), making it a priority for computer vision in construction.

In recent years, the architecture has undergone significant evolution in construction applications. Recent studies [14] applied earlier v8 iterations of YOLO, enhanced with a normalization-based attention mechanism, to detect building surface defects. As a result of continuous development, Ultralytics introduced the latest generation of the architecture, the YOLO26 model [15], which is also used in this research. In earlier versions (e.g., v8, v11), the network often predicted many overlapping boxes that had to be filtered out using a computationally heavy post-processing algorithm, the Non-Maximum Suppression (NMS) step. The main technological innovation of YOLO26 is its "End-to-End" operational logic, which eliminates the NMS phase and directly outputs the final detections and segmentation masks. This architecture speeds up model execution and increases pixel-perfect masking precision [15], which is a critical prerequisite for the robust segmentation of the large number of densely packed masonry units (bricks) focused on in this study.

2.5. Research gap and relevance of the current study

While the literature pays attention to YOLO-based detection and the application of deep learning models in construction, most studies focus on the accuracy of out-of-the-box models (bounding-box based detection) and pay less attention to the operational challenges of data preparation, pixel-perfect segmentation, and the training phase. For on-site quality control—such as checking masonry joints, bricks, and potential construction inaccuracies—providing a simple bounding box is insufficient; precise masking and segmentation are required. Generating segmentation datasets consumes huge amounts of human resources (annotation time).

An identifiable gap in the literature is the lack of an optimized framework, applicable in industrial practice, that algorithmically refines raw AI-generated predictions (segmentation polygons) before presenting them to a human expert for approval. This research aims to fill this gap by combining YOLO-based segmentation with the Human-in-the-Loop (HITL) methodology, geometric smoothing algorithms (Douglas-Peucker), and IoU-based cleaning, specifically optimized for quality control in masonry workflows.

3. Research methodology and iterative model development

3.1. Problem statement and research objective

The long-term goal of quality control for masonry structures is the automated, real-time inspection of correct brick bonds and overall geometric accuracy of the wall. This research implements the first and most critical step of this comprehensive system: developing an artificial intelligence (AI) based computer vision model capable of detecting each installed brick with high reliability and pixel-perfect segmentation in its proper spatial position. The complexity of the task lies in the homogeneous texture and high density of the bricks, which presents a significant challenge for object detection algorithms.

3.2. Data collection and primary annotation (round 1)

The first step was capturing raw visual data and creating the initial dataset. Data labeling (annotation) was carried out in an isolated, Docker-containerized CVAT (Computer Vision Annotation Tool) environment (Fig. 1). The initial training dataset was created using strictly manual polygon annotation. Using this relatively small dataset, we performed the primary baseline training of the YOLO (You Only Look Once) segmentation model.

Initial results and validation data highlighted the limitations of conventional training: although the model could detect some of the masonry elements, significant anomalies occurred. It failed to identify many bricks, the predicted segmentation traces were overly fragmented (jagged), and due to the dense layout, overlaps and duplications on the same surface were frequent.

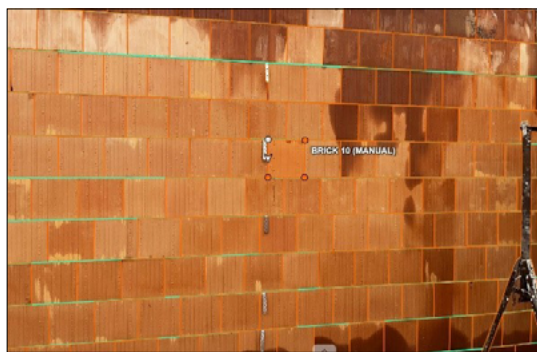


Fig. 1. Example of a labeled photo in the CVAT environment.

3.3. Algorithmic optimization and the Human-in-the-Loop (HITL) method

To avoid feeding back the faulty and noisy outputs generated by the model, we developed a custom Human-in-the-Loop (HITL) feedback loop and an algorithmic cleaning procedure. Before loading them back into the CVAT interface, the raw predictions (pre-labeling) generated by the 1st-round model were processed using a custom-developed Python script that addressed two critical problems (Fig. 2):

- Reducing fragmentation (Douglas-Peucker algorithm): The script algorithmically smoothed the overly complex polygons generated by the model using the Douglas-Peucker algorithm. The system dynamically increased the simplification (epsilon) value until the polygon point count dropped below a predetermined, optimal maximum (e.g., 6 points/brick). This was complemented by the YOLO model's high-resolution mask generation (retina_masks=True) feature.
- Filtering duplications and overlaps (IoU intersection analysis): To remove false predictions, the script calculated the overlap (Intersection over Union - IoU) between polygons using the Shapely geometric library. For overlaps exceeding a critical threshold, the algorithm automatically discarded the less confident duplicate.

This cleaned dataset was loaded into CVAT, where expert human supervision was reduced to replacing missed bricks and making minimal edge adjustments, significantly speeding up the annotation process (based on our measurements, we achieved an efficiency increase of approximately 40%).

3.4. Iterative fine-tuning and the final model

ADuring the research, data cleaning and model fine-tuning were carried out iteratively in multiple rounds to continuously improve quality.

In the intermediate training rounds, the model received data that had been cleaned with the Douglas-Peucker and IoU algorithms and then manually reviewed. Here, the model stopped learning its own previous mistakes (fragmented polygons) and gradually stabilized the geometric boundaries.

In the fourth and final fine-tuning round, we achieved stable operation capable of eliminating duplications and clearly segmenting bricks even in dense masonry structures.

The multi-step iteration proved that consecutive algorithmic filtering, combined with the HITL methodology, can refine the model even with a low initial image count and guarantee the pixel-perfect segmentation essential for running future masonry quality control algorithms.

4. Results and evaluation

The effectiveness of the iterative, Human-in-the-Loop (HITL) based data optimization presented in this research is confirmed by the output metrics and visual predictions of the repeated training rounds. The results clearly demonstrate the justification for Douglas-Peucker and IoU-based filtering in masonry segmentation.

4.1. Learning dynamics and convergence of the model

The stability of the multi-step fine-tuning process is validated by the learning curves. Based on the analysis of the training (train) and validation (val) loss functions, it can be concluded that the

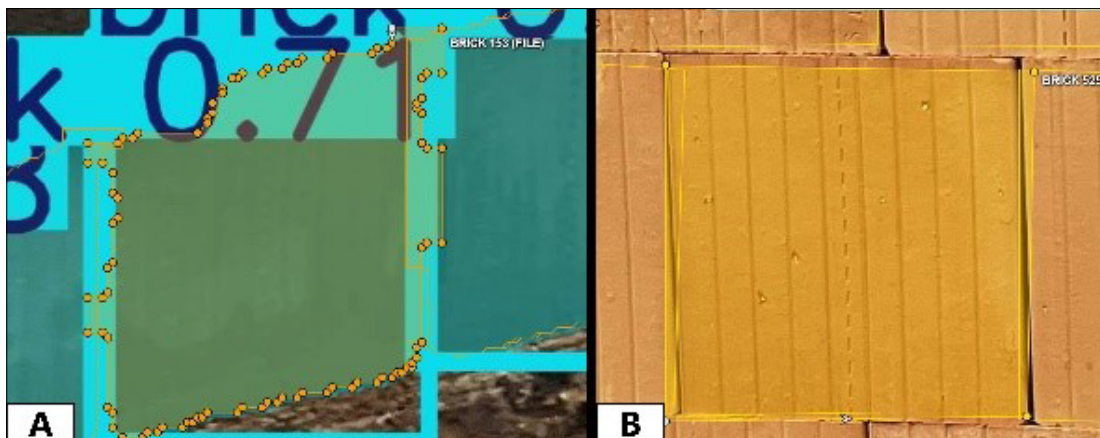


Fig. 2. Illustration of the HITL method: "A" State before running script, „B" state after running script.

model is free from overfitting. The loss evaluating bounding box positioning (box_loss) and the loss measuring pixel-perfect masking (seg_loss) decreased sharply as the training cycles progressed (Fig. 3). This means that with the prepared dataset—free of fragmentation and duplications—the neural network could learn the geometric characteristics of the bricks with optimal gradient descent, without redundant information.

4.2. Classification accuracy and confusion matrix analysis

The model's classification reliability is evaluated in most detail by the normalized confusion matrix (Fig. 4). The analysis focused on separating the background from the target object (brick). Based on the matrix data, the model correctly identified the masonry elements with a functional 87% (True Positive) rate. The background error rate dropped to a minimum, confirming that visual noise behind the wall, potential mortar residue, or scaffolding parts only partially interfere with detection.

4.3. Segmentation metrics (mAP)

The final performance of the fine-tuned network is quantified by Mean Average Precision (mAP) metrics. By the end of the fourth iteration round, the model achieved a 60.3% mAP50 (0.603) accuracy for segmentation masks. What is even more relevant from an industrial perspective: the highly strict mAP50-95 metric, which measures pixel-perfect fit, rose to 42.6% (0.426). Although recognizing dense building materials with homogeneous textures is generally a challenge for computer vision, this increase compared to the raw, first-round model results (where the value stagnated around ~32-36%) is directly due to the algorithmic edge smoothing (Douglas-Peucker) and the HITL methodology.

4.4. Visual predictions and industrial applicability

The numerical results are also supported by visual tests run on the validation dataset. The analysis of prediction outputs shows that the model successfully identifies the masonry elements. It is important to highlight that due to the strict IoU filtering set during preprocessing, duplicated masks have disappeared in the dense masonry structure. The edges of the predicted polygons are quite straight and fit the physical boundaries of the bricks as accurately as possible.

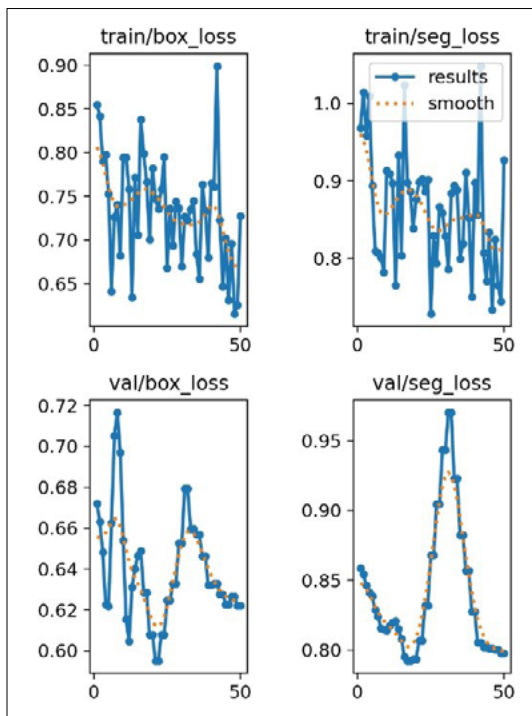


Fig. 3. Training and validation loss curves of the YOLO segmentation model during the 4th iteration.

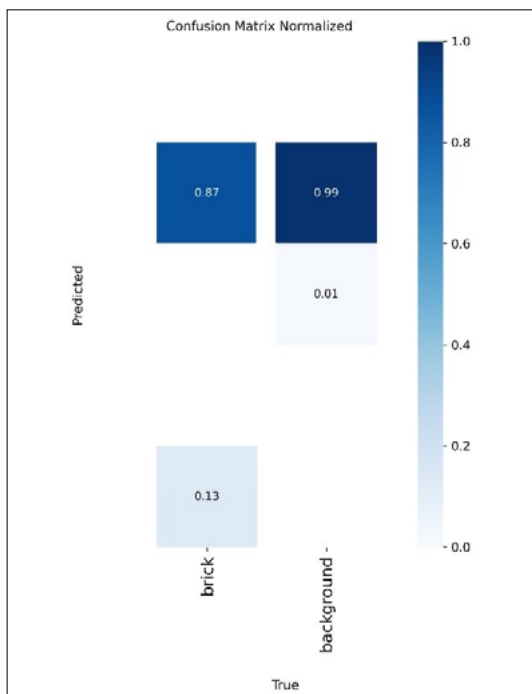


Fig. 4. Normalized confusion matrix.

5. Summary and conclusion

This study investigated one of the tasks of computer vision in construction: artificial intelligence-based brick detection and segmentation required for the quality control of masonry structures. The research highlighted the technological problem that raw, out-of-the-box YOLO segmentation models cannot immediately provide industrial-grade reliability in the homogeneous, texture-rich, and dense environment of the construction industry. Training on uncleaned data results in fragmented polygons and duplicated recognitions, which during model fine-tuning only leads to the conservation of existing errors.

The main scientific and practical contribution of this research was the development and validation of an optimized Human-in-the-Loop (HITL) workflow. It was proven that cleaning raw AI predictions using automated Python scripts - polygon edge smoothing via the Douglas-Peucker algorithm and IoU-based duplicate filtering - significantly speeds up manual annotation work in the CVAT environment. As a result of iterative training on the cleaned data, the model's recognition accuracy increased significantly, the mAP50 value for masks exceeded 60%, while the human resources spent on annotation dropped to a fraction.

Overall, the presented data-centric AI approach provides a promising foundation for construction automation. Future research directions will build on the currently developed, stable detection model: the geometric analysis of segmented polygons will enable the fully automated, real-time software inspection of correct brick bonds, surface flatness, and joint thicknesses on construction sites, even by non-expert clients.

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VALIDATION VS ACCREDITATION IN ARCHITECTURAL EDUCATION: FROM ADMINISTRATIVE RATIONALITY TO THE INSTITUTIONAL RECOGNITION OF DESIGN KNOWLEDGE

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Abstract

The aim of this paper is to clarify the distinction between accreditation and validation in the context of architectural education and to demonstrate that these mechanisms rest on different conceptions of quality. The analysis shows that European higher education quality assurance systems—particularly ESG-based accreditation—primarily interpret quality in terms of structural compliance, documented procedures, and measurable learning outcomes. This approach ensures institutional stability and legal legitimacy. However, architectural education is based on a specific form of knowledge. Design knowledge is integrative, context-dependent, and partly implicit, emerging through reflective and iterative processes within studio-based learning environments. These characteristics limit the applicability of purely compliance-based quality frameworks. The paper argues that validation—especially within the UNESCO–UIA framework—represents a different institutional logic. While accreditation focuses on operational conditions, validation addresses pedagogical coherence and professional orientation through peer review processes. As a result, the paper proposes a layered model of quality in architectural education, distinguishing structural, pedagogical, and professional dimensions. Within this framework, accreditation and validation are not alternatives but complementary mechanisms.

Keywords: *administrative rationality; design knowledge; architectural epistemology; studio-based pedagogy; validation; accreditation; quality assurance; peer review; institutional logics; professional legitimacy; architectural education; UNESCO–UIA; ESG.*

1. Introduction: The Transformation of the Concept of Quality

The concept of quality in higher education has undergone a fundamental transformation over the past few decades. The previously implicit understanding of quality, based on professional reputation and academic autonomy, has gradually been replaced by a formalized, documentable, and auditable quality assurance framework. The Bologna Process and the establishment of the European Higher Education Area (EHEA) have grad-

ually institutionalized the concept of quality and placed it within a regulated framework. The ESG (Standards and Guidelines for Quality Assurance in the European Higher Education Area) framework adopted by the European Higher Education Area (EHEA) increasingly defines quality in terms of structural compliance, documented procedures, and alignment with measurable learning outcomes [1].

This is of particular significance in architectural education, as the quality of programme is not limited to structural compliance: a significant por-

tion of design knowledge is implicit, integrative, and reflexive in nature. This raises the question of whether quality interpretation can be confined to purely administrative and compliance-based frameworks.

The transformation of the concept of quality has dual implications for architectural education. On the one hand, accreditation ensures the stability and legitimacy of operations. On the other hand, it emphasises the need for the interpretive framework of quality not to be limited solely to compliance, but also to create opportunities for the institutional representation of the specific nature of design knowledge.

In this context, the study examines the relationship between accreditation and validation and argues that, alongside the current interpretation of quality based on administrative rationality, it is essential to develop normative and professional frameworks that promote the institutional recognition of design knowledge.

2. Administrative Rationality and the Institutional Logic of Accreditation

2.1. The formalization of quality within the ESG framework

The Bologna Process and the establishment of the European Higher Education Area (EHEA) have gradually transformed quality into a regulated, documented, and auditable category. The central reference framework for this is the ESG, adopted by the EHEA Ministerial Conferences and regularly reviewed [1].

The ESG has a dual purpose: on the one hand, it ensures that the operations of higher education institutions are transparent, verifiable, and professionally reliable; on the other hand, it promotes the comparability of European higher education systems and the mutual recognition of qualifications. The ESG structures higher education quality assurance around three main areas: first, the institutions' internal quality assurance systems, which include curriculum design and development, the definition of learning outcomes, the collection of student feedback, and the operation of assessment and examination systems; secondly, external quality assessment procedures, including program and institutional accreditation, as well as quality assurance audits; and thirdly, the regulation of the operation of quality assurance and accreditation organizations, which defines the operating principles of these organizations and ensures their independence and credibility.

This structure links quality to formalized procedures, documented data, processes, and auditable procedures. Accordingly, formalization creates a standardized reference framework, strengthens documentability, and makes auditability a central principle, whereby external experts examine whether operations comply with prescribed standards. Quality is thus increasingly linked to explicitly defined, measurable, and auditable learning outcomes.

2.2. The Theoretical Background of Administrative Rationality

This transformation fits into a broader process of rationalization, a classic analysis of which was described by Max Weber as one of the fundamental characteristics of modern organizational operations: activities increasingly take place within regulated, formalized, and verifiable frameworks [2], thus quality becomes not primarily a matter of interpretation but of verification, and therefore an administrative category. This administrative rationality is evident in ESG-based accreditation systems. Administrative rationality is not merely a technical procedure but a specific form of modern institutional operation, the aim of which is to ensure that decisions are based not on personal preferences but on general rules. Higher education quality assurance systems are manifestations of this logic. ESG-based accreditation evaluates according to predefined standards, requires documented learning outcomes, monitors institutional operations through external expert audits, and operates within a cyclical review system.

Weber, however, warned of the limits of rationalization, its "iron cage": formalized rationality tends to reduce goals to means and to prioritize formal compliance over substantive values [2]. In this sense, the formalization of the concept of quality cannot be regarded as a completely value-neutral process. Accreditation interprets quality along structural and procedural categories. These mechanisms are indispensable for ensuring legal legitimacy, institutional credibility, and international compatibility. Systems based on structural compliance and measurable learning outcomes, therefore, tend to reduce quality to indicators and replace complex professional judgment with formal criteria. This becomes particularly problematic where knowledge is implicit, integrative, and context-dependent—such as in architectural design and studio-based pedagogy—since these forms of knowledge are more

difficult to represent within the framework of compliance-based quality assurance.

This study argues that accreditation operates within a framework of rationality where its task is not to provide a comprehensive interpretation of professional knowledge, but solely to ensure the structural conditions for its operation. The issue is not the existence of administrative rationality itself, but its implicit dominance as the sole legitimate interpretation of quality. This realization leads to an examination of how validation represents a different institutional logic: one that emphasizes not compliance, but professional orientation and the articulation of forms of knowledge.

2.3. The Function of Accreditation

Having clarified the theoretical background of administrative rationality, it is worth precisely defining the functional role of accreditation within the higher education system. Accreditation is not merely an evaluation process, but an institutional mechanism whose primary role is to ensure the legal and institutional legitimacy and operational stability of higher education programs. In national quality assurance systems aligned with the ESG, a program can only operate if it meets the specified structural and quality requirements[1]. Accreditation authorizes the launch and maintenance of a program and ensures the official recognition of the degree. Without this function, the operation of the higher education system would become unstable and unpredictable; therefore, accreditation is a fundamental tool for institutional legitimacy.

In this context, the purpose of quality assurance is to ensure that the operations of higher education institutions are transparent and verifiable, and that the qualifications awarded reflect reliable educational quality for students, the labor market, and society. To this end, accreditation employs transparent evaluation procedures, involves external experts, and examines the operation of institutions through a cyclical review system. Within this framework, quality is primarily manifested as audited compliance.

One of the most important tasks of accreditation is to ensure minimum standards. Given the diversity of the higher education system, it is necessary to define basic requirements that guarantee the professional and organizational soundness of programs. Accreditation, therefore, typically examines the coherence of the curriculum, the competencies of faculty, the adequacy of infra-

structure, and the functioning of internal quality assurance.

Accreditation also contributes to the international comparability of qualifications. Within the European Higher Education Area (EHEA), a unified quality assurance framework facilitates the mutual recognition of qualifications and student mobility, which is particularly important for regulated professions—such as architecture. However, it can be observed that the scope of accreditation is fundamentally limited to structural dimensions: it does not assess the quality of professional thinking or the depth of pedagogical culture but rather examines the conditions of operation. Accreditation, operating within the framework of administrative rationality, is therefore indispensable but offers an incomplete interpretation of quality. This realization leads to the question of what mechanism is capable of expressing and institutionally recognizing the integrative nature of design knowledge—that is, the institution of validation.

3. Design Knowledge as a Distinct Form of Knowledge

3.1. Reflective practice

The interpretation of the quality of architectural education cannot be separated from the question of what form of knowledge it conveys. Design knowledge cannot be reduced to a set of declarative facts, but is a specific mode of cognition in which thinking, action, and decision-making appear in a mutually shaping process. A classic analysis of this phenomenon was provided by Donald A. Schön in his work **The Reflective Practitioner**. Schön criticizes the traditional model of professional practice known as technical rationality [3], according to which the professional applies theoretical knowledge and appropriate methods to predefined problems. Schön, however, points out that in complex professions—including architecture—problems are not predetermined but emerge during the design process. The designer does not merely solve a problem but interprets and reframes it.

The central concept of reflective practice is reflection-in-action [3]: professional decisions arise from the thought process during action. The designer experiments, interprets, provides feedback, and modifies; problems and solutions mutually shape one another. This iterative process is clearly observable in the architectural studio,

where students develop their designs through critiques and reinterpretations.

Schön also points out that a significant portion of professional knowledge is implicit (tacit) knowledge [3, 4]. Designers often make decisions based on experiential patterns and precedents that cannot be fully formalized. In architectural education, therefore, knowledge is not merely the transfer of information, but the development of design thinking and judgment.

It follows that quality is captured not only in the final product but also in the reflective design process. Conformity-based quality assurance can examine structures and procedures, but it struggles to interpret the quality of reflective decision-making. The theory of reflective practice thus points out that design knowledge cannot be fully reduced to formalized structures and compliance criteria.

3.2. Designerly Ways of Knowing

The theory of reflective practice highlights that design goes beyond technical problem-solving; it is therefore an interpretive and iterative thought process. This idea is further explored in Nigel Cross's **Designerly Ways of Knowing**, which interprets design as a distinct mode of knowing [5]. According to Cross, design cannot be classified under either the scientific or humanistic categories of knowing, but rather represents an independent mode of knowing.

According to one of Cross's central theses, design represents a distinct "third" mode of cognition alongside scientific and humanistic cognition, with its own unique logic of thinking and problem-solving. While science seeks to describe and explain the world, design is concerned with creating possible futures. The designer therefore not only analyzes existing conditions but also examines possible future configurations. Design thinking is thus generative and projective.

Cross emphasizes that one of the most important characteristics of design is *problem framing*. The designer does not seek optimal solutions to pre-defined problems, but rather shapes the interpretive framework of the problem themselves. This phenomenon resonates with the theory of reflective practice: during the design process, thinking and action are in constant dialogue. Defining the problem is, in itself, the act of design.

Another defining element of *Designerly Ways of Knowing*—that is, the specific modes of knowing inherent to design—is visual and spatial thinking. Drawings, models, and diagrams are not merely

tools of communication but also media of thought. Through drawings and models, the designer explores alternatives, modifies, and reframes decisions. A significant part of design knowledge is based on the use of precedents and analogies, which serve an inspirational and structuring role.

One of the fundamental characteristics of design is the acceptance of ambiguity. Scientific rationality often seeks to reduce uncertainty, whereas design requires the productive management of uncertainty. A design problem rarely leads to a single objectively optimal solution. This openness also complicates the issue of evaluation. Design quality cannot be reduced to a single indicator or metric. Evaluation always includes an interpretive dimension.

These characteristics indicate that the institutional interpretation of design knowledge goes beyond a narrow focus on the logic of structural conformity.

3.3. Wicked Problems and Complexity

Examining the nature of complex problems is key to understanding the characteristics of design thinking. One of the defining concepts in design theory is "*wicked problems*" (ill-structured problems). Richard Buchanan made this a central element of design discourse in his study *Wicked Problems in Design Thinking*, which builds on Rittel and Webber's analysis of urban planning [6]. *Wicked problems* are fundamentally different from well-structured problems: they are not clearly defined, allow for multiple interpretations, and do not have a single definitive solution.

Architectural design typically deals with such problems. In the case of a building or urban intervention, a complex system of technological, social, aesthetic, and economic considerations emerges. During the design process, defining the problem is itself part of the solution process.

The mutual evolution of the problem and the solution is a fundamental characteristic of design thinking. Throughout the process, the designer redefines the situation, examines various interpretive frameworks, and develops potential solutions based on them. Complexity, therefore, refers not only to the number of factors but also to the openness of the interpretive horizon.

The built environment can be understood as a complex adaptive system in which social, technological, and environmental factors interact dynamically. The effects of a design decision often manifest in the long term and in a non-linear manner. Solutions are therefore not simply

“right” or “wrong,” but more or less adequate within a given context.

It follows that quality in architectural design is a relational category: it depends on the extent to which the design is able to integrate various perspectives and organize them into a coherent system. This dimension is difficult to capture in quality assurance systems based solely on indicators and structural compliance.

3.4. The Studio as an Integrative Knowledge-Building Environment

The distinctive features of design knowledge in architectural education are primarily manifested in the operation of the design studio. In studio-based, design-centered education, students do not merely seek solutions to predefined problems, but interpret and shape complex, multidimensional situations. The design process involves the integration of technological, aesthetic, social, and ethical considerations. In most architecture programs, the studio is a central element of the curriculum. It is based on project-based, long-term, and iterative workflows, accompanied by regular critiques and feedback. Learning thus takes place not in a linear lecture–exam model, but in a cyclical design process.

Integration is a key element of the studio's operation. During the design task, structural, environmental, technological, aesthetic, and social aspects are woven together into a single coherent system. In this sense, quality manifests itself in the depth of integration and the coherence of decisions.

Criticism is an important element of the studio's pedagogy. Students regularly present their work, which is then reflected upon by the instructors and the group. This dialogic process is not merely an evaluation exercise but a knowledge-building mechanism: students learn to articulate their decisions and reflect on their own design processes.

Iterative experimentation—exploring sketches, models, and alternatives—is the practical manifestation of design thinking. The studio also serves as a collaborative learning space where students learn from each other's work, and knowledge takes on a collective dimension.

Accreditation can assess the structural elements of the studio—such as the number of hours, credit value, or the instructor-student ratio—but it can only capture the studio's integrative and reflective pedagogical culture to a limited extent. This distinction highlights that the quality of architectural education extends beyond structural com-

pliance and can thus be understood as integration and reflective competence.

3.5. The design studio as an implicit platform in validation systems

Before proceeding to a detailed comparison of the differences between accreditation and validation, it is necessary to clarify the intermediate level that actually underpins the functioning of these systems: the role of the architectural design studio. In contemporary professional validation frameworks—particularly in the practice of the Royal Institute of British Architects (RIBA) [7] – the studio occupies a structurally central yet theoretically under-reflected position. Although professional policy documents and validation criteria do not explicitly name the studio as a knowledge-forming medium, their operation is nonetheless built upon this medium [7].

In the RIBA validation system, as well as in related educational discourse, the emphasis is primarily on learning outcomes, graduates' competencies, and professional aptitude. Among these, adaptability, collaboration, and the ability to handle complex, real-world problems play a prominent role [8]. At the same time, the learning environment in which these competencies are actually developed is not explicitly theorized; it appears implicitly within the structure of studio-based education.

In this sense, the design studio functions as an integrative platform. It unites different areas of knowledge—design thinking, technical and structural knowledge, and the interpretation of environmental and social contexts—within a project-based, iterative learning process. This integrative nature is consistent with theories regarding the specific nature of architectural design knowledge. In particular, the concept of “designerly ways of knowing” [5], and the design process as a reflective practice [3]. The studio is also the venue for performance and assessment. Validation processes rely primarily on outputs such as portfolios, designs, and project work, which are inherently studio-based. In this way, the studio becomes the space where learning outcomes are not only created but also made visible and assessable. Abstract competencies are translated here into concrete architectural proposals. Furthermore, the studio can also be interpreted as a simulated environment for professional practice. Through collaborative work, critical discourse, and engagement with complex design tasks, the studio mirrors the functioning of architectural



Fig. 1. The design studio as an integrative knowledge-generating environment in architectural education Source: author's conceptual framework.

practice in many respects. This is consistent with validation requirements that prioritize professional competence and practical applicability. Despite all this, a significant gap remains. The studio does not explicitly appear as an independent knowledge-forming system. Tacit knowledge [4], reflective practice (2), and the theory of community learning and *communities of practice* [9] are largely absent from the validation discourse. The epistemological nature of the studio thus remains hidden, even though the functioning of validation systems is fundamentally based on it. This points to a fundamental tension. Professional validation frameworks rely on the design studio as the primary medium for the development and assessment of competencies, yet they interpret it primarily as a platform for educational organization and assessment, rather than as a knowledge-generating system. Bridging this gap is crucial for a deeper understanding of the quality of architectural education, as it is not only necessary to examine what is measurable but also how design knowledge itself is generated. Validation systems are based on the design studio in their operation, yet they do not make their knowledge-generating nature explicit.

4. Validation as a Normative and Professional Interpretive Framework

4.1. The UNESCO–UIA Charter

In the previous chapters, we argued that the quality of architectural education is not limited to structural compliance. Given the integrative, reflexive, and complexity-managing nature of design knowledge, the interpretation of quality requires both normative and professional dimensions. In this context, validation can be understood as a peer-review-based, normative-professional framework that interprets the coherence, integration, and professional orientation of architectural education beyond compliance-based criteria. It is at this point that the institution of validation becomes relevant, as it operates according to a different institutional logic than accreditation, which is based on administrative rationality.

One of the defining reference frameworks for international architectural education is the *Charter for Architectural Education* developed by UNESCO–UIA [10]. The Charter is not a legal text nor a collection of accreditation standards; rather, it is a normative document that articulates the fun-

damental principles of architectural education based on global professional consensus.

The UNESCO–UIA Charter articulates the fundamental values and orientation of architectural education. The document is not bound by national legal systems and is not a binding regulation; rather, it is a professional guideline. This fundamentally differs from ESG-based accreditation: while accreditation examines the structural conditions of operation, the Charter articulates the purpose and ethos of architectural education.

The central principle of the Charter is integration. In architectural education, design, technology, theoretical knowledge, and professional responsibility are not separate elements but appear as an interconnected system. The Charter emphasizes the central role of design thinking, the integration of technical and environmental considerations, and the architect's social responsibility in shaping the built environment.

The UNESCO–UIA validation is based on this normative framework. It is not a legal authorization mechanism, but rather a professional evaluation process that assesses the extent to which the training program is coherent, integrated, and professionally oriented. During the professional evaluation and peer review, the process involves not only reviewing documents but also interpreting the educational concept and the program's professional orientation.

Thus, validation not only confirms operational compliance but also serves to institutionally recognize the values of architectural education. While accreditation focuses on compliance with standards, validation examines the extent to which the program aligns with international professional principles of architectural education. The two mechanisms are therefore not alternatives to one another, but rather quality dimensions with distinct functions.

4.2. Peer Review and Professional Horizons

Building on this understanding, the UNESCO–UIA validation process operates through peer review as its primary evaluative mechanism. This is a collegial evaluation mechanism in which active participants in the discipline (practicing architects, architecture educators, and experts with international experience) examine and interpret the program's professional quality. This mechanism fundamentally differs from the logic of an administrative audit: while an audit checks compliance with standards, peer review is based

on a professional assessment of the program as a whole.

During validation, the review examines not only whether formal requirements are met, but also what pedagogical concept organizes the training, how different areas of knowledge are integrated, and how professional responsibility is reflected throughout the curriculum. The evaluation is thus interpretive in nature: it acknowledges that the quality of architectural education cannot be captured solely by measurable indicators.

The professional evaluation also compares the program to the international professional landscape. Validation does not expect a uniform form or style but rather examines whether the program fits coherently into the current professional discourse of the architectural discipline. The evaluation is therefore fundamentally discursive, grounded in professional dialogue: it takes shape through presentations, questions, and critical discussion.

In this sense, validation is not merely a certification process, but rather institutional recognition and professional positioning. While accreditation focuses on meeting minimum standards, validation interprets the program's professional orientation and coherence, thereby making visible both the normative and discursive dimensions of quality.

4.3. Institutional Legitimacy

In the context of validation, the concept of institutional legitimacy is central. It does not merely denote administrative status, but rather the process through which a form of knowledge—in this case, design knowledge—gains a legitimate place within institutional structures and professional discourse. While accreditation ensures the legal and organizational legitimacy of operations, validation contributes to the institutional reinforcement of the professional status of design knowledge.

Due to the specific nature of design knowledge, it can only be captured to a limited extent by compliance-based indicators. If quality is interpreted exclusively within the framework of administrative rationality, there is a risk that the essential dimensions of this form of knowledge will be pushed into the background.

In this sense, the UNESCO–UIA validation can be understood as a mechanism that makes design knowledge visible within an international professional context. The program's pedagogical concept, integration, and professional orientation

become the subject of reflexive interpretation during the validation process, and the training becomes interpretable within the international professional discourse.

Institutional recognition is thus not a static rating, but rather the formation of a professional horizon and positioning. While accreditation ensures the legal legitimacy of operations, validation makes the professional legitimacy of design knowledge visible. The two mechanisms are therefore not alternatives to one another, but represent different qualitative dimensions in the interpretation of architectural education.

This realization forms the central thesis of the study: accreditation and validation operate according to different institutional logics, and the institutional recognition of design knowledge represents a qualitative dimension that becomes interpretable beyond the framework of administrative rationality.

5. European and Central and Eastern European Context

The difference between accreditation and validation is not merely a theoretical issue but can be understood within an institutional and cultural context. The EHEA's quality assurance structures provide a relatively homogeneous framework through the ESG [1], yet the quality culture of individual countries differs significantly for historical and institutional reasons.

With the introduction of ESG in Europe, a multi-level quality assurance system has emerged based on national accreditation agencies, ensuring transnational comparability and mutual recognition. The system also structures the internal quality management of higher education institutions. A distinctive feature of the European model is that it is not fully centralized: the ESG provides common guidelines, but implementation takes place at the national level. Consequently, accreditation exists in every country but operates with varying emphases. In some systems, institutional self-assessment dominates, while in others the role of external audit is stronger.

In the case of architectural education, the European quality assurance system is also linked to the dimension of professional regulation. Architectural licensing is not merely a matter of higher education but also of professional chambers, which is why accreditation is a fundamental prerequisite for professional legitimacy.

Higher education systems in Central and Eastern Europe have historically evolved from strongly state-centered models. The legacy of centralized educational structures remained palpable even after the transition, which is also reflected in the functioning of quality assurance. In this region, accreditation is generally a strictly legally regulated decision-making mechanism falling under central authority, which often serves as the primary source of legitimacy for its operation. Consequently, the concept of quality is often compliance-based: the emphasis is on documentation, formal requirements, and the verification of organizational structures. In Hungary, for example, the national accreditation system aligned with the ESG is operated by the Hungarian Higher Education Accreditation Committee (MAB) [11], which ensures European compatibility and legal stability; however, structural compliance dominates the interpretation of quality.

In this highly regulated environment, UNESCO–UIA validation plays a unique role. Since it is not a legal accreditation mechanism but a normative professional framework, it does not compete with state accreditation; rather, it operates in a different dimension. Validation creates an opportunity for the training program to align not only with national standards but also with international professional discourse. In addition, it strengthens institutional self-reflection, as the integration of pedagogical concepts and training becomes the focus of interpretation. The process also shapes institutional identity, since the training program is not merely presented as a unit of compliance but also positions itself through its own professional profile.

Based on an analysis of the European and Central and Eastern European contexts, quality assurance can be understood as a layered system. The first layer is linked to the logic of administrative rationality, which ensures legal compliance, organizational stability, and standardized structures. The second layer is the professional-normative dimension, which focuses on pedagogical coherence, integration, and professional accountability. These two layers are not mutually exclusive but form complementary dimensions. In Central and Eastern European systems, however, the dominance of the first layer often overshadows the significance of the second. In this context, validation serves as a complementary mechanism that enables institutional recognition and professional articulation of design knowledge alongside accreditation.

6. A Layered Model of Quality

The previous chapters of this study have argued that the quality of architectural education cannot be understood based on a single institutional logic. Accreditation, which is based on administrative rationality, and validation, which represents a normative-professional horizon, fulfills different functions. This difference should be interpreted not as competition but as stratification. In the following, we summarize this insight in the form of a model.

6.1. The Three Layers of Quality

The quality of architectural education can be understood in terms of at least three layers that build upon one another but operate according to different logics.

The first structural-legal layer is linked to the dimension of administrative rationality. This ensures the basic conditions for the operation of higher education institutions: legal compliance, organizational stability, documented procedures, and the fulfillment of minimum standards. The primary institutional tool of this dimension is accreditation. Its function is indispensable, as it guarantees transparency, public trust, and international compatibility. Its scope, however, is fundamentally limited to structural dimensions. The second, pedagogical-integrative layer concerns the program's internal functioning and coher-

ence. Here, quality manifests itself in the operation of design knowledge: in the central role of the studio, in the integration of technological, theoretical, and social dimensions, and in the practice of reflective decision-making and complex problem-solving. The logic of “designerly ways of knowing” and the handling of “wicked problems” become a pedagogical reality in this layer. Quality is thus not merely compliance, but the practice of design thinking.

The third, normative-professional layer represents the program's professional horizon and identity. This includes embeddedness in international professional discourse, professional accountability, and the coherent articulation of the pedagogical concept. In this dimension, design knowledge becomes explicit as a specific form of professional knowledge. The institutional mechanism of this layer is validation, which does not ensure legal legitimacy but rather professional positioning.

6.2. The Relationship Between the Layers

The three layers are not hierarchical; rather, they are complementary.

Without the first layer, the system would become unstable; without the second layer, the pedagogical content of education would become hollow; and without the third layer, design knowledge would remain implicit and difficult to articulate.

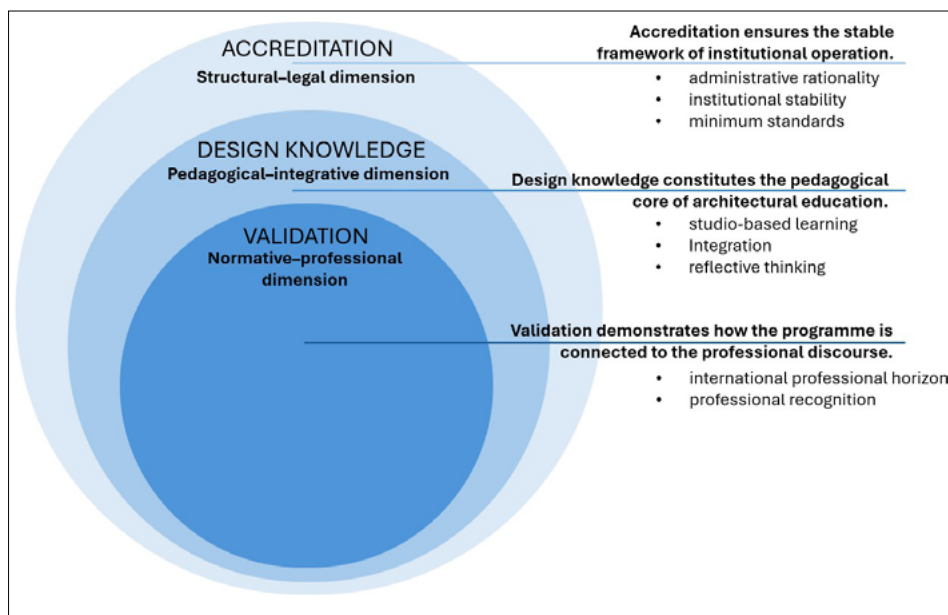


Fig. 2. The layered model of quality in architectural education Source: author's conceptual framework.

If quality is understood solely in its structural dimension, the specific form of knowledge inherent in design is pushed into the background. If, on the other hand, we interpret it solely in pedagogical or normative terms, the framework of institutional stability and accountability is missing. The essence of the layered model is precisely that these dimensions together constitute a comprehensive interpretation of quality in architectural education.

6.3. Administrative Rationality and Design Knowledge

The arc described in the title of this study—from administrative rationality to the institutional recognition of design knowledge—does not imply rejection but rather a complementary relationship.

Administrative rationality ensures stability, standardizes operations, and makes them auditable. Institutional recognition of design knowledge, on the other hand, creates a professional horizon and discourse, and makes the value of design thinking explicit. Together, these two logics enable adequate capture of the various dimensions of the quality of architectural education.

6.4. Implications for Central and Eastern Europe

In Central and Eastern European higher education systems, the culture of quality has traditionally been highly formalized and primarily based on the logic of compliance. In this context, the layered model is particularly significant because it highlights that structural compliance is not synonymous with professional quality.

The model creates an opportunity for institutional self-reflection and legitimately highlights the specific nature of design knowledge. In this sense, validation is not a competitor to accreditation, but rather a complementary mechanism that opens up a broader professional horizon.

6.5. Concluding Remarks

The quality of architectural education can only be properly understood if we also take into account the specific nature of design knowledge. While administrative rationality is necessary, it is not, on its own, a sufficient condition for quality.

According to the proposed model, quality assurance does not operate according to a single logic, but rather as the combined operation of structural, pedagogical, and normative dimensions. Accreditation ensures the conditions for operation, while validation makes design knowledge visible

and articulated. Together, these two mechanisms constitute the full quality horizon of architectural education.

7. Conclusions

The aim of this study was to conceptually clarify the distinction between accreditation and validation in the context of architectural education and to demonstrate that these two mechanisms operate along distinct institutional logics. The analysis highlighted that European higher education quality assurance systems—particularly ESG-based accreditation—interpret quality within the framework of administrative rationality. This approach is based on structural compliance, documentability, and auditability, and plays a fundamental role in ensuring institutional stability and legal legitimacy.

Architectural education, however, is based on a specific form of knowledge. Reflective practice, Designerly Ways of Knowing, and the handling of complex, so-called wicked problems represent dimensions of quality that cannot be reduced to mere compliance indicators. Design knowledge is integrative, context-dependent, and normative, and the studio is not merely a form of education but a space for integrating knowledge formation.

Based on this insight, the study argued that UNESCO–UIA validation, understood as a peer-review-based normative-professional framework, is not an alternative to accreditation but rather a distinct dimension of quality. While accreditation examines the conditions of operation, validation focuses on interpreting pedagogical coherence and professional orientation. The discursive nature of peer review enables the institutional recognition of design knowledge, that is, making it explicit and reflective.

The study, therefore, proposes a layered model of quality that distinguishes three dimensions: the structural–legal, the pedagogical–integrative, and the normative–professional layers. Within this framework, accreditation and validation are not alternatives to one another; rather, they are complementary mechanisms. This approach is particularly relevant in the Central and Eastern European context, where the culture of quality is traditionally highly formalized, and the logic of compliance plays a dominant role.

One of the study's most important findings is that the quality of architectural education cannot be understood without accounting for the specific nature of design knowledge. Administrative ra-

tionality is a necessary but insufficient condition for quality; institutional recognition of design knowledge requires a professional horizon that goes beyond structural compliance.

The study also identifies further research directions. It would be worthwhile to explore in greater detail how validation influences pedagogical practice and institutional self-interpretation, and how the dimensions of design knowledge might be more explicitly reflected in the discourse on quality assurance. Moreover, the issue of institutional recognition of design knowledge may be relevant not only for architectural education but also for other design-based disciplines. This approach extends beyond architectural education and offers a framework for interpretation of other design-based disciplines as well.

In summary, it can be concluded that the difference between accreditation and validation reflects not only procedural distinctions but also differing interpretations of the concept of quality. The normative dimension, which complements administrative rationality, enables the quality of architectural education to be recognized in the European higher education area not merely as compliance but also as a professional and pedagogical value.

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COMPARATIVE PERFORMANCE ANALYSIS OF HEAT PUMPS OPERATING WITH R290 AND R32 REFRIGERANTS

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Abstract

From the perspective of sustainable energy management, heat pump technology holds significant importance, as efficient conversion of heat extracted from the environment contributes to reduction of fossil energy demand and carbon dioxide emissions. [1] The operational efficiency of such systems is strongly influenced by the selected refrigerant, where favourable thermodynamic properties, environmental compatibility, and safety requirements all play a decisive role. [2] The present study aims to provide a comparative analysis of a heat pump operating with two different refrigerants (R-290 and R-32). The physical and chemical properties of the investigated fluids are presented, and analysis of experimental results enables determination of the energy efficiency of systems operating with the different refrigerants. [3]

Keywords: R290, R32, COP.

1. Introduction

Over the past decade, the European Union has tightened its regulations on refrigerants in order to reduce global warming. Regulation (EU) No. 517/2014 and the updated Regulation (EU) 2024/573 both aim to phase down high-GWP F-gases [4, 5] The latest regulation requires an 80% reduction in HFC use by 2030, which pushes manufacturers toward lower-GWP alternatives such as R32, HFO blends, and natural refrigerants like R290. [3, 6]

The rules define inspection and leakage-control requirements based on CO₂-equivalent charge. This means that even relatively small R32 charges already require periodic leakage checks. For natural refrigerants such as R290, the main limitation is not GWP but the A3 flammability class, which restricts the allowable charge according to EN 378 and the installation environment. Indoor systems can only use small charges, while outdoor monoblock units can safely operate with larger amounts. Because of this, manufacturers typically use hermetically sealed, low-charge monoblock designs for R290 to meet safety standards and reduce indoor risks.[3, 6]

2. Conceptual overview

2.1. Requirements of R32 and R290

Modern refrigerants today must satisfy a wide range of environmental and operational requirements. One of the most important expectations is a low GWP value, meaning the refrigerant should contribute as little as possible to global warming, along with zero ozone depletion potential (ODP) to avoid damaging the ozone layer. [7] Safety is also a key consideration, including low flammability, the feasibility of appropriate fire-protection measures, and the requirement that the refrigerant must not be toxic or pose significant health risks even in the event of leakage. From a practical perspective, good handling characteristics are essential as well, covering ease of installation, maintainability, and compatibility with existing systems. [7]

R32 is a partially fluorinated hydrocarbon (HFC) with a GWP of approximately 675, making it significantly more favorable than the previously used R410A blend, while also offering efficient heat-transfer properties. It is classified as mildly flammable (A2L), which allows for relatively safe

handling, although leak detection and adequate ventilation remain necessary. Due to its operating characteristics, it has become widely used in residential and commercial heat pumps, and its simple molecular structure enables easier recycling. [7, 8]

R290 is natural propane with an extremely low GWP of around 2, resulting in minimal environmental impact. Its thermodynamic performance is generally superior to that of R32. However, it is highly flammable (A3), requiring stricter safety measures, proper ventilation, and effective leak-prevention systems. When the necessary precautions are taken, it can be safely applied in both residential and industrial systems. [7, 8]

2.2. Quantitative and qualitative assessment

2.2.1. Quantitative assessment

First, we write the output provided by the unit, which is the difference between the energy content of the supply and return lines; in our examined system this is given by the following expression: [9, 10]

$$\dot{Q}_0 = c \cdot \dot{m}_{cool} \cdot (T_{c,2} - T_{c,1}) \quad (1)$$

$$\dot{Q}_C = c \cdot \dot{m}_{heat} \cdot (T_{h,1} - T_{h,2}) \quad (2)$$

where:

- $\dot{Q}_0$ specific heating capacity [W];
- c heat capacity of the heating/cooling medium [$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$];
- $\dot{m}_{cool}$ cooling system mass flow rate [$\text{kg} \cdot \text{s}^{-1}$];
- $T_{c,2}$ cooling return water temperature [K];
- $T_{c,1}$ cooling supply water temperature [K];
- $\dot{Q}_C$ specific cooling power [W];
- $\dot{m}_{heat}$ heating system mass flow rate [$\text{kg} \cdot \text{s}^{-1}$];
- $T_{h,1}$ heating supply water temperature [K];
- $T_{h,2}$ heating return water temperature [K].

Heating and cooling systems can be characterized by two quantitative performance indicators. The first is obtained by dividing the useful thermal output by the electrical power required to produce it. Several names and symbols are used for this indicator in practical applications, with separate terminology for cooling and for heating. [11]

$$COP_R = \frac{\dot{Q}_0}{P_K} = \varepsilon_C = COP_{cool} = EER \quad (3)$$

$$COP = \frac{\dot{Q}_C}{P_K} = \varepsilon_H = COP_{heat} \quad (4)$$

where:

- COP_R coefficient of performance in cooling [-];
- P_K the electrical power input from the compressor [W];

COP coefficient of performance in cooling [-].

The efficiency of the unit depends on its construction, the refrigerant used, the outdoor temperature, and the temperature requirements of the heating or cooling water circuit. At low outdoor temperatures the system must overcome a larger temperature difference, which causes the heating COP to decrease, while in cooling mode the opposite effect occurs. The highest efficiency is generally achieved during transitional seasons, when the temperature difference between the indoor and outdoor environment is minimal. [9, 12]

Although the COP follows the classical concept of efficiency, its value can exceed 1 (or 100%), which makes it necessary to introduce a second indicator that resembles a traditional efficiency measure. This second quantitative performance indicator is the figure of merit, which expresses the ratio between the actual performance and the theoretically ideal reversed Carnot cycle: [10]

$$\eta_C = \frac{COP_R}{COP_{R,C}} = COP_R \cdot \frac{T_C - T_0}{T_0} \quad (5)$$

$$\eta_H = \frac{COP}{COP_C} = COP \cdot \frac{T_C - T_0}{T_C} \quad (6)$$

where:

- η_C the efficiency in cooling [%];
- $COP_{R,C}$ theoretical maximum specific cooling capacity [-];
- T_C condensator temperature [K];
- T_0 evaporation temperature [K];
- η_H efficiency in heating [%];
- COP_C theoretical maximum specific heating capacity [-].

2.2.2. Qualitative assessment

Qualitative energy assessment focuses not on the amount of energy but on its quality and usability. Energy can be divided into two main components: anergy and exergy. Anergy is the portion that cannot be converted into other forms of energy, while exergy represents the useful, convertible part. The higher the exergy content, the more valuable the energy is. [9] Electrical energy is considered entirely exergy, whereas in the case of thermal energy, the so called Carnot efficiency must be applied to determine its exergy content. In this study, two quality indicators are examined: the exergetic system efficiency and the total exergetic system efficiency. The first evaluates system quality from the perspective of the refrigerant, while the second assesses it from the perspective of the secondary working fluid. [10]

Exergetic efficiency

When defining this indicator, the exergy content of the heat flow removed in the evaporator or released in the condenser is divided by the exergy content of the energy flow absorbed by the refrigerant in the compressor. [9]

$$\eta_{Ex,C} = \frac{Ex_0}{Ex_K} = \frac{\dot{Q}_0 \cdot \left(\frac{T_x - T_0}{T_0} \right)}{P_K} = COP_R \cdot \frac{T_x - T_0}{T_0} \quad (7)$$

$$\eta_{Ex,H} = \frac{Ex_C}{Ex_K} = \frac{\dot{Q}_C \cdot \left(\frac{T_C - T_x}{T_C} \right)}{P_K} = COP \cdot \frac{T_C - T_x}{T_C} \quad (8)$$

where:

- $\eta_{Ex,C}$ cooling exergetic efficiency [%];
- Ex_0 exergy content of the cooling heat flow [W];
- Ex_K exergy of the compressor power input [W];
- T_x reference temperature [K];
- $\eta_{Ex,H}$ heating exergetic efficiency [%];
- Ex_C exergy content of the heating heat flow [W].

There is a direct proportional relationship between the COP and the exergetic efficiency: a high COP results in high exergetic efficiency, while a low COP indicates that the system cannot absorb or reject sufficient heat, leading to a decrease in both exergy content and exergetic efficiency. The formula also shows that lower exergy content always results in lower exergetic efficiency; therefore, a low COP necessarily entails low exergetic efficiency. [10, 11]

Total exergy system efficiency

We divide the exergy content of the energy flow required to operate the heat pump by the exergy content of the energy flow demanded by the cooling or heating system it supplies: [13]

$$\eta_{sys,C} = \frac{\Delta Ex_{sec,C}}{\Delta Ex_r} = COP_R \cdot \left(\frac{T_{K,2} \cdot T_x}{T_{c,1} \cdot T_{c,2}} - 1 \right) \quad (9)$$

$$\eta_{sys,H} = \frac{\Delta Ex_{sec,H}}{\Delta Ex_r} = COP \cdot \left(1 - \frac{T_{K,2} \cdot T_x}{T_{h,1} \cdot T_{h,2}} \right) \quad (10)$$

ahol:

- $\eta_{sys,C}$ total cooling exergetic efficiency [%];
- $\Delta Ex_{sec,C}$ exergy requirement of the cooling system [W];
- ΔEx_r exergy requirement of the driving energy flow [W];
- $T_{K,2}$ outdoor temperature [K];
- $\eta_{sys,H}$ total heating exergetic efficiency [%];
- $\Delta Ex_{sec,H}$ exergy requirement of the heating system [W].

The total exergetic system efficiency, unlike the simple exergetic efficiency, does not evaluate only the machine itself; it also takes into account the thermodynamic characteristics of the connected

secondary systems. [9] Equations 9 and 10, the exergy content of the heat pump's cooling (Equation 11) and heating (Equation 12) systems is also included, defined as follows: [10, 13]

$$\Delta Ex_{sec,C} = \dot{Q}_0 \cdot \left(\frac{T_{K,2} \cdot T_x}{T_{c,1} \cdot T_{c,2}} - 1 \right) \quad (11)$$

$$\Delta Ex_{sec,H} = \dot{Q}_C \cdot \left(1 - \frac{T_{K,2} \cdot T_x}{T_{h,1} \cdot T_{h,2}} \right) \quad (12)$$

As a result, it provides a comprehensive picture of the overall system performance, making it possible to assess the effectiveness of both the heat pump and the associated heating or cooling systems. Based on this, the heating or cooling system can be optimized for the specific type of heat pump. [9, 13]

3. Materials and methods of measurement

The aim of the investigations was to perform a comparative analysis of the energetic and exergetic performance of monoblock heat pumps operating with two different refrigerants (R290 and R32). The measurements were carried out in the certified laboratory of HAJDU Hajdúsági Ipari Zrt. under standardized conditions. The examined units were a 9 kW nominal capacity heat pump operating with R32 refrigerant (Hajdú HPAW 10) and a 10 kW nominal capacity heat pump operating with R290 refrigerant (Hajdú V10W D2N7 E30). For both units, factory catalogue data and experimental measurement data were available, enabling a comparison between nominal and actual operating parameters. The investigations can be divided into two main parts: functional tests and quantitative performance measurements.

During the functional tests, the proper operation of the units was verified in heating, cooling, and domestic hot water (DHW) modes, including compatibility with different heat distribution systems (radiators, surface heating, fan coil units). The purpose of these tests was to confirm operational safety and system stability.

In the quantitative measurements, the operating parameters of the primary (calorimetric) and secondary (hydraulic) circuits were recorded through continuous data acquisition. On the primary side, the electrical characteristics of the compressor (voltage, current, input power) were provided by the built in measurement system. The compressor was controlled by a frequency inverter, which converted the single phase supply

into three phase power, enabling precise control of rotational speed and thus output capacity. On the calorimetric side, the refrigerant state variables were determined using digital pressure sensors and high accuracy NTC temperature sensors. Measurement of suction and discharge pressures and temperatures allowed the determination of the thermodynamic states of the refrigeration cycle, including superheating and subcooling values. The condensation and evaporation mid point states were determined based on the saturation temperatures corresponding to the measured pressures.

On the secondary side, the supply and return water temperatures were measured using thermocouple based methods, while the volumetric flow rate was measured with an integrated spiral rotor flow meter. Data were collected and recorded via a Modbus communication protocol. From the measured parameters, the mass flow rate and the heating or cooling capacity delivered or absorbed by the heat pump could be determined.

Based on the measurement data, the energetic indicators of the units were calculated, primarily the heating capacity, cooling capacity, and performance factors (COP, EER). These were determined using the secondary side temperature differences and mass flow rate, together with the electrical power input of the compressor. The resulting values enabled a comparative energetic evaluation of the systems. All measurements were performed in accordance with standardized requirements in a controlled laboratory environment, where ambient conditions, installation configuration, and the accuracy and calibration of the measuring instruments ensured the reproducibility and reliability of the results.

4. The result of the measurements

During the measurement, in addition to the ambient temperature, the supply and return temperatures of the coil were also recorded (Fig. 1). The tests for both units were carried out at an ambient temperature of 20 °C, which is considered one of the most favorable operating conditions for heat pumps. Under these conditions, stable and uniform system operation can be ensured, along with optimal heat transfer in the heat exchangers. The purpose of the measurements was to evaluate the performance and thermal behavior of the two refrigerant based units under these ideal conditions.

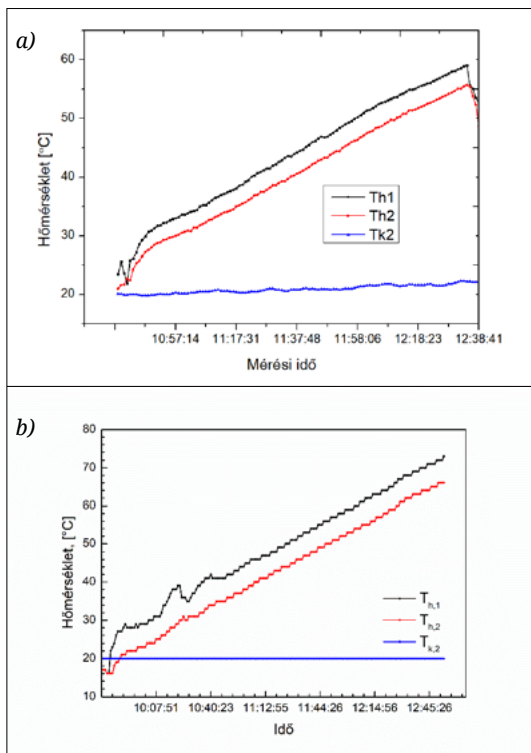


Fig. 1. a) Supply and return temperatures of the medium produced by the unit operating with R32
b) R290, refrigerant, together with the ambient temperature.

Fig. 1 shows the water temperature differences of the two systems, which were typically between 3 and 4 °C. At start up, the water temperature measured in the piping system was 22 °C for the R32 unit and 15 °C for the R290 unit. In the supply line, the heat pumps increased these temperatures to 60 °C and 70 °C, respectively, while the maximum return temperatures reached 55 °C and 65 °C. Thus, a 10 °C temperature difference can be observed between the two units. As expected, the R290 unit provides a higher supply-water temperature due to its more favorable thermodynamic properties, making it more suitable for secondary heating systems that require a supply temperature of around 50 °C.

Based on the measurement data series, the instantaneous heating capacity of the secondary system and the evolution of the exergy content can be determined. Their temporal distribution is illustrated in Fig. 2 .

The black curve represents the heating capacity. For both heat pumps, the nominal heating capaci-

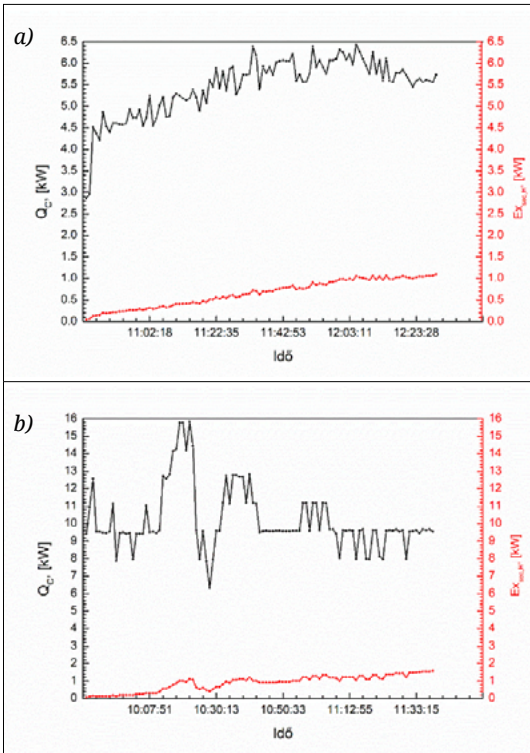


Fig. 2. a) Heating capacity ($\dot{Q}_c$) produced by the unit operating with R32 refrigerant and its exergy content ($Ex_{sec,H}$), expressed in kW. b) Heating capacity ($\dot{Q}_c$) produced by the unit operating with R290 refrigerant and its exergy content ($Ex_{sec,H}$), expressed in kW.

ty was 10 kW. The R290 charged heat pump maintained this value, with minor fluctuations. In contrast, the R32 charged heat pump was able to deliver an average heating capacity of only 5.5 kW. This was due to the flow related characteristics of the connected primary and secondary systems. The low flow velocity did not allow sufficient heat transfer on the calorimetric side.

The figure also illustrates the heating exergy content, shown in red. During the measurement, the exergy produced by the R32 unit exceeded 1 kW, while in the case of the R290 unit it reached 1.5 kW. This represents a 500 W difference, meaning that the heat energy produced by the R290 unit is capable of performing a greater amount of useful work, and is therefore energetically more valuable. However, if we take into account that the R32 unit achieved this exergy level at 5.5 kW, whereas the R290 unit required 10 kW to reach its value, a more favorable exergy ratio is obtained for the R32 unit. Quantitatively, this corre-

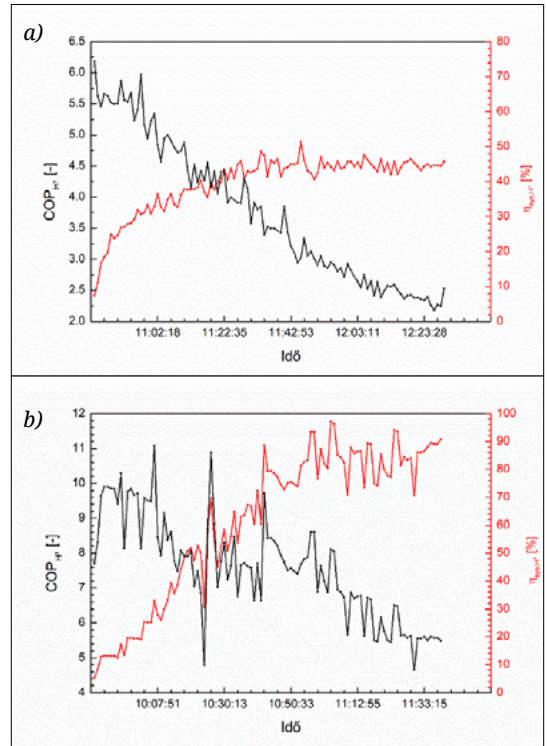


Fig. 3. a) COP_H and total exergetic system efficiency ($\eta_{sys,H}$), achieved by the unit operating with refrigerant R32 in heating mode b) COP_H and total exergetic system efficiency ($\eta_{sys,H}$), achieved by the unit operating with refrigerant R290 in heating mode.

sponds to an average of 8.3% for R290 and 11.9% for R32. These values are considered acceptable in the context of heat pump systems, though not outstanding in a general thermodynamic comparison (Fig. 3).

At the beginning of the measurement, the COP of both units is higher because the electrical consumption of the compressor is still low. As the amount of produced heating water increases, the power consumption also rises, which leads to a decrease in COP, while the system efficiency index increases. The efficiency of heat pumps is primarily evaluated in the 35–45 °C supply temperature range, as they operate for most of their runtime within this interval. In this range, the average COP of the R32 unit is 4.5 kW, while that of the R290 unit reaches 8 kW, which is due to the high ambient temperature and the superior heat transfer properties of R290. The η_{sys} value indicates how effectively the caloric side of the heat

pump cooperates with the primary and secondary hydraulic circuits.

The flow related issues observed in the R32 systems are also reflected in this indicator, whereas in the case of R290, the appropriate water side design clearly results in better overall system efficiency.

Based on the available measurement data series, it was also possible to determine the cooling capacity and EER values of the R290 heat pump (Fig. 4a), as well as to examine the temporal evolution of its exergetic efficiency in both heating and cooling modes (Fig. 4b).

After a rapid initial rise, the cooling capacity gradually decreases and eventually stabilizes around an average value of 9 kW. In parallel with this, the EER shows a continuous decline from the more favorable partial load range at the beginning of the measurement, and over the full measurement period it averages around 6. (This level of cooling efficiency is considered high for heat pump operation, although it does not reach the higher efficiency typically observed in heating mode.) This characteristic behavior is a natural

consequence of the increasing compression ratio and the thermodynamic losses associated with delivering higher cooling capacity.

The Figure 4b shows the temporal evolution of the exergetic efficiency in both cooling and heating modes. The opposite trends of the two curves clearly illustrate that the compressor's power is converted into useful exergy on the heating side, whereas in cooling mode the same power acts against the cooling exergy. As a result, the heating exergetic efficiency gradually improves, while the cooling exergetic efficiency decreases, and at a certain point during the measurement the heating exergy efficiency becomes dominant. Overall, this indicates that the unit achieves significantly more favorable exergetic performance in heating operation.

5. Conclusion

In this study, the energetic, environmental, and safety related characteristics of the R290 and R32 refrigerants were compared, and the results of the laboratory measurements were evaluated. From an environmental perspective, R290 represents the more favorable choice, as it is a naturally occurring refrigerant with a significantly lower GWP value, making it more compliant with increasingly stringent climate policy regulations. Both refrigerants are stable under operating conditions, do not decompose, and are compatible with lubricants, ensuring reliable system operation. From a safety standpoint, although both meet the fundamental requirements, their differing flammability classifications mean that the use of R290 necessitates enhanced fire and explosion protection measures. This risk can be effectively managed in monoblock systems—particularly when reduced refrigerant charge is applied—although it may impose additional burdens on manufacturing and logistics processes.

Based on the laboratory measurements, the COP and exergetic system efficiency values were found to be higher for R290. This indicates that the system operating with R290 utilizes energy more effectively under the given conditions. However, it cannot be stated unequivocally that R32 is thermally inferior, as the achievable performance depends on numerous factors, including ambient temperature, installation conditions, and refrigerant charge quantity.

In summary, if climate protection regulations restrict the applicability of R32, R290—when accompanied by appropriate safety measures—may

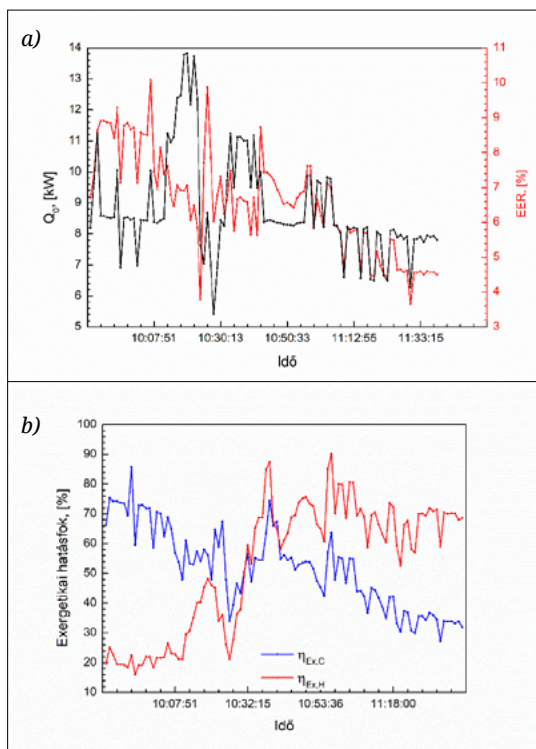


Fig. 4. a) $\dot{Q}_0$ and EER (COPR) values for the system operating with R290; b) Cooling and heating exergetic efficiencies.

serve as an efficient alternative for future heat pump systems.

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ANALYSIS OF STEEL BEAM-TO-CONCRETE COLUMN CONNECTION

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Abstract

This study investigates the load-bearing capacity of an external steel beam-to-concrete column connection formed with post-installed anchorage systems, derived from the connection presented in reference [1]. Two connection types are analysed: chemical and mechanical anchor solutions. Both analytical and numerical methods were applied in the investigation. The analytical calculations were carried out based on the European standard EN 1992-4:2018 [2], while the numerical analyses were performed using the Hilti PROFIS Engineering software. The aim of the study is to determine the ultimate moment capacity of the examined connections, identify the governing failure component, and compare the analytical and software-based results. A parametric study was also conducted to evaluate the influence of the anchor embedment depth on the load-bearing capacity of the connection. The comparison of the obtained results with previous studies [1, 3] on steel and composite connections contributes to a deeper understanding of the behaviour of post-installed anchorage systems in steel-to-concrete joints.

Keywords: *steel beam-to-concrete column connection, post-installed anchorage system, chemical anchor, mechanical anchor.*

1. Introduction

The behaviour of structural connections fundamentally determines the global load-bearing capacity and stiffness of building structures. Numerous studies have investigated the strength and stiffness of steel and composite connections using both experimental and numerical methods. The post-installed fastening solutions examined in the present study - developed for establishing connections between a steel beam and a concrete column - are derived from the experimental configurations presented in reference [1], which originally investigated connections between a steel column and a composite beam.

The experimental configurations examined in reference [1] are illustrated in Fig. 1. The authors analysed alternative connection configurations, including one internal (T1) and two external (T2, T3) specimens. The proposed external connection detail is of particular relevance, as traditional

solutions often require a small cantilever to ensure an adequate anchorage length for the slab reinforcement, which in many cases limits the building design. To avoid this limitation, one of the main objectives of the experimental program [1] was to consider the possibility of eliminating the cantilever on semi-rigid external connections. According to the proposed solution, the reinforcement was passed through the flanges of the steel column and attached either by threaded ends or by headed bars that act as a buffer.

The investigated experimental configurations consisted of connections between a 1.30 m long cantilevered IPE270 composite beam and a HEB240 simply supported steel column. The IPE270 steel beam was connected to a 10 cm thick and 1 m wide reinforced concrete slab using shear studs with a diameter of 19 mm and a height of 75 mm. In total, eleven shear studs were welded to the beam with a spacing of 10 cm. The

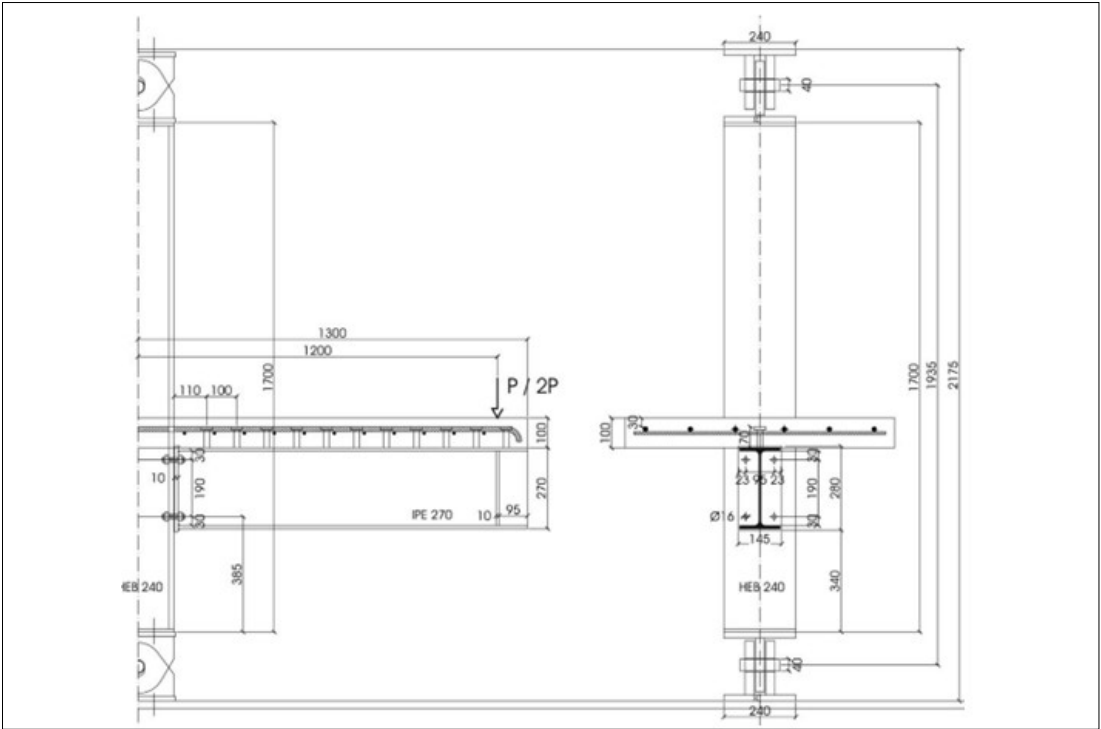


Fig. 1. The geometry of the tested specimens presented in reference [1].

load application point at the free end of the beam was located 1.20 m from the axis of the steel column. A 10 mm thick flush end plate was welded to the beam end, which was connected to the column using four M16 grade 10.9 bolts. Both the column and the beam were made of S275 steel grade.

The bending moment resistances ($M_{j,Rd}$) of the external composite connections (T2, T3) presented in reference [1] are summarised in Table 1. Based on the experimental results, study [3] analytically and numerically investigated isolated steel beam-to-steel column connections derived from the same configurations. These analyses primarily focused on the parametric evaluation of joint stiffness, load-bearing capacity, and the behaviour of individual connection components. The bending moment resistance of the steel connection with a 10 mm thick end plate (P10mm) examined in [3] is presented in a Table 2.

Building on previous research, the present study investigates a modified connection configuration in which the steel column is replaced by a concrete column, while the geometry of the steel beam, the associated end plate, and the bolt layout remain unchanged. The connection is realised using a post-installed fastening method, em-

ploying either chemical or mechanical anchors. Such connections are increasingly used in modern construction practice due to their practical advantages, however, their load transfer mechanism is complex, and their structural behaviour requires further investigations.

The bending moment resistance of post-installed fastening systems is influenced by several factors, including the anchorage depth of the anchors, the concrete strength, the reinforcement

Table 1. Bending moment resistances of the composite connections T2 and T3 [1]

Connection	$M_{j,Rd}$ [kNm]
T2	147.4
T3	163.1

Table 2. Bending moment resistance of the steel connection with a 10 mm end-plate (P10mm)[3]

Connection	$M_{j,Rd}$ [kNm]		
	Analytical calc.	Consteel	Idea StatiCa
P10mm	34.28	34.00	31.02

layout, the distance of the anchors from the edges of the connected elements, and the stiffness of the end plate. Accurate knowledge of the load-bearing capacity of such connections is essential for safe structural design and for the validation of analytical and numerical procedures.

During the investigations, both analytical and software-based methods were applied. The analytical calculations were performed in accordance with the requirements of the EN 1992-4:2018 standard [2] while the software-based analyses were carried out using the Hilti PROFIS Engineering software. The analysis focuses only on the moment resistance and includes a parametric study, which evaluates the effect of the anchorage length on the moment resistance of the connection.

2. Analytical and software-based investigations

The analytical assessments are based on the provisions of standard EN 1992-4:2018 [2]. The standard defines four possible failure modes for tensioned anchors, which include steel failure of the fastener, concrete cone failure, pull-out failure of the fastener from the concrete member, and splitting failure of the concrete member.

The software-based assessments were carried out using the Hilti PROFIS Engineering software. The software's calculation procedure is based on the component-based model established in accordance with EN 1992-4:2018 [2], and the relevant technical assessment documents [4, 5]. The software interprets the connection as a detailed model in which the load transfer mechanisms of the steel, the concrete, and the anchoring system are treated separately, while their interactions are also taken into account. During the calculation process, tensile, shear, and combined load effects are determined for each individual anchor and anchor group, along with the corresponding failure modes. The results provided by the software include the utilization ratios of the individual components, and the dominant failure mode. A key advantage of using PROFIS Engineering is that it evaluates concrete cracking, concrete cone overlap, and the influence of reinforcement based on a three-dimensional model, while also considering the manufacturer's requirements regarding minimum spacing, edge distances, and embedment depths.

During the investigations, Hilti HIT-RE 500 V4 chemical anchors, Hilti HAS-U threaded rods of M16 diameter and grade 8.8, as well as Hilti HST3

mechanical anchors were used. The mechanical anchor fixings were evaluated up to a maximum embedment depth of 160 mm, since the software, despite the availability of M16x260 and M16x300 types in the product catalogue, allows a maximum of M16x220 for mechanical anchors. The investigations were carried out on a concrete column with a cross-section of 50×50 cm made of C25/30 strength class, which provides the fundamental geometric and material parameters for the investigated configurations. The results of the analytical and software-based investigations were essentially identical; therefore, the software-based procedure was primarily used for the following calculations.

The software deviates from the provisions of standard EN 1993-1-8:2005 [6] when determining the minimum distance measured from the centre of the hole to the edge of the end plate. Hilti PROFIS Engineering assumes the minimum edge distance to be 1.5 times the hole diameter, while reference [6] specifies 1.2 times the hole diameter. Consequently, the width of the end plate in the model had to be increased from 145 mm to 150 mm. The modified end plate of the connection is shown in Fig. 2.

During the investigations, the effects of the behaviour of the rigid and flexible plates were compared. The behavioural modes of steel end plates are also described in detail in reference [7]. In the model assuming rigid plate behaviour, the end plate is not capable of significant deformation, therefore, the loads on the anchoring bolts are distributed almost linearly, and the outer bolts of the anchor group carry the highest loads. Fig. 3 shows the force distribution corresponding to the rigid plate assumption, where the tensile forces in the anchors increase in a linear manner. The

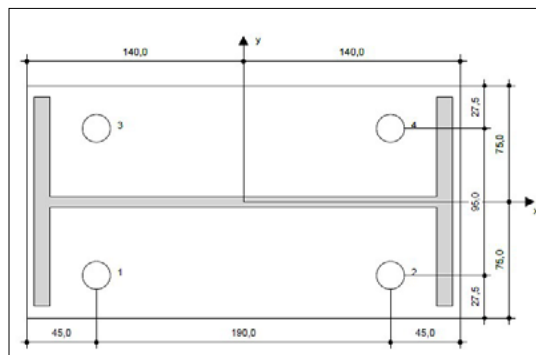


Fig. 2. The modified end plate of the investigated connection in the software.

dimensions and material properties of the steel components of the connection are identical to those used in reference [1].

In contrast, the behaviour of a flexible plate allows for significant plate deformation under loading. In this case, load transfer can no longer be considered as transmission between rigid elements: due to the deformation of the base plate, a non-linear tensile force distribution develops among the elements of the anchor group. The anchors positioned along the plate edge are subjected to higher tensile forces due to the local deformation of the plate, while the anchors in the inner zone are subjected to much lower loads and may even become unloaded in extreme cases. Under higher bending moments, this phenomenon becomes more pronounced, as the line of action of the bending moment concentrates the tensile forces in the outer region of the plate. Fig. 4 illustrates the characteristic force distribution for a flexible plate, along with the corresponding deformation pattern.

The calculation method described in standard [2] is valid only when a rigid end plate is used, in which the loads are distributed linearly, and plate deformations are negligible. In contrast, the Hilti PROFIS Engineering software is capable of modelling the behaviour of flexible plates as well,

since it uses a finite element-based (FEM) numerical method to determine the internal forces. This approach enables the software to simulate the actual behaviour of the investigated connections.

In the case of the end plate connection designed between the investigated steel beam and concrete column, the anchors must primarily be checked for tensile loading due to the acting bending moment. Within the examined load range, the deformation of the end plate is negligible; therefore, the plate deformation has practically no influence on the distribution of internal forces. Consequently, only minor differences appear between the bending resistances calculated assuming a rigid plate and those obtained assuming a flexible plate.

This phenomenon can be explained by the fact that the bending moments are relatively small, therefore, the 10 mm thick end plate – which would tend to deform significantly under higher loads – does not undergo substantial deformation within this load range. Since plate deformation does not become a primary factor, the force distribution within the anchor group remains nearly identical in both the rigid and flexible plate models.

Table 3 presents the moment resistances of the connections with rigid and flexible end plates.

During the investigation of the connection between the steel beam and the concrete column,

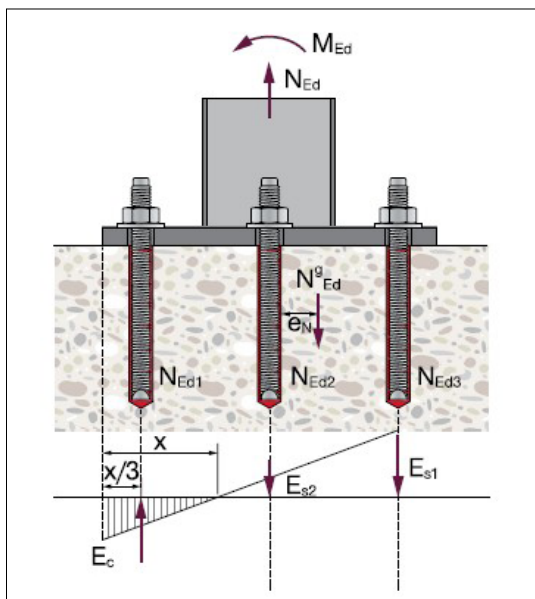


Fig. 3. Linear distribution of strains and anchor forces for a fastening system subjected to bending moment and normal force, assuming a rigid plate. [7]

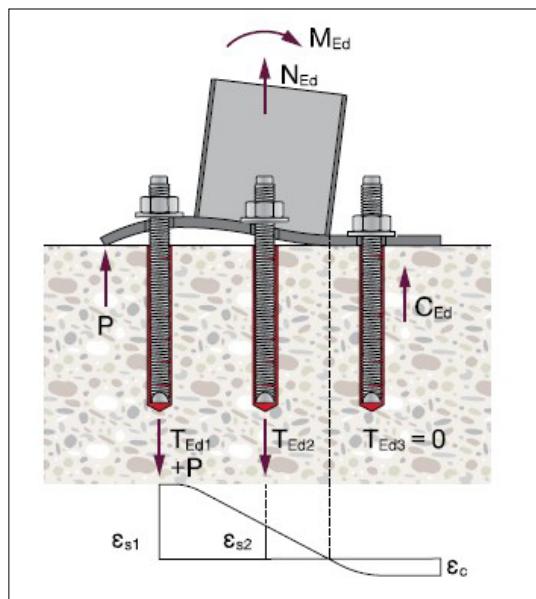


Fig. 4. Non-linear distribution of strains and forces in a fastening system subjected to bending moment and normal force, assuming a flexible plate. [7]

chemical and mechanical post-installed anchor-
age solutions were compared. The load transfer
mechanisms of the two anchor types differ, which
may lead to differences in moment resistance. For
chemical anchors, the tensile force is transferred
primarily through the bond between the concrete
and the adhesive, resulting in load transfer being
activated along the entire embedment depth. In
comparison, the expansion mechanism of me-
chanical anchors creates a more concentrated
stress state within the anchorage zone, which
may provide more favourable load-bearing be-
haviour at certain embedment depths.

The results showed that for the investigated
connections, mechanical anchors exhibit slightly
higher moment resistance than chemical anchors
at an embedment depth of 100 mm. However, the
difference is moderate and cannot be considered
significant within the examined load range.

Table 4 illustrates the moment resistance values
of the connections with chemical and mechanical
anchors.

The calculations were carried out in all cases
without the use of supplementary reinforcement.
Accordingly, only the basic structural reinforcement
is present in the concrete column, and no
additional tension bars were installed that could
increase the load-bearing capacity of the connection.

Fig. 5 illustrates the model of the investigated
connection created in the Hilti PROFIS Engineer-
ing software.

3. Discussions and Results

Based on the observations, both the analytical
calculations and the numerical analyses per-
formed with the Hilti PROFIS Engineering soft-
ware indicated that, at an embedment depth of
100 mm, concrete cone failure was the dominant
failure mode for both chemical and mechanical
anchors. Since the moment resistance of the con-
nection is limited in this case by the concrete cone
capacity, the parametric investigations focused
on the possibilities of increasing the capacity
associated with this failure mode. The concrete
cone failure mode for post-installed anchorage
systems is illustrated in **Fig. 6**.

Several geometric and material parameters in-
fluence concrete cone failure. However, in the
investigated connection configuration, many of
these parameters - such as the edge distance mea-
sured from the anchors and the spacing between
the anchors - are fixed, as they correspond to the

Table 3. Moment resistances of the connections with
rigid and flexible end plates for an embed-
ment depth of 100 mm.

Connection h_{ef} 100 mm	$M_{j,Rd}$ [kNm]		$\Delta M_{j,Rd}$ [%]
	Rigid plate	Flexible plate	
Chemical anchor	7.10	6.80	-4.23
Mechanical anchor	7.25	7.30	0.69

Table 4. Moment resistances of the connections with
chemical and mechanical anchors for an
embedment depth of 100 mm.

Connection h_{ef} 100 mm	$M_{j,Rd}$ [kNm]		$\Delta M_{j,Rd}$ [%]
	Chemical anchor	Mechanic. anchor	
Rigid plate	7.10	7.25	2.11
Flexible plate	6.80	7.30	7.35

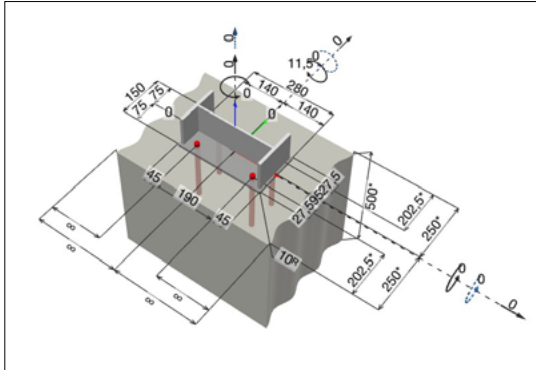


Fig. 5. The software model of the investigated connection.

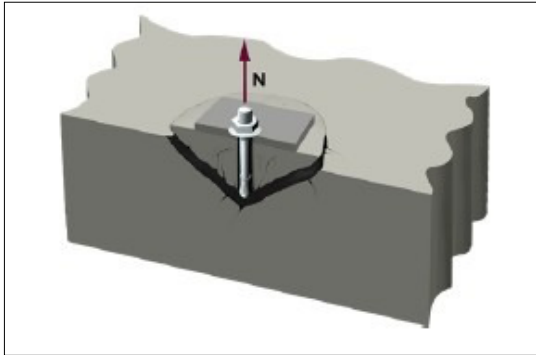


Fig. 6. Concrete cone failure mode for post-installed
anchorage systems [8]

original bolt layout of the end plate connection presented in reference [1], and these parameters were not modified in the present study. For this reason, the moment resistance can realistically be increased only by increasing the embedment depth (h_{ef}) and by altering the concrete strength.

The results of the parametric analyses performed with the Hilti PROFIS Engineering software showed that increasing the embedment depth led to an increase in the moment resistance of the connection for both anchor types, although to different extents and with different failure modes.

For the chemical anchors, the parametric study showed a gradual increase in load-bearing capacity with increasing embedment depth. Increasing the embedment depth from 100 mm to 200 mm resulted in an approximately 66% increase in capacity, as also reflected in the data of Table 5. Throughout the increase in embedment depth,

concrete cone failure remained the dominant failure mode for the chemical anchors.

For the mechanical anchors, the increase in moment resistance was significantly more moderate, as also confirmed by Table 6.

At an embedment depth of 120 mm, the moment resistance exceeded the capacity of the reference configuration by 19.2%, and at 140 mm embedment the increase was also 19.2%. In both ranges, the dominant failure mode was pull-out failure. In a pull-out failure, the fastener is extracted from the entire embedment zone without causing significant damage to the concrete body. This failure mode is illustrated in Fig 7.

However, when the embedment depth was increased to 160 mm, the dominant failure mode shifted to concrete splitting failure (Fig. 8). As a result, the moment resistance no longer increased, instead, it decreased slightly by -1.37% compared to the reference configuration with 100 mm em-

Table 5. *Moment resistance of the chemical anchor connection as a function of embedment depth for a flexible end plate*

Flexible plate Chemical anchor	$M_{j,Rd}$ [kNm]	$\Delta M_{j,Rd}^{100}$ [%]
$h_{ef}=100\text{mm}$	6.80	0
$h_{ef}=120\text{mm}$	8.75	28.68
$h_{ef}=140\text{mm}$	10.30	51.47
$h_{ef}=160\text{mm}$	10.65	56.62
$h_{ef}=180\text{mm}$	10.95	61.03
$h_{ef}=200\text{mm}$	11.30	66.18

Table 6. *Moment resistance of the mechanical anchor connection as a function of embedment depth for a flexible end plate*

Flexible plate Mechanical anchor	$M_{j,Rd}$ [kNm]	$\Delta M_{j,Rd}^{100}$ [%]
$h_{ef}=100\text{mm}$	7.30	0
$h_{ef}=120\text{mm}$	8.70	19.18
$h_{ef}=140\text{mm}$	8.70	19.18
$h_{ef}=160\text{mm}$	7.20	-1.37

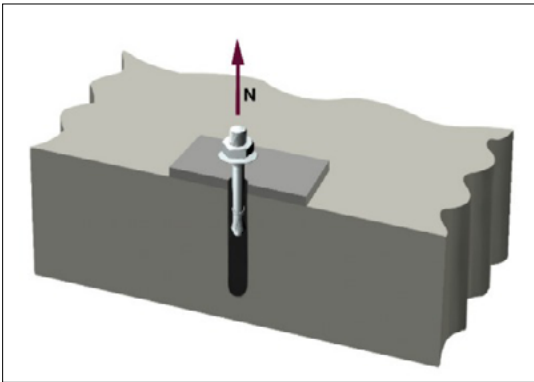


Fig. 7. Pull-out failure mode for post-installed anchorage systems. [8]

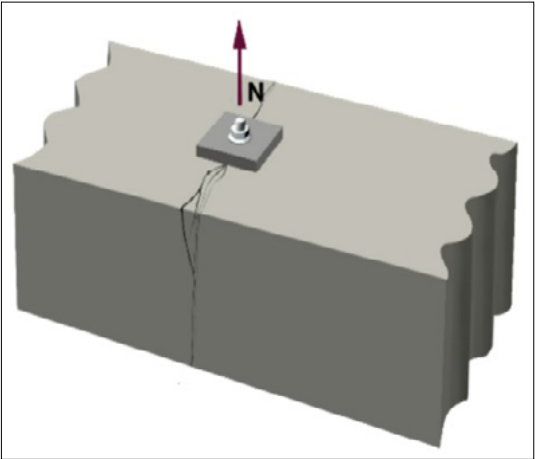


Fig. 8. Concrete splitting failure mode for post-installed anchorage systems. [8]

bedment depth. Concrete splitting failure occurs when the installation torque is applied, and the expansion force generated by anchors, exceed the tensile strength of the concrete. A typical characteristic of splitting failure is the development of multi-directional crack patterns originating from the axis of the anchor.

The change in failure modes can be well explained by the fact that pull-out failure depends primarily on the number and diameter of the anchors, as well as on the concrete strength, while concrete splitting failure is sensitive to the spacing between anchors, the edge distance, the tensile strength of the concrete, the concrete thickness, and the increase in embedment depth. In the investigated connection configuration, the number and diameter of the anchors, as well as the edge and anchor spacing, are fixed and cannot be modified. Therefore, increasing the embedment depth of mechanical anchors eventually reaches a point - approximately around 160 mm - where the risk of concrete splitting becomes more dominant than that of pull-out failure. Consequently, the moment resistance no longer increases at larger embedment depths; instead, it begins to decrease, clearly indicating the anchorage depth limitation associated with the structural behaviour of mechanical anchors.

In the next step, the authors evaluated the effect of the concrete strength class on the moment resistance of the connection. For this purpose, parametric calculations were carried out similarly to the embedment depth analysis using concrete strength classes C25/30 and C30/37.

For the chemical anchors, increasing the concrete strength resulted in concrete cone failure remaining the dominant failure mode at all investigated embedment depths. The changes in

moment resistance obtained by increasing the concrete strength class from C25/30 to C30/37 are summarized in [Table 7](#).

The results presented in [Table 7](#) indicate that increasing the concrete strength class leads to an approximately 10% increase in moment resistance, regardless of the embedment depth. The highest capacity among the investigated connections occurred at an embedment depth of 200 mm, where the moment resistance reached a value of 12.45 kNm.

For the mechanical anchors, when increasing the concrete strength - similarly to the observations made during the embedment depth analysis - the dominant failure mode did not remain uniform but changed depending on the embedment depth. The software results showed that at 100 mm embedment depth, concrete cone failure continued to occur, while at 120 mm and 140 mm embedment, pull-out failure became the dominant mode. At 160 mm embedment, splitting failure governed. [Table 8](#) summarises the corresponding moment resistance values for the respective embedment depths.

In terms of load-bearing capacity, switching from concrete strength class C25/30 to C30/37 resulted in an approximately 10% increase in moment resistance for the mechanical anchors at all investigated embedment depths. Thus, the improvement in moment resistance is clearly observable in this case as well; however, the occurrence of splitting failure at larger embedment depths imposes limitations on the potential for further capacity enhancement.

Based on the results of the parametric analyses, the highest moment resistance for chemical anchors was achieved with the configuration embedded 200 mm into C30/37 concrete providing a

Table 7. *Moment resistance of the chemical anchor connection as a function of embedment depth for a flexible end plate and C30/37 concrete*

Flexible plate Chemical anchor	$M_{i,Rd}$ [kNm]		$\Delta M_{i,Rd}^{100}$ [%]
	C25/30	C30/37	
$h_{ef} = 100\text{mm}$	6.80	7.5	10.29
$h_{ef} = 120\text{mm}$	8.75	9.6	9.72
$h_{ef} = 140\text{mm}$	10.30	11.40	10.68
$h_{ef} = 160\text{mm}$	10.65	11.75	10.33
$h_{ef} = 180\text{mm}$	10.95	12.10	10.50
$h_{ef} = 200\text{mm}$	11.30	12.45	10.18

Table 8. *Moment resistance of the mechanical anchor connection as a function of embedment depth for a flexible end plate and C30/37 concrete*

Flexible plate Mechanical anchor	$M_{i,Rd}$ [kNm]		$\Delta M_{i,Rd}^{100}$ [%]
	C25/30	C30/37	
$h_{ef} = 100\text{mm}$	7.30	8.05	10.27
$h_{ef} = 120\text{mm}$	8.70	9.60	10.34
$h_{ef} = 140\text{mm}$	8.70	9.60	10.34
$h_{ef} = 160\text{mm}$	7.20	7.95	10.42

moment capacity of 12.45 kNm. For mechanical anchors, the maximum capacity occurred with the configuration embedded in C30/37 concrete at embedment depths of 120–140 mm, where the moment resistance reached 9.60 kNm. Comparing the most favourable configurations of the two anchorage technologies, it can be concluded that the chemical anchor connection provides approximately 30% higher moment resistance than the mechanical solution. Accordingly, among the examined configurations, the chemical anchor system with 200 mm embedment depth in C30/37 concrete resulted in the highest moment capacity.

Table 9 summarizes the moment resistance of the various beam-to-column connections, including experimentally determined, numerically calculated, and code-based design values. The first two configurations in the table (T2 and T3) correspond to the composite connections presented in reference [1] and they show the moment capacities measured in laboratory tests. Since these are actual experimental results, they serve as reference values in the following comparisons.

In reference [3] the connections labelled as NI and NC refers to steel beam-to-steel column connections, whose moment resistances were determined numerically. The designation “NC” corresponds to calculations performed using the Component Method implemented in the Consteel software, while “NI” refers to finite element models for which capacity was determined by CBFEM (Component-Based Finite Element Method) procedure in the Idea StatiCa software. These numerical methods employ different safety factors and idealized material models, which typically lead to conservative capacity values; consequently, the

actual moment resistance measured through experimental investigations may be higher.

The last two rows of the table present the results of the post-installed steel beam-to-concrete column connections examined in this study. The designation ‘CA’ refers to the chemical anchor configuration, while ‘MA’ denotes the mechanically anchored connection. The notation ‘p10mm’ corresponds to the 10 mm thick end plate, and ‘h_{ef}’ indicates the applied embedment depth. The moment resistances of these configurations are derived from the detailed verification procedure implemented in Hilti PROFIS Engineering, which follows the EN 1992-4:2018 [2] standard and incorporates multiple safety factors. As a result, the calculated capacities typically underestimate the experimentally attainable load-bearing resistance.

From **Table 9** it is clear that the T3 configuration serves as the absolute reference value (163.10 kNm). In comparison, the moment resistances of the steel column-to-steel beam connections (NC and NI models) are approximately 80% lower. The capacities of the post-installed connections show an even greater reduction: the chemical anchor configuration with a 200 mm embedment depth reached a resistance of 12.45 kNm, while the mechanically anchored solution achieved 9.60 kNm. Relative to the reference T3 experimental capacity, these values represent reductions of approximately 92% and 94%, respectively.

The results in the table therefore highlight that although the investigated post-installed anchored connections possess adequate moment capacity; their resistance is significantly lower compared to steel or composite connections. Due to the safety factors incorporated in the Hilti PROFIS Engineering calculations, these values are expected to be conservative, meaning that the actual behaviour could be more favourable in experimental conditions - as illustrated by the measured capacities of the T2 and T3 joints.

Table 9. *Moment resistances and comparison of the connections between composite beam-to-steel column [1], steel beam-to-steel column [3], and steel beam-to-concrete column configurations*

Connection	M _{i,Rd} [kNm]	ΔM _{i,Rd} ^{-T3} [%]
T3 [1]	163.10	0
T2 [1]	147.40	-9.62
NC-p10mm [3]	34.00	-79.15
NI-p10mm [3]	31.02	-80.98
CA-p10mm- h _{ef} 200mm-C30/37	12.45	-92.37
MA-p10mm- h _{ef} 140mm-C30/37	9.60	-94.11

4. Conclusion

The aim of this study was to investigate the moment resistance of an end plate connection between a steel beam and a reinforced concrete column, realised using post-installed anchors. The investigation was carried out by comparing analytical calculations based on the provisions of EN 1992-4:2018 [2] with numerical results obtained from the Hilti PROFIS Engineering software. The two methods showed good agreement, confirm-

ing that the software implements correctly the code-based checks and is suitable for providing reliable estimates of the load-carrying capacity for the investigated connection configurations.

The parametric investigations revealed that the moment resistance of the examined connection is primarily influenced by two factors: the embedment depth of the anchors and the concrete strength class. Due to geometric constraints (edge distances and bolt spacing), other parameters could not be modified.

Chemical anchor connections showed a strong sensitivity to increases in embedment depth: when the embedment length was increased from 100 mm to 200 mm, the moment resistance increased by approximately 66%, while the dominant failure mode consistently remained concrete cone failure. Increasing the concrete strength from C25/30 to C30/37 resulted in an additional improvement of nearly 10% at all investigated embedment depths. The highest capacity, 12.45 kNm, was obtained for the chemical anchor connection with 200 mm embedment depth installed in C30/37 concrete.

The behaviour of the mechanical anchors differed due to the characteristics of their anchorage mechanism. Although an increase in moment resistance of approximately 19% was observed up to an embedment depth of 120–140 mm, at 160 mm embedment splitting failure became the dominant failure mode, resulting in a reduction of capacity. Increasing the concrete strength also led to an improvement of nearly 10% in moment resistance; however, for mechanical anchors the limiting factor is the risk of concrete splitting, which restricts the applicability of larger embedment depths. The highest achieved capacity for this solution was 9.60 kNm.

The comparison of the different connection types indicates that the load-bearing capacity of the investigated post-installed concrete-to-steel connections is significantly lower compared with both the experimentally tested composite connections (T2, T3) and the numerically analysed steel-to-steel connections. This is due partly to the limited load-transfer capacity of anchor connections, and partly to the conservative safety factors ap-

plied in the checks prescribed by EN 1992-4:2018 [2] which are expected to underestimate the actual structural behaviour.

Overall, it can be concluded that post-installed connections between steel beams and reinforced concrete columns are capable of providing moment transfer; however, their capacity is significantly lower compared to conventional steel-to-steel or composite connections. At the same time, the investigations highlight that with appropriate parameter selection the performance of the connection can be optimized, and the system may offer a viable alternative for certain engineering applications.

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INTEGRATED ASSESSMENT OF BUILDING ENERGY PERFORMANCE AND LOCAL FUEL SUPPLY IN SUSTAINABLE DEVELOPMENT OF DEPRIVED RURAL SETTLEMENTS

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Abstract

The energy transition of disadvantaged rural settlements requires cost-effective development approaches based on local resources. This study examines the combined role of energy self-sufficiency and cost-optimal building energy retrofits in sustainable development in 24 settlements in Southern Transdanubia, Hungary. The analysis evaluates a development model that considers the energy performance of the building stock, the fuel demand of households dependent on solid fuels, and the energy supply potential of municipal land across three development scenarios. Results show that local biomass production can supply about 14% of heating demand, while integrating heating system upgrades and building retrofits can increase average self-sufficiency to 73%. Potential municipal CO₂ emission reductions are estimated at 56–81 percentage points.

Keywords: rural energy transition, energy self-sufficiency, building energy efficiency, biomass energy, short rotation coppice, rural energy poverty, sustainable rural development, building retrofit.

1. Introduction

The goal of the European Green Deal is to achieve climate neutrality on the European continent by 2050, which requires strategic measures spanning all sectors and industries. In the European Union (EU), the residential sector accounts for 40% of total energy consumption and 36% of greenhouse gas emissions, levels primarily attributable to an outdated and energy-inefficient building stock [1]. Directive 2024/1275/EU on the Energy Performance of Buildings [2] requires Member States to establish a national building renovation strategy that defines the necessary measures to achieve residential decarbonization by 2050. To ensure the integrity of the regulatory framework, EU Regulation 2018/1999 [3] required Member States to integrate the content of their renovation strategies into their National Energy and Climate Plans, define the vulnerable groups most exposed to the effects of climate change, and develop dedicated measures to reduce energy vulnerability and

improve the energy performance of buildings. Recent studies have confirmed that this vulnerability is unevenly distributed within the country and is typically concentrated in rural areas [4], highlighting the need for diversified policy-making within the country. In contrast, another study highlighted that marginalized rural regions—particularly solid fuel-dependent households—are severely underrepresented in the current policy environment and excluded from development priorities [5]. These regions typically suffer from the lack of resources at both the municipal and household levels; consequently, the transition toward sustainability necessarily offers a low-cost, long-term solution, reduces municipal CO₂ emissions, and improves quality of life.

Based on this, this paper examines, within the framework of a data-driven urban development model, the effectiveness of energy self-sufficiency and rationalized building energy efficiency improvements in the transition toward sustainable

development, with a particular focus on solid fuel-dependent households. On one hand, the study defined the energy performance of the building stock, its conditions, and annual energy demand for 24 deprived settlements in South Transdanubia based on representative datasets. On the other hand, it examined the potential emission reductions, energy efficiency, and economic performance associated with the utilization of municipal green spaces for energy purposes under three development scenarios.

2. Results

2.1. Energy parameters of the building stock and estimated annual fuel demand

This chapter discusses the fundamental conditions for the integration and effectiveness of the development model aimed at adaptive energy self-sufficiency, including the extent of the settlement's development potential, the energy performance of the building stock, and its energy demand. The total building stock of settlements included in the study comprises 3,621 households. Settlement size ranges from 69 to 360 households, with an average of 126 households per settlement. Occupied households account for 89% of the total housing stock.

According to the study parameters, this research considered solid-fuel dependent households among occupied households, accounting for 49–99% depending on the settlement and 84% of the total building stock, as summarized in Fig. 1.

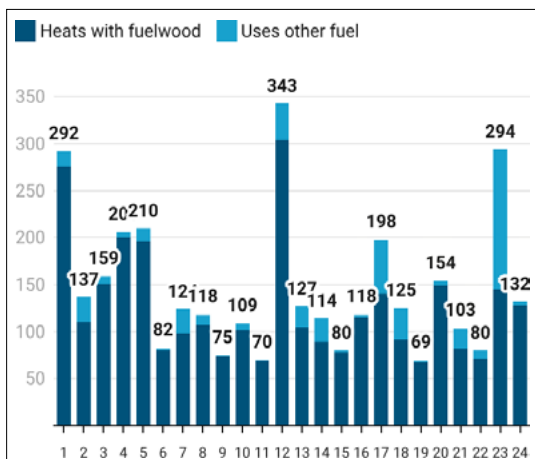


Fig. 1. Number of households and proportion of household heating with solid fuels by settlement. Source: Compiled by the authors based on KSH data (reference year: 2022) [6].

Fig. 2 illustrates the age distribution of the examined building stock in comparison to the national building stock. Nearly 43% of the building stock was built 80 years ago or earlier. The average age of the buildings is 65 years, exceeding the national average by 12 years. The disadvantaged status of the settlements, together with the socio-economic data reported by the databases, suggest that building modernization has either not been undertaken or has only been partially implemented, typically focusing on improving interior comfort conditions (e.g., the installation of bathrooms, washrooms, and kitchens). This observation is further supported by energy certificate data from the South Transdanubia region, which similarly to the North Hungary region, demonstrates the lowest household energy performance, with an average annual primary energy demand of 251,6 kWh/m² [7].

The examined building stock has an average floor area of 84 m², approximately 5% above the national average in Hungary. Across the settlements, the building stock is predominantly composed of dwellings with a floor area of 60-99 m², followed by those exceeding 100 m², as shown in Fig. 3. Consequently, annual energy demand is driven both by the poor thermal performance of the buildings and by the increased demand associated with larger floor areas.

The fuel demand of the sampled buildings, expressed in mass, was estimated by dividing the annual energy demand [7] by the calorific value

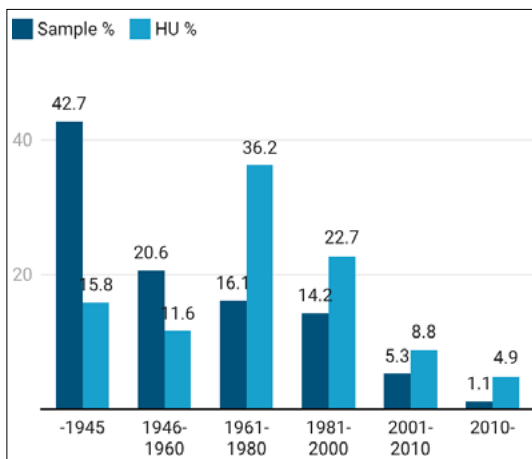


Fig. 2. Distribution of the examined building stock by construction year relative to the national building stock. Source: Compiled by the authors based on KSH data (reference year: 2022) [6].

of fuelwood [8] as shown in the following equation:

$$M_F = \frac{A_{AV} \times ePED}{uNCV_{wood}} \tag{1}$$

The average household fuel need in volumetric terms was estimated as the ratio of mass-based fuel demand to the bulk density coefficient of fuelwood [9] as shown in the following equation:

$$V_F = \frac{M_F}{\rho b_{wood}} \tag{2}$$

According to equations (1) and (2), the annual fuel demand of fuelwood-dependent households in the sample amounts to 4,6 tons, equivalent to approximately 9,6 m³. In accordance with Government Decree No. 57/2013 [10] households in disadvantaged settlements receive 1m³ of fuelwood annually under the Warmth of Home (in Hungarian: “Otthon Melege”) program, covering roughly 10% of their seasonal fuel demand.

2.2. Parameters, energy capacity, and conditions of energy development by settlement

The evaluation of energy self-sufficiency potential incorporated the concept of short-rotation coppice (SRC) plantations. SRC systems are defined by the dense cultivation of fast-growing woody species (commonly poplar and willow), harvested at 2-8-year cycles through coppicing

at ground level, enabling a productive lifespan of 25-30 years [11]. Within this study, SRC is considered not only as a means of reducing reliance on illegal fuel use through improved energy-self-sufficiency, but also as a multifunctional land-use system supporting sustainable development in several domains. In addition to enhancing habitat diversity and biodiversity [12] SRC exhibits high CO2 sequestration capacity and favorable energy balance [13, 14].

Within sustainable development frameworks, SRC plantations are typically associated with the utilization of low-productivity agricultural land, ensuring a balance between environmental sustainability, food supply, and energy production [15, 16, 17]. Consistent with this approach, the inclusion of municipally owned marginal lands in the present concept fulfills key criteria for sustainable land use. Fig. 4 provides an overview of the extent, typology, and spatial distribution of these areas across the settlements.

The study accounts for both municipally owned green areas and land linked to vacant properties. The availability of suitable green infrastructure exhibits substantial variability across settlements, with an average of 5,7 hectares per settlement identified as suitable for development.

Although SRC plantations are harvested in multi-year cycles, their yield is conventionally expressed in tons per hectare per year. Actual yield is determined by climatic conditions, soil char-

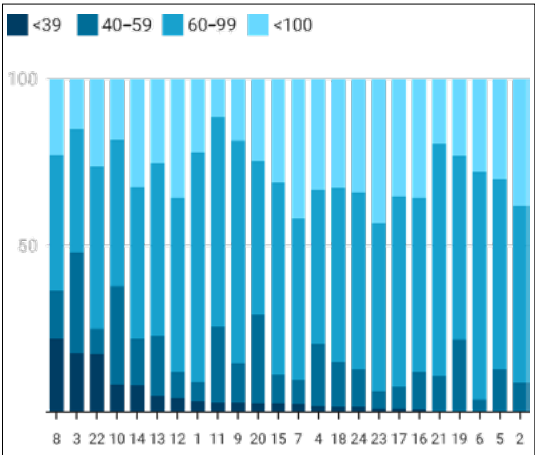


Fig. 3. Distribution of the examined building stock by floor area, by municipality, expressed in m2. Source: Compiled by the authors based on the KSH Census database (reference year: 2022) [6].

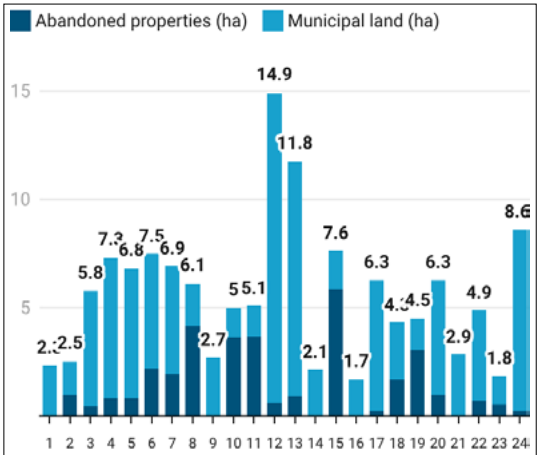


Fig. 4. Types of settlement green spaces integrated into development, by settlement. Source: Compiled by the authors based on the KSH Census database (2022) [6] and the National Spatial Development and Planning Information System (TEIR) database (2021) [18].

acteristics, precipitation, and management practices [19]. Under varying conditions, yields are expected to range from 5 to 27 t/ha/year, with an average of 12,5 t/ha/year. Based on these parameters, the fuel supply capacity of municipal green infrastructure can be estimated with an average annual output of 70,7 tons per settlement, as summarized in Fig. 5.

2.3. Development Scenarios Examined and Their Efficiency in Energy Self-Sufficiency

Energy self-sufficiency potential was evaluated through three development scenarios incorporating improvements in both building energy performance and heating system technologies as summarized in Table 1. Scenario S1 focuses on the energy production capacity of underutilized municipal land. Scenario S2 extends this approach by integrating the modernization of wood-based heating systems to enhance fuel efficiency. As reported in a previous impact study [20] outdated conventional heating systems operate at around 36% efficiency, while modern eco-design stoves can reach 82%, resulting in a relative fuel saving of 56%.

Scenario S3 extends the previous cases by further integrating cost-optimal improvements in building energy performance. The current regional average of approximately 251 kWh/m²/year corresponds to a “G”-rated energy performance class [21]. In this scenario, an improved level of 110 kWh/m²/year is assumed, representing a “C”-rated energy class performance. Buildings at this performance level are typically characterized by upgraded fenestration systems and moderately improved thermal insulation [2].

Considering the variability in fuel demand arising from building energy needs, alongside the constant value of municipal energy self-sufficiency potential, the ratio of fuel-sufficiency relative to the total fuel demand was derived according to the following equation:

$$\sum_{S1}^{S3} SS\% = \frac{M_F \times \Sigma_n H}{FC_{LAND}} \tag{3}$$

where: M_F denotes the unit quantity of fuel demand by mass, $\Sigma_n H$ denotes the number of households, and FC_{LAND} denotes the fuel capacity of land areas by fuel mass.

Fig. 6 illustrates the proportion of fuel self-sufficiency achieved across settlements under the S1-S3 scenarios. The results demonstrate that re-

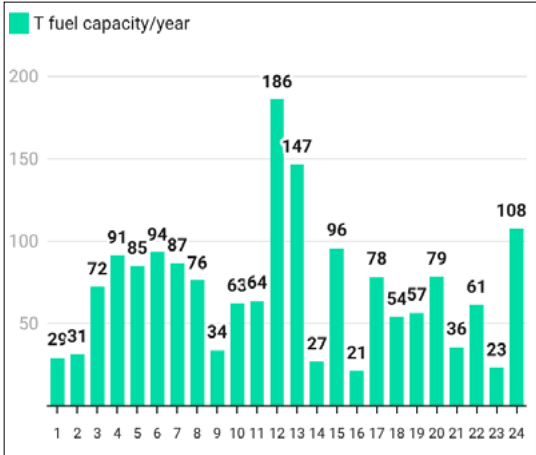


Fig. 5. Energy capacity of green land integrated into development, expressed in tonnes per municipality. Source: Compiled by the authors

Table 1. Integrated development parameters of the examined scenarios

Integrated development component	S1	S2	S3
Energy self-sufficiency	x	x	x
Modernization of heating equipment (modern stove)	n.a.	x	x
Cost-optimized building energy efficiency improvements	n.a.	n.a.	x

lying solely on underutilized municipal land and vacant properties for energy production covers only a fraction of total energy demand. Despite the substantial variability in the extent of available land, the corresponding energy supply potential exhibits lower variability when expressed relative to total fuel demand. Overall, S1 scenario provides between 2-31% energy demand, with an average contribution of 14%.

In Scenario S2, the reduction in fuel demand resulting from the adoption of modern combustion technologies increased the energy self-sufficiency by nearly 45 percentage points compared to Scenario S1. In Scenario S3, the combined energy system and building energy improvements resulted in energy self-sufficiency rates exceeding 60% in nine settlements, while in one settlement the energy production capacity surpassed total local energy demand. The land areas associated with these settlements, ranging from 5 to 11 hectares, exceed the average municipal green infrastructure by approximately 1.5 hectares.

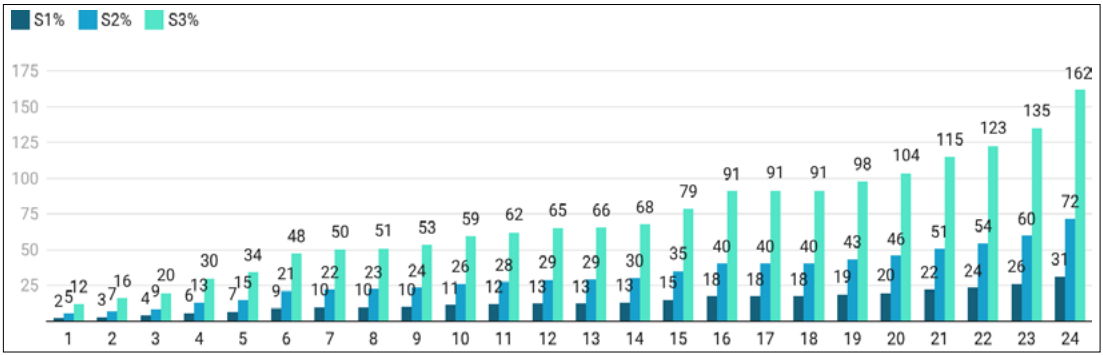


Fig. 6. Share of the adaptive energy self-sufficiency development model's performance relative to total municipal fuel demand for scenarios S1–S3

High performing settlements are further characterized by a relatively low number of households, ranging between 69 and 105. In contrast, settlements with a high number of households and/or limited green infrastructure are unable to achieve significant levels of energy self-sufficiency under any scenario examined. Nevertheless, according to the best-case scenario model, settlements exhibit an average energy self-sufficiency potential of 73%.

2.4. Financing Schemes, Economic Return, and the Implementation of the Regional Development Model in Sustainable Settlement Development

The economic viability of the examined integrated development framework was evaluated by comparing the current financing scheme of the Warmth of Home program with the costs of the SRC based development approach. The analysis considered total costs over a 25-year period for both approaches. For the existing scheme, the equivalent cost of 1 m³ fuelwood support per solid fuel-dependent households was considered, whereas in the proposed development model, costs related to SRC installation, maintenance, harvesting, and infrastructure were included, as detailed in Table 2. Owing to local production conditions and land-use characteristics, land leasing and fuel transportation costs were not incorporated into the SRC cost structure. The model further assumes the partial use of abandoned houses as infrastructure for drying and processing activities following harvest.

Under the existing social financing scheme, total costs were estimated by multiplying the unit cost of 1m³ of fuelwood by the number of subsidized households over a 25-year period, in accordance with the following equation:

$$\sum_{1}^n \bar{C}_{EFS} = uC_{FUEL} \times \Sigma_n H \quad (4)$$

where: uC_{FUEL} denotes the unit fuel cost, and $\Sigma_n H$ denotes the number of subsidized households.

For the adaptive energy self-sufficiency model under investigation, total costs were estimated using the cost components presented in Table 2 accounting for their frequency over the study period, as shown in the following equation:

$$\sum_{1}^n \bar{C}_{AEM} = \bar{C}_{ES} + \bar{C}_R + \bar{C}_Y \quad (5)$$

where: $\bar{C}_{ES}$ denotes the one-time installation cost, $\bar{C}_R$ denotes the costs considered per rotation (every 2 years), and C_Y denotes the annual costs.

The payback period was determined based on the cost difference between the existing financial scheme and the adaptive energy self-sufficiency model. The analysis considered total investment costs over a 25-year time horizon, disaggregated on an annual basis. The resulting cost differences, based on equation (4) and (5), are illustrated in Fig. 7.

As the adaptive model provides fuel only from the third year following installation, the analysis considers both the initial investment costs and the continuation of the existing scheme during the first two years. Under these assumptions, the model achieves payback in the third year compared to the baseline. The rapid return in investment suggests that optimized budget reallocation could enable the integration of significant energy efficiency improvements without the integration of additional financial resources. Over a 25-year period, total cost savings are estimated to exceed

Table 2. Unit costs of the examined financing schemes. Source: Compiled by the authors based on references [11, 22].

Type	Unit	Frequency	Cost
<i>Short Rotation Coppice (SRC) – examined scheme</i>			
Total establishment cost			
On-site inspection	EUR/ha	at installation	42.9
Design		at establishment	42.9
Soil preparation	EUR/ha	at establishment	128.6
Propagation material	EUR/ha	at establishment	256
Planting	EUR/ha	at establishment	256
Total maintenance cost			
Weed control	EUR/ha	per year	100
Plant protection	EUR/ha	per year	28.6
Nutrient supply	EUR/ha	per year	114.3
Total harvesting cost			
Harvesting	EUR/ton (dry)	per rotation	5.7
Shipping	EUR/ton (dry)	n.a.	n.a.
Disposal cost	EUR/ha	per rotation	257.1
Total overhead costs			
Land rent	EUR/ha	n.a.	n.a.
Technical consulting	EUR/ha	per year	28.6
<i>Social firewood subsidy – current scheme</i>			
Total purchase cost			
Fuelwood	euros/household	per year	168

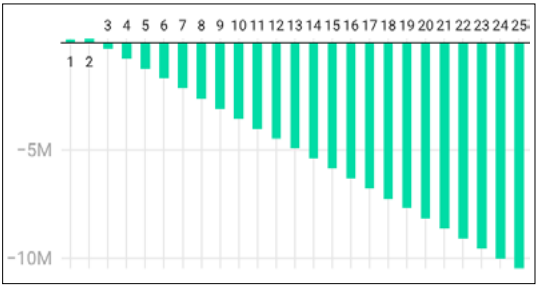


Fig. 7. Relative cost recovery of the adaptive energy self-sufficiency settlement development model over the 25-year study cycle. The X-axis represents the annual cycles, and the Y-axis represents the relative cost of the adaptive model compared to the existing financing scheme.

EUR 10 million. It should be noted that the analysis excludes administrative, labor, and fuelwood distribution costs.

In addition to economic evaluation, the study examined the environmental performance of the S1-S3 scenarios in terms of CO₂ emissions. Emissions were calculated for each settlement by multiplying scenario-specific fuel demand by the unit CO₂ emission factor for fuelwood combustion [23, 24] as shown in the following equation:

$$\sum_{S1}^{S3} Em = M_F \times U_{EM_{wood}}, \tag{6}$$

where: M_F (kg) denotes the mass of fuel required, and $U_{EM_{wood}}$ denotes the emission factor per unit of firewood burned (kg/kg).

The estimated annual CO₂ emissions for the settlements across scenarios, calculated according to Equation (4), are summarized in Fig. 8.

The results indicate significant variation in estimated annual household CO₂ emissions from heating across the examined scenarios. Scenario S1, addressing only fuel self-sufficiency, does not reduce fuel demand; consequently, emission levels remain unchanged relative to current heating practices. In contrast, Scenario S2 achieves an average emission reduction of 56% due to decreased fuel demand following heating system modernization. Scenario S3 yields a further 44% reduction compared to S2 and an overall reduction of 81% relative to S1, driven by the combined effects of rationalized and optimized building energy performance.

3. Conclusions

As illustrated in Fig. 9 the existing social fuel subsidy scheme primarily addresses the reduction of household heating expenditures and, as such, contributes only to a limited extent to broader municipal sustainable development processes. Although the principal aim of the proposed development model is to satisfy local energy demand and decrease dependence on the energy sector, it simultaneously operates as a multifunctional framework supporting sustainable development across several dimensions. These encompass both the improvement of household socioeconomic conditions and the reduction of environmental impacts associated with municipal energy use.

The socioeconomic dimension includes reduced household energy expenditures, job creation and alignment with Just Transition principles. In ad-

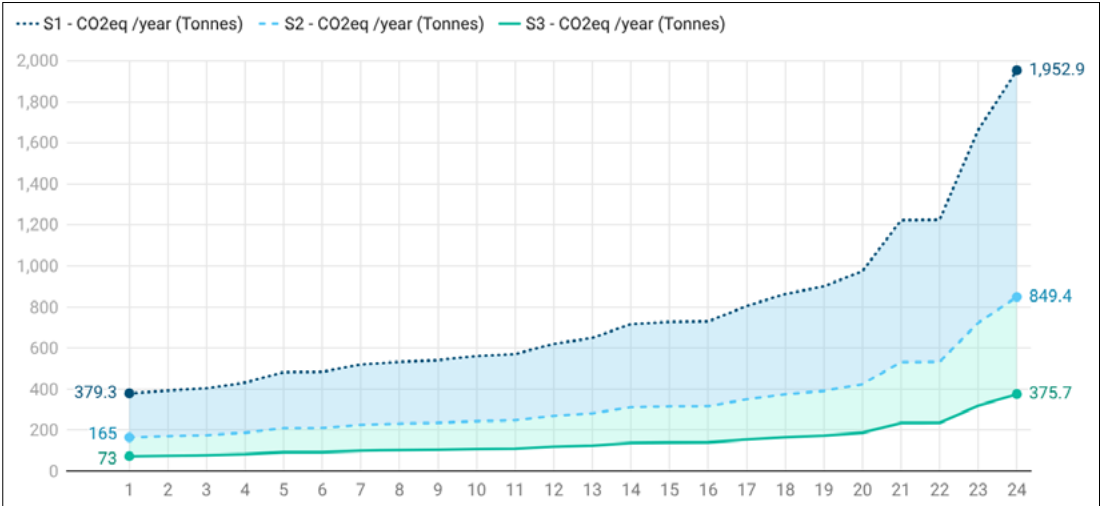


Fig. 8. Estimated annual CO₂ emissions for Scenarios S1–S3, expressed in tonnes , by settlement.

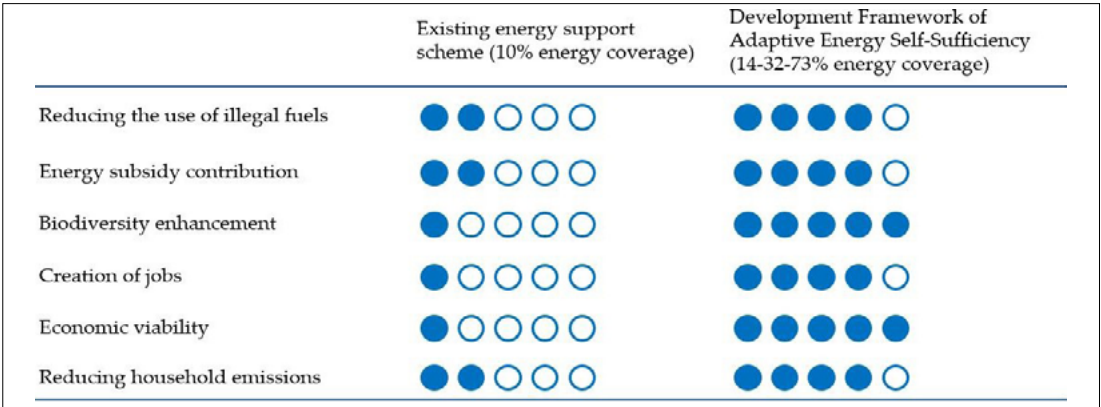


Fig. 9. Performance evaluation of the examined models, taking into account economic efficiency, environmental, and social contributions.

dition to relatively low installation and maintenance costs, the model contributes to household economic stability, mitigates the use of illegal fuels, and enhances community-level energy self-sufficiency.

However, it is essential to differentiate the effectiveness of the development scenarios included in the assessment. The use of municipal green land for energy purposes alone supports decentralized energy access and reduces household energy expenditures; however, its effectiveness only marginally surpasses that of existing social energy subsidy schemes. A critical environmental outcome of the concept is the reduction of municipal CO₂ emissions, which depends fundamentally on improving building energy performance. These cost-optimized measures, implemented in Sce-

narios S2 and S3, result in an estimated emission reduction of 56-81%.

The implementation of such developments poses significant financial challenges in regions facing resource constraints both at household and settlement levels. Nonetheless, the economic viability assessment demonstrates that the proposed development model achieves a return on investment within three years relative to the baseline scenario. This finding implies that re-allocating existing budgetary resources may allow for the integration of building energy efficiency measures without additional funding requirements. However, the detailed cost structure and its relation to available financial capacity require further analysis.

The policy implications of these findings underscore the necessity of integrated, community-based approaches to energy transition in deprived rural regions, emphasizing local resource-based energy production, targeted building retrofits, and appropriate financing mechanisms. To broaden the applicability of such cost-efficient, complex models requires further empirical investigation, accounting for local variations in building stock conditions, renovation needs, and development costs.

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