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TABLE OF CONTENTS
(С О Д Р Ж И Н А)

MOTOR VEHICLES
(Моторни возила)

LOGISTICS
(Логистика)

MECHANOTRONICS
(Механотроника)

APPLIED MECHANICS
(Применета механика)

ENVIRONMENT
(Животна средина)

INDUSTRIAL ENGINEERING AND MANAGEMENT
(Индустриско инженерство и менаџмент)

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Original scientific paper

DESIGN, ANALYSIS, AND OPTIMIZATION OF THE STEERING COLUMN SYSTEM FOR AN ELECTRIC STREET SWEEPER

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A b s t r a c t: This study explores the challenges and solutions related to improving the interior ergonomics of a small street sweeper, with a specific focus on redesigning the steering column and brake pedal system. The initial design faces issues such as obstructed field of view and limited space in the operator's knee area. The primary objective is to enhance comfort and safety for the operator within the constraints of the existing design. The proposed solution involves a new steering column structure that integrates the brake pedal system. Siemens Jack software was employed for ergonomic analysis, revealing improved operator comfort and larger field of view with the modified design. Dynamic analysis using ADAMS View confirmed that the new brake pedal system met the requirements outlined in the ECE R13 regulation. This solution improves ergonomics, offers larger field of view, and ensures optimal brake performance.

Key words: steering column; brake pedal; vehicle ergonomics; street sweeper

ДИЗАЈН, АНАЛИЗА И ОПТИМИЗАЦИЈА НА УПРАВУВАЧКИОТ СТОЛБ НА ЕЛЕКТРИЧНА МАШИНА ЗА ЧИСТЕЊЕ УЛИЦИ

А п с т р а к т: Ова истражување ги истражува предизвиците и решенијата поврзани со подобрување на ергономијата на машина за чистење на улици, со фокус на редизајнирање на управувачкиот столб и педалот на сопирачката. Почетниот дизајн се соочува со ограничувања како што се намаленото видно поле и ограничениот простор во пределот на колената на операторот. Примарната цел е да се подобри удобноста и безбедноста на операторот во рамките на ограничувањата на постојниот дизајн. Предложеното решение вклучува модифициран модел на управувачкиот столб во кој е интегриран педалот од системот за сопирање. Програмскиот пакет Siemens Jack е користен за ергономска анализа, потврдувајќи дека новиот дизајн има подобра удобност и поголемо видно поле. Динамичката анализа со помош на ADAMS View потврдува дека педалот и преносниот механизам на сопирачките ги исполнуваат барањата наведени во регулативата ECE R13. Новото решение ја подобрува ергономијата, нуди зголемување на видното поле и обезбедува оптимални перформанси на сопирачките.

Клучни зборови: управувачки столб; педал од системот за сопирање; ергономија на возила; машина за чистење улици

1. INTRODUCTION

Ergonomic methods are applied in the earliest stages of the vehicle design process since they include considering crucial points which determine the comfort and safety of both the driver and occupants, such as: the driver's body position, intuitive interactions at workstations, unobstructed field of view, easily reachable and useable controls, etc. [1]. The goal is to achieve an optimal "fit" between the drivers and the vehicle in a manner that eliminates, or greatly reduces, the risk of mistake and misuse that might lead to system failures and injuries [2]. Ergonomics is what makes the design safe, comfortable and convenient. However, the ergonomic tasks can be quite challenging when designing the vehicle interior subsystems – seats, controls, pedal systems, dashboards, and other elements, within the very limited space. Moreover, the vehicle interior design encompasses various aspects and standards [3]. In that sense, a systems approach is commonly used which includes analyzing the driver, the vehicle and the environment as interconnected systems with specific characteristics [2]. The input information required to help these systems function and exchange information successfully is a combination of multi-disciplinary data – ergonomic guidelines, anthropometric measurements, vehicle regulations, recommended practices for car interior design, etc. [2, 4]. The input information directly influences the interior design process.

The design and placement of the pedal systems is among the top priority vehicle ergonomic tasks since the accelerator, clutch and brake are the most frequently used controls in a vehicle. Authors Garg, Bhide and Gupta [5], emphasize that ensuring their proper positioning in alignment with human anthropology is of paramount importance, particularly concerning driver comfort. In their research, the authors highlight that the particular SAE standards (J1100, J1516, J1517) which provide the ideal pedal point position do not fully consider the differences in drivers of various percentiles. Therefore, they provide a model for optimizing the pedal points according to several inputs and packaging constraints: effective H30 value, pedal plate angle, pedal lever angle and length, anthropometric data, and also seat travel and torso angle [5].

In the study of Zarizambri bin Ahmad [6], an analysis was conducted to enhance and further optimize the pedal box system for a small race car (Formula SAE Third Race Car). The author takes into consideration the ergonomic recommendations for accessibility of controls, the dimension constraints of the specific vehicle type, seat and safety features, the requirements for the pedal systems and relevant regulations. Based on all considered parameters, the author designs a new pedal box and evaluates it through virtual ergonomic tools, FEM analysis and kinematic and dynamic simulation tools [6]. Similarly, in the project of Evan Beery the pedal box assembly for the electric formula SAE racecar team's 2016 racecar was designed and produced [7]. The design is based on interior measurement standards, as well as durability, manufacturability, and cost requirements [7].

The work of Ravan et al. [8], on the other hand, is the design and ergonomic considerations precisely for a clutch pedal assembly. The research assesses the subjective comfort levels experienced by various drivers of different stature percentiles when using the clutch pedal. Additionally, the study aims to analyze the pedal lever and its mounting arrangement using software tools. Conclusions include that the H-point (hip-point) to AHP (accelerator-heel-point) distance should be 650 mm so that the pedals can be optimally used by different stature drivers by adjusting the seat placement. In addition, preferences regarding all pedal clearance and dimensions are given – clearance of 30 mm between clutch and steering column, 47.5 mm between steering column and brake, and 60 mm between brake and accelerator [8].

Slightly differently, the paper of Zhang et al. [9] proposes a kind of pure mechanical lifting pedal applied to rail transit vehicles. This pedal is engineered to accommodate various vehicle structures and operators, significantly enhancing its versatility and reliability across applications.

The review of existing scientific literature on the ergonomics of vehicle pedals has furnished valuable insights. This research includes several of the previously stated methodological approaches with the goal to design, analyze and optimize a brake pedal system according to ergonomic requirements and packaging constraints given by a street sweepers' manufacturer. This paper elaborates a case study and an evaluative research involving comparisons of performance in using different vehicle brake pedal system designs and determining the most convenient to use, with a focus on a user – centered approach. Input data is used from several sources (vehicle characteristics; specific production requirements; required performance according to the ECE R13 regulation; anthropometric data; ergonomic recommendations; ISO standards for physical dimensions of operators, minimum operator space envelope, zones of comfort and reach of controls; etc.) to design a brake pedal system assembly incorporated in the steering column construction. Furthermore, this research utilizes a combination of ergonomic and dynamic assessment tools.

The main objectives of this research, the used methodology, as well as the multi-body and ergonomic simulation, optimization results, and discussions, are elaborated in the following sections.

2. PROBLEM STATEMENT

The research elaborated in this paper is the outcome of the work on a specific engineering task where the main requirement was to improve the interior ergonomics of a small street sweeper. Due to very limited cabin interior space there was insufficient clearance around the vehicle operator, uncomfortable use of the brake pedal and obstructed field of view. The issue with the field of view was due to the size of the new steering column which was positioned higher in order to incorporate (beside the steering wheel components) the given brake pedal cylinder and two control screen holders. Therefore, there was a need to redesign the brake pedal system while keeping the same type of master brake cylinder and achieving the required brake performances and brake pedal force according to the ECE R13 regulation, but incorporating all components in a reduced steering column construction that does not invade the operator space envelope and the view of the road while the sweeper is working. In addition, the rules for an ergonomic brake pedal, in terms of pedal size, angle and placement needed to be followed.

Table 1 displays all the general input data required for the steering column and brake system design.

Table 1

Input data

Vehicle characteristics	
Vehicle type	Street sweeper
Brake cylinder	Single master cylinder
Max pedal force	700 N
Cabin interior size (height × width × depth)	1365 × 990 × 1160 mm
Vertical distance between the accelerator heel point (AHP) and the seating reference point (SgRP) – H30	440 mm
Horizontal distance between accelerator heel point (AHP) and seating reference point (SgRP) – L53	720 mm
Vertical distance between accelerator heel point (AHP) and steering wheel midpoint – H17	710 mm
Horizontal distance between accelerator hell point (AHP) and steering wheel midpoint – L11	125 mm
Ergonomics parameters [2, 10, 11]	
Foot angle	6.5°
Ankle angle	96.5°
Knee angle (for comfort and reaching the brake pedal with a force of 338 – 507 N)	110°
Spine angle from the thigh bone	100°
Comfortable head tilt	30° up and down
Brake resistance	44.5–222.4 N
Pedal travel	13–64 mm
Height above accelerator (for unassisted foot operation)	91 mm
Pedal dimensions – minimal (height × width)	25.4 × 76.2 mm
Pedal spacing	About 50 mm
ISO 3411:2007 Physical dimensions of operators and minimum operator space envelope	
Horizontal sitting surface height	400–495 mm
Eye height sitting	690–858 mm
Buttock–knee length	530–670 mm
Knee height, sitting (with shoes)	500–627 mm
Hip breadth, sitting	320–456 mm
Width within space for legs	>560 mm
Clearance between enclosure and operator’s shoe working pedal	>30
ISO 6682:1986 Zones of comfort and reach for controls	
Foot control location comfort zones, forward from the SgRP (side view)	600–900 mm
Foot control location comfort zones, from the SgRP to the floor (side view)	150–500 mm
Foot control location comfort zones, left and right from the SgRP (top view)	300 mm

This research is based on the application of the given input data in the design of a new solution that will have an improved steering column and brake pedal system of the street sweeper, from both ergonomic and brake performance perspectives.

The main research questions that were addressed are:

1) What do the results of the ergonomic analysis reveal about the comfort assessment and field of view of the initial steering column design?
2) Does the modified model of the steering column and brake pedal offer improved cabin ergonomics?
3) Does the modified brake pedal system achieve satisfactory brake performance while adhering to the given requirements?

Addressing these questions was essential to understand the limitations of the initial brake pedal design and to establish guidelines for improved solutions. Furthermore, a new modified model was introduced, in which the shortcomings of the initial design were addressed. Additionally, in this research a verification process is conducted to confirm that the ergonomic and dynamic parameters of the modified model adhere to acceptable values.

3. METHODOLOGY

The diagram in Figure 1 outlines the steps taken to address the main research questions. Firstly, data was extracted primary from academic literature and publication, as well as SAE recommended occupant packaging, ISO standards and other ergonomic recommendations. Next, the problem was thoroughly defined with all the critical parameters that need to be optimized. In this stage, the objecttives were listed and all the input data regarding the vehicle characteristics, required brake pedal features, as well as the extracted ergonomic information were systematized (Table 1). The following step was the development of the new design. The initial model served as a base, and according to the input data modifications were made and a new brake system and steering column were modeled using SolidWorks. To validate the modified model, two types of analysis were made. For generating a simulated workspace to evaluate the driver's comfort and the field of view and compare the ergonomics of initial design and the proposed solution, Siemens Jack software was chosen as a virtual ergonomics tool. The ergonomic tests were followed by a dynamic simulation of the brake pedal model in ADAMS in order to test the brake pedal and master cylinder performances and to conduct an optimization. Finally, the results were analyzed and conclusions were drawn.

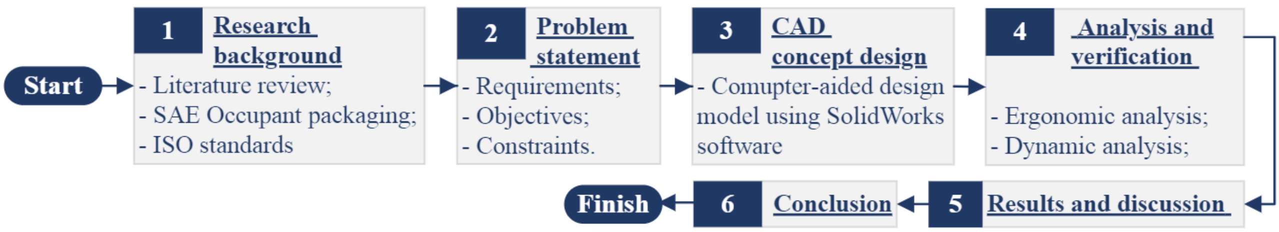
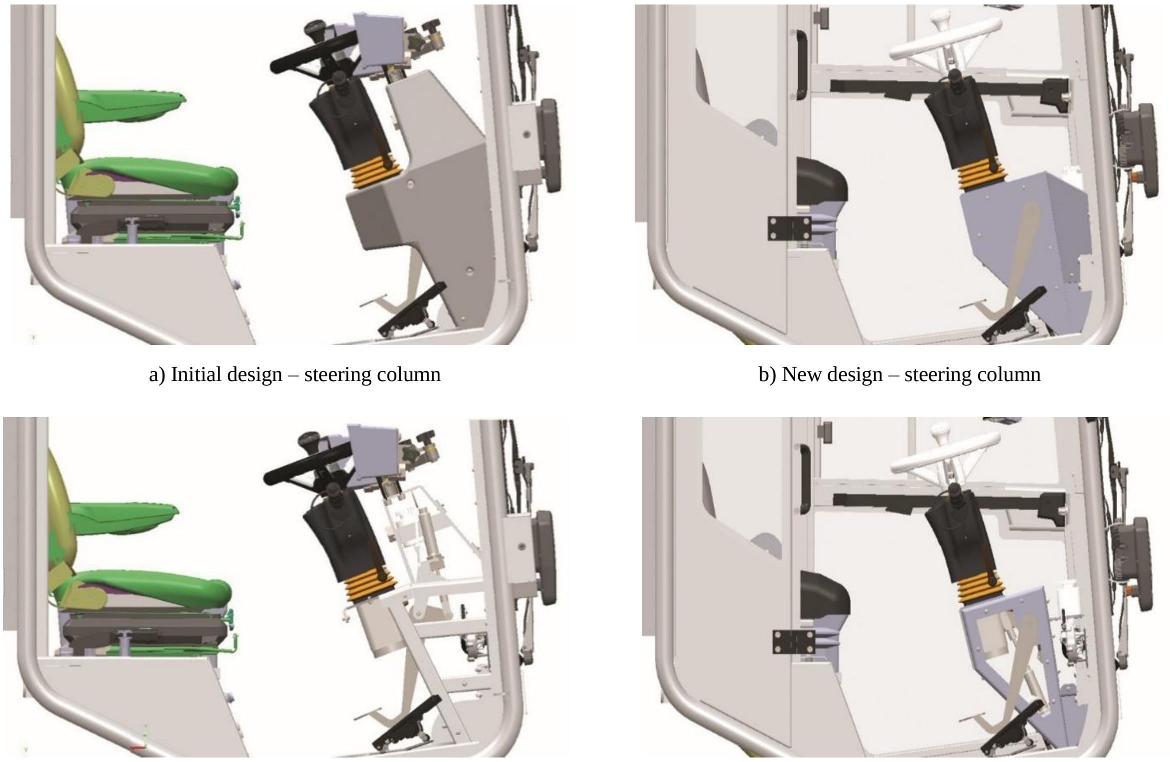


Fig. 1. Research methodology flowchart

4. CAD CONCEPTS

The CAD model of the initial design is given in Figure 2 (a and c). The height of the steering wheel column construction is 651 mm, or 800 mm including the steering wheel and screens. The distance between the steering column and the seat in this case is 300 mm. This increased height of the column construction is due to the design of the brake pedal system which has a cylinder positioned in an upward direction. In addition, two screens are incorporated, with their holders connected to the column, positioned to the left and right side of the operator.

In the modified design, given in Figure 2 (b and d), a new orientation of the brake cylinder is chosen to create a more compact design and as a result the column is significantly reduced in height. The new height of the column is 400 mm. The screen holders are also removed from the column construction and added to the left and right main profile of the cabin. This results in additional field-of-view-obstruction clearing. The steering column is also shortened in the front for more clearance around the operator’s knees, and the new distance achieved between the column and seat is 330 mm.



a) Initial design – steering column
b) New design – steering column
c) Initial design – brake pedal system within the column construction
d) New design – brake pedal system within the column design

Fig. 2. SolidWorks model of the initial and new design of the steering column and brake pedal system

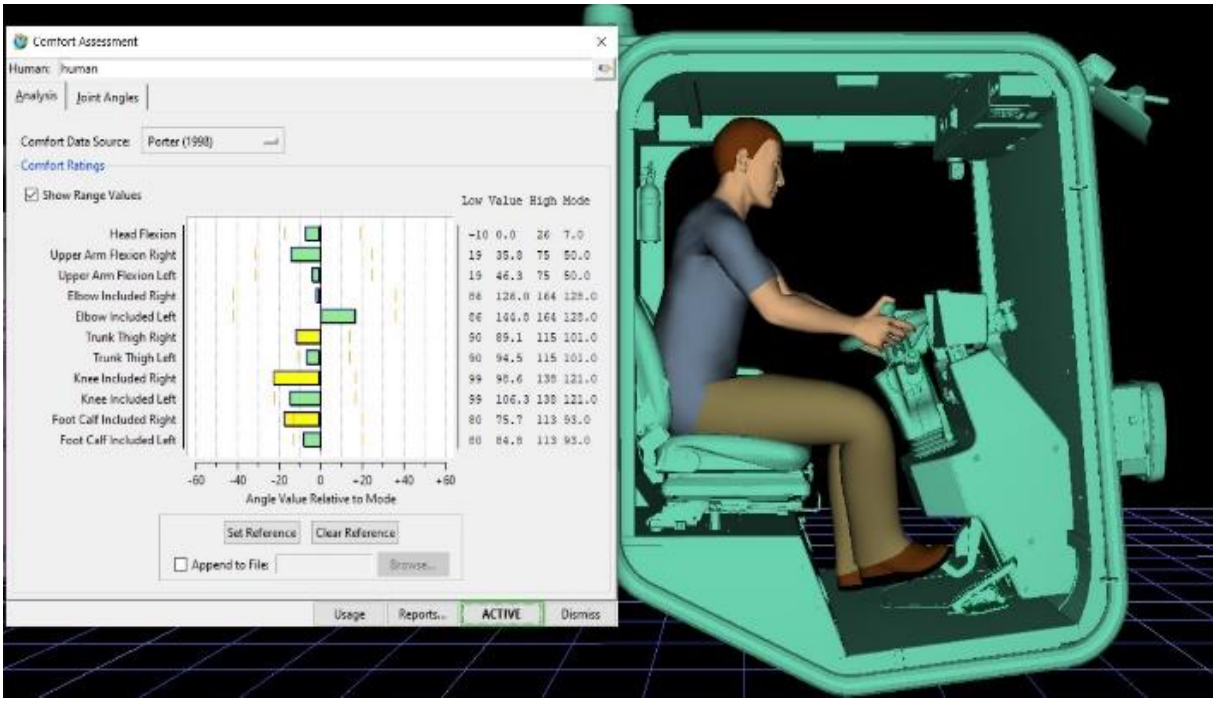
5. ANALYSIS AND RESULTS

As previously explained, this research includes two types of validation analysis – ergonomic and dynamic. The obtained results and comparisons between the two models are elaborated in this section.

5.1. *Ergonomic analysis*

A total of four simulations were conducted using Siemens Jack, by using two different tools for both the initial and modified model. The street sweeper cabin together with the steering column and the brake pedal were imported in Jack's software. The default male mannequin, with a height of 175 cm, belonging in the 50th height percentile, was used and adjusted in a static position that helped to conduct ergonomic analysis for comfort assessment and field of view of the initial and modified design. In the first case, the mannequin was positioned in the vehicle cabin with the initial steering column design, in a seated position. The right leg was placed on the brake pedal, while the left leg remained free, and both hands were firmly placed on the steering wheel. After that, from the Occupant Packaging Toolkit, the Comfort Assessment tool and Obstruction Zones tool were applied. The Comfort Assessment tool helps to check whether a given Jack model is in a comfortable seated posture based on individual joint angles and overall body posture. It generates bar graphs which indicate if the body parts and joints are within the comfort range (green bars – comfort values; yellow bars – outside of the recommended range; red bars – extreme positions). The Obstruction Zones tool, on the other hand, requires the selection of the mannequin's eye point sight, and the obstruction segment (in this case the whole steering column) to generate planes which illustrate the obstructed part of the field of view. In the second case, the same procedure (same mannequin placement and same tools) was conducted using the new design as well.

The results of the Comfort Assessment analysis are given in Figure 3 (a – initial design; b – new design). The comparison of these results shows that the initial model exhibits worse outcomes and discomfort in the right thigh muscle, right knee, as well as the right calf muscle of the leg (shown with yellow bars). These less favorable values are a consequence of limited space and minimal room for accommodating a steering column. In contrast to that, the results from the comfort assessments for the modified model show better outcomes, falling within the range of allowable values.

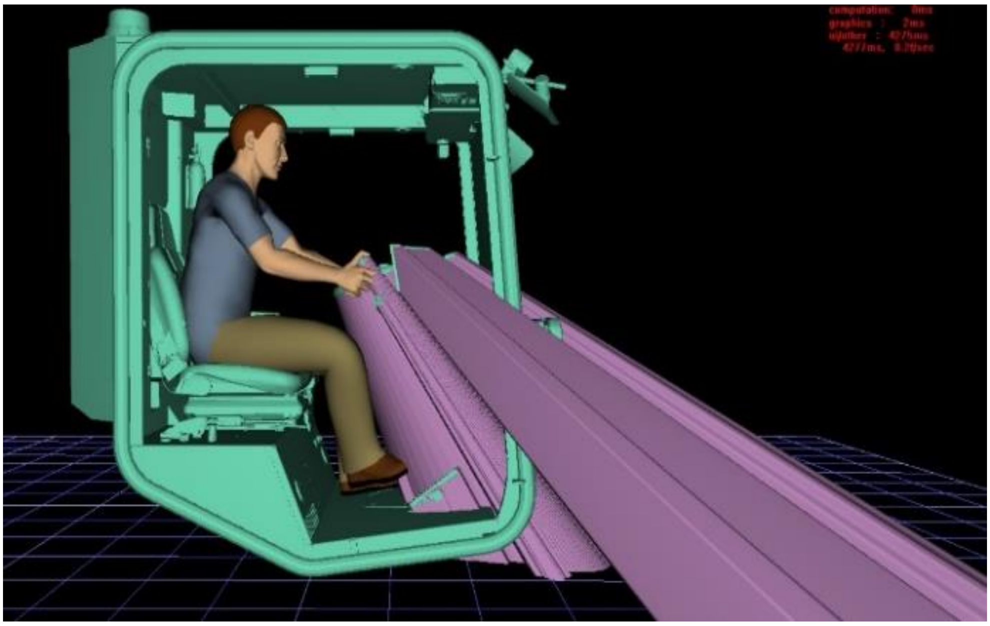


a) Comfort assesment results for the initial design

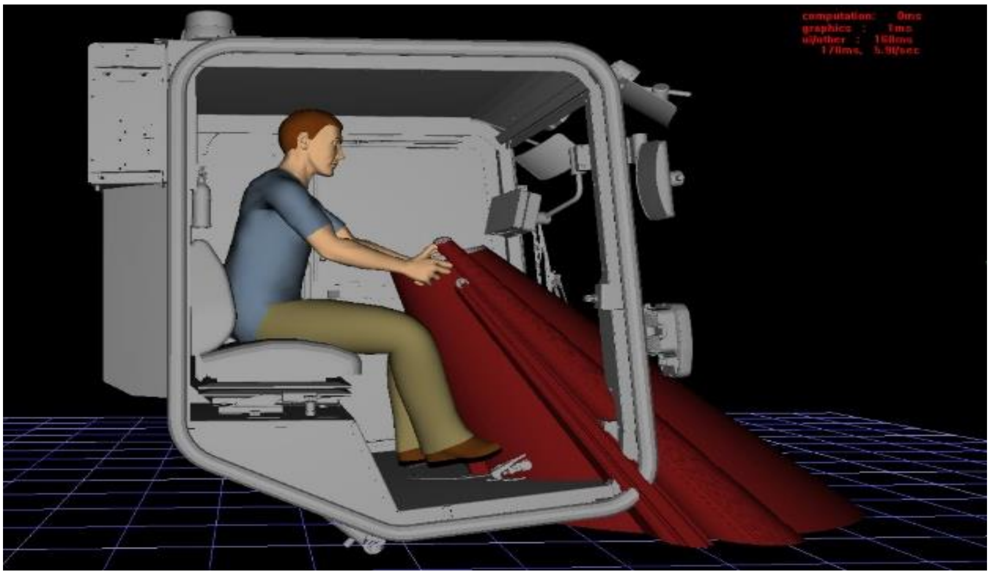
b) Comfort assesment results for the new design

Fig. 3. Comparison of results from the ergonomic analysis using the Comfort Assessment tool in the Occupant Packaging Toolkit in Siemens Jack software

The results of the Obstruction Zones analysis are given in Figure 4 (a – initial design; b – new design). Since for the street sweeper operator an important task is to constantly monitor the road ahead the field of view should be as clear as possible. From the field of view comparison of both models, it is clear that with the second variant, where the steering column is reduced mostly due to the new pedal system design, the operator has a better field of view. This is visible from reduced angle of the planes illustrating the obstructed part of the field of view.



a) Obstruction Zones results for the initial design



b) Obstruction Zones results for the new design

Fig. 4. Comparison of results from the ergonomic analysis using the Obstruction Zones tool in the Occupant Packaging Toolkit in Siemens Jack software

5.2. *Kinematic and dynamic analysis*

In order to ensure the effectiveness of the braking system, a multibody dynamic analysis was conducted using ADAMS View. To fulfil the ECE R13 regulation, a 60 bar hydraulic pressure is needed to be achieved and the minimum needed piston stroke was determined to be 16.5 mm. Therefore, the minimal required actuation force of the cylinder had to be 1710 N.

The ECE R13 regulative mandates that the pedal force should not exceed 700 N, thus the applied force of the virtual model is equal to the maximum one allowed, in order to test the braking performances in extreme conditions.

The results of the original design can be observed in Figures 6 and 7 where it can be obtained that the results are satisfactory and the required goals for minimal cylinder force and piston stroke are achieved. But, for the purpose of achieving improved braking performances and reducing the necessary pedal force, an optimization was conducted. Due to the design space limits, and defined required ergonomic parameters, limited number of changes were available to the design of the system. The pedal and master cylinder positions were not changed, while the attachment position of the pedal (Point 1 – P1) and the connecting point (Point 2 – P2) between the master cylinder rod and the connector plate were modified. These positions are presented in Figure 5. P1 was chosen to be the origin of the coordinate system.

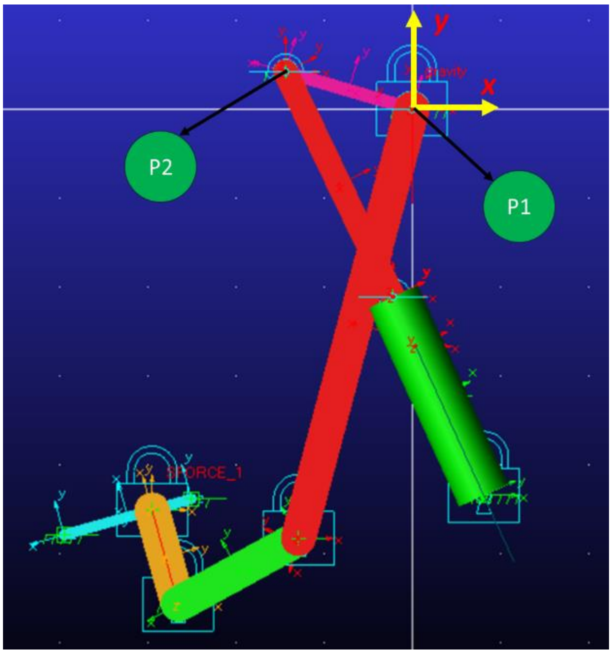


Fig. 5. Virtual multibody model

Table 2 presents the created design variables (DV) and their range. The range was determined based on the limits of the column construction.

During the optimization process, 3 iterations were made to determine more optimal position of the connecting points. The results of the optimization and the position of the connecting points is presented in Table 3.

Table 2

Design variables parameters

Design variable	Initial position	Position change range
Point 1 – DV 1	0	(–25, 20) translation along *y* axis
Point 2 – DV 2	–71.84	(–130, –50) translation along *x* axis
Point 2 – DV 3	20.94	(–30, 40) translation along *y* axis

Table 3

Optimization results

Iterations	Master cylinder force (N)	DV1	DV2	DV3
Original design	2129.7	0	–71.84	20.94
Iteration 1	2710.9	–8.2	–50	–40
Iteration 2	3282.2	18.493	–50	–30
Iteration 3	3369.3	17.895	–50.04	–30

The optimization results show increase in braking force by 58% (Figure 6). This shows that even the minor modifications in a tight space can improve the braking performance. Although this force is almost two times higher than the minimal required one, it must not be forgotten that the simulation is conducted with maximal pedal force of 700 N. Therefore, the required minimal force can be achieved by applying smaller brake pedal force, thus increasing driver's comfort and satisfaction.

The only negative side is the need for bigger piston stroke of the brake cylinder (Figure 7), but fortunately the current master cylinder can achieve that.

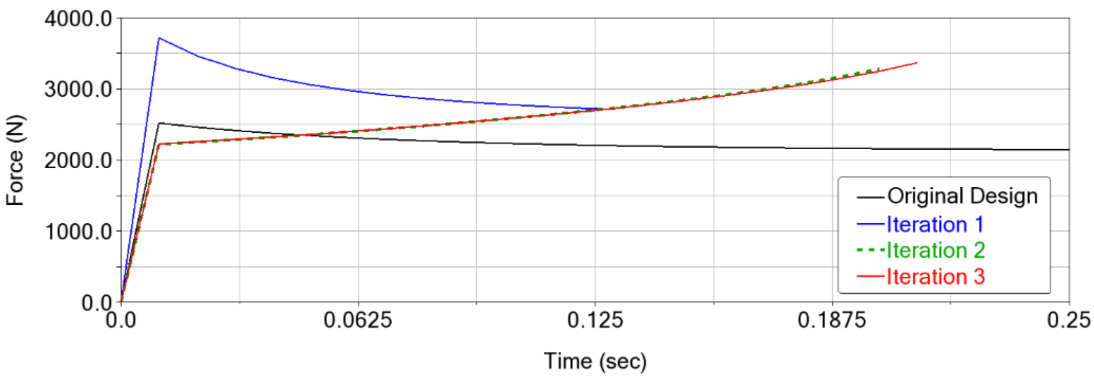


Fig. 6. Master cylinder braking force output

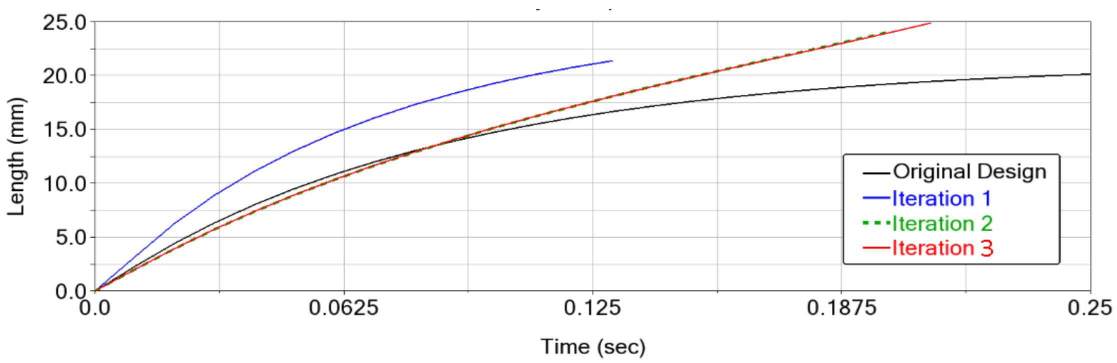


Fig. 7. Master cylinder piston stroke

6. CONCLUSIONS

This study is based on a specific methodological approach used in order to develop, assess, and enhance a brake pedal system that complies with specified ergonomic and packaging constraints. This paper presents a study and evaluation that compares the performance of two vehicle brake pedal system designs, aiming to identify the most user-friendly option. The main goal was to utilize the available input data (such as vehicle specifications, manufacturing requirements, ECE R13 regulation for necessary performance, anthropometric data, ergonomic guidelines, ISO standards, etc.) to create an alternative brake pedal system assembly integrated into a steering column structure which is designed in a manner that does not cause insufficient clearance around the operator, or uncomfortable use of the brake pedal, and does not obstruct the field of view.

There were two main challenges of the task: (1) solving the issue with obstructed field of view and limited space in the knee area of the operator due to the initial design of the steering column, and (2) redesigning the brake pedal system to fit in a smaller steering column while keeping the same type of master brake cylinder and achieving the required brake performances and brake pedal force according to the ECE R13 regulation.

To respond to the given requirements, a modified steering column structure was proposed with an integrated brake pedal system which featured a new orientation of the brake cylinder chosen to create a more compact design and reduce the size of the steering column. To verify the new design, ergonomic and dynamic analysis were made using Siemens Jack and ADAMS View.

Based on obtained results, it is evident that the ergonomic issues were successfully reduced. According to the Comfort Assessment analysis, more natural positions of the operator's body and joints while using the steering wheel and brake pedal were noted with the smaller steering column. Issues with discomfort of the thigh muscle, knee, and calf muscle of the right leg were overcome with the new design which is more compact and allows more space for leg movements. In addition, based on the Obstruction Zones analysis, we can see a reduced angle and height of the generated obstruction plane, meaning that a clearer view over the street and sweeper brushes will be possible with the new steering column.

The results from the multibody dynamic analysis of the new brake pedal arrangement were also satisfactory and the required goals for minimal cylinder force and piston stroke were achieved. Moreover, an optimization of the new brake pedal system was done to achieve improved braking performance which was conducted by varying the attachment position of the pedal and the position of the connecting point between the master cylinder rod and the connector plate. No other optimization modifications were made since the rotated orientation of the brake cylinder and limited interior space did not allow a possibility for more drastic variations. However, even with a small modification in the previously mentioned points, the optimization results showed an increase in the braking force and improved braking performance.

In the end, the new steering column with optimized braking system was implemented in the street sweeper and the solution was verified on the real model. The same brake cylinder was used, but with the new orientation the interior became more ergonomic. In addition, as previously elaborated, due to tested variations of the attachment position of the pedal and the connecting point between the master cylinder rod and the connector plate, optimum braking force output was achieved.

In conclusion, we can state that the initially given research questions were successfully addressed: (1) the ergonomic analysis revealed specific issues about the comfort assessment and field of view of the initial steering column design; (2) the modified model of the steering column and brake pedal did offer improved cabin ergonomics; and (3) the modified brake pedal system achieved satisfactory brake performance while adhering to the given requirements and reducing the needed brake pedal force applied by the driver.

REFERENCES

[1] Chowdhury, Anirban, and Chaitanya Kachare (2021): *Ergonomic evaluation of a car interior: a case example on shelby Cobra*. Ergonomics for Improved Productivity: Proceedings of HWWE 2017. Springer Singapore.

[2] Bhise, Vivek D. (2011): *Ergonomics in the Automotive Design Process*. CRC Press.

[3] Gkikas, Nikolaos, ed. (2012): *Automotive Ergonomics: Driver–Vehicle Interaction*. CRC Press.

[4] Reed, Matthew P., et al. (1999): *New concepts in vehicle interior design using ASPECT*. SAE transactions, 1867–1884.

[5] Garg, S., Bhide, S., Gupta, S. (2017): *Analysis of Automotive Control Pedals Ergonomics through Mathematical Modelling Based on Human Anthropometry*. No. 2017–26–0252, SAE Technical Paper. https://doi.org/10.4271/2017-26-0252.

[6] Zarizambri Bin Ahmad (2008): *Design and Analysis of a Pedal Box System for a small Race-car*.

[7] Beery, Evan (2016): *2016 FSAE Electric Vehicle Pedal Assembly Design*.

[8] Ravan, Girish, et al. (2011): *Ergonomic Considerations of Clutch Pedal Design for a Heavy Commercial Vehicle*. No. 2011–28–0092. SAE Technical Paper,.

[9] Zhang, Yingyong, et al. (2020): Research on pure mechanical lifting pedal applied to rail transit vehicles. *Journal of Physics: Conference Series*. Vol. **1605**. No. 1, IOP Publishing.

[10] Macey, S., Geoff Wardle (2009): *H-Point: the fundamentals of car design & packaging*. (No title).

[11] Tilley, Alvin R. (2001): *The Measure of Man and Woman: Human Factors in Design*. John Wiley & Sons,

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DETERMINING OPTIMAL ORDER PICKING ROUTE IN WAREHOUSES

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A b s t r a c t: The objective of this research paper is to find the optimal order picking route thus improving the operational efficiency of logistics processes. Computing and selecting the best route are crucial for minimizing order completing time and operational costs. To achieve this, an algorithm is developed by use of several warehouse logistics methods. This algorithm is applied to a single warehouse and the paths are computed using the s-method, the return method, the middle point method, and the composite method. The verification of the algorithm is conducted through thirty cases, each with different order picking locations. This research shows that when larger number of parts need to be picked from various racks, the paths created by the composite method and the s-method provide the shortest route for the designated warehouse.

Key words: path-optimization; order picking; warehouse

ОДРЕДУВАЊЕ ОПТИМАЛНА ПАТЕКА ЗА ПОДГОТОВКА НА НАРАЧКА ВО МАГАЦИНИ

А п с т р а к т: Истражувачкиот труд има за цел да ја пронајде оптималната патека при подготовка на нарачка за испорака, а со тоа да ја подобри ефикасноста на логистичките процеси. Пресметката и изборот на оптималната патека е од суштинско значење за минимизирање на времето за подготовка на нарачка и оперативните трошоци. За да се постигне тоа, развиен е алгоритам користејќи неколку методи на логистика во складиштата. Овој алгоритам е применет на едно складиште и патеката е пресметувана според „***s***-методот", „методот на враќање", „методот на средна точка" и „композитниот метод". Верификација на извршниот алгоритам е извршена преку пресметка на триесет случаи кои вклучуваат различни локации во складиштето од кои треба да се земе стока. Истражувањето покажува дека патеките формирани според „композитниот метод" и „***s***-методот" во сите случаи кога е потребно да се земаат голем број кутии од различни рафтови ја даваат најкратката патека за конкретното складиште.

Клучни зборови: оптимизација на патека; подготовка на нарачка за испорака; складиште

1. INTRODUCTION

The aim of logistics is consistently centered on finding faster, accurate, timely, and flexible methods for delivery. This research paper focuses on the specific aspect of logistics known as intra-logistics. The need for research is supported by a review of earlier surveys in the field of intra-logistics, order picking and optimization of logistics processes in warehouses.

Firstly, Ratliff [1] introduces an algorithm for order picking in warehouses. The objective of the algorithm is to select the optimal path, thereby minimizing the time required for order picking. Kruithof [2] in his research outlines the steps on how to programme an algorithm aimed at optimizing warehouse path. Additionally, Wang [3] in his thesis used a mathematical model, which is based on the Traveling Salesman Problem (TSP), combined with Genetic Algorithms. Puka [4] conducts a comparative analysis of four order picking methods to determine the optimal approach. Liu [5], similarly, presents a comparison of the s-method, the return method, and the composite method. In alignment with previous research, Esra [6] compares the s-shape method, the midpoint method, and the largest gap method.

Lanza [7], in the research paper, gives a thorough explanation of how to optimize the path for order picking using a programming language. Korbacher [8] also seeks to compare paths using the midpoint method, the return method, and the largest gap method. Additionally, Shetty [9] introduces vehicle routing based on order picking in warehouses to further reduce travel time and distance.

The literature review shows that the selection of the shortest path during order picking has been extensively discussed since the second half of the twentieth century. Given that approximately 50% of the time needed for the preparation of a delivery order is attributed to the movement of the order picker, it becomes necessary to optimize the path taken during the execution of this process, thereby reducing the time spent. Within the realm of logistics, order preparation emerges as a critical segment with significant potential for optimizing logistics cost and enhancing productivity [10].

Based on the conducted research, it is evident that addressing the challenge of selecting the shortest path in a warehouse is particularly complex due to the varied shapes and internal layouts of warehouses. Consequently, the primary objective of this study is to identify and capitalize on an opportunity to optimize a pivotal segment of the logistics process-order picking. The focus of this research was to gather data and generate an algorithm for path optimization in the warehouse. Generating and using a Matlab code, this research should efficiently enable the selection of the shortest path in order picking within a certain warehouse. This research paper contributes in solving important and contemporary issues in scientific and professional research into intra-logistics.

2. METHODOLOGY

The data used in this paper was primarily gathered from academic literature and publications. The keywords used in the search are: order picking methods and optimization of pick path in warehouse. Figure 1 illustrates the steps taken in this research.

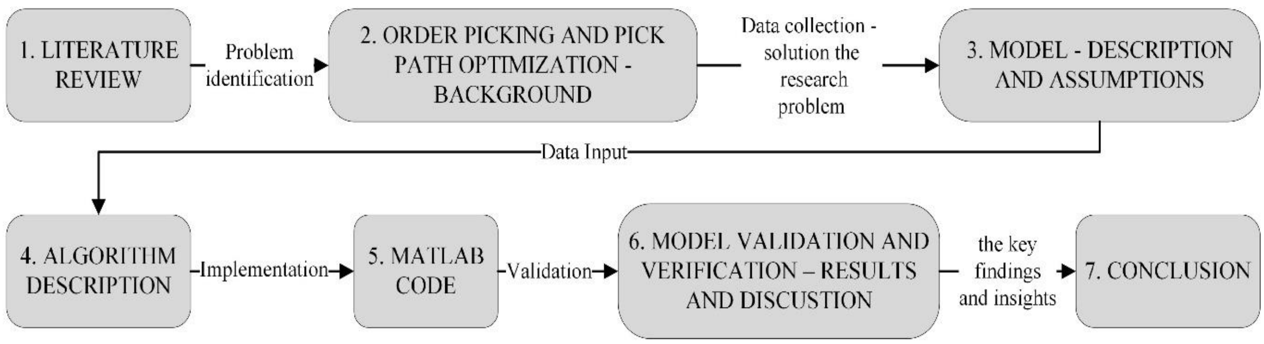


Fig. 1. Research methodology

3. ORDER PICKING METHODS AND PICK PATH OPTIMIZATION

Optimizing order picking involves determining the sequence for order completion and selecting the most suitable path. In the context of rack warehouses, various heuristic methods are employed to generate movement routes. Additionally, algorithms are utilized to ascertain the most appropriate path, whether it be optimal or suboptimal [11].

3.1. *Order picking methods*

a) *S-shape method*

Moving the order picker using the s-shape method is the most straight-forward method to implement. Using this method every rack containing at least one item for retrieval is traversed along its entire length [12, 13]. Conversely, racks devoid of items slated for collection are entirely bypassed. Figure 2 illustrates an example of preparing a delivery order using the s-shape method.

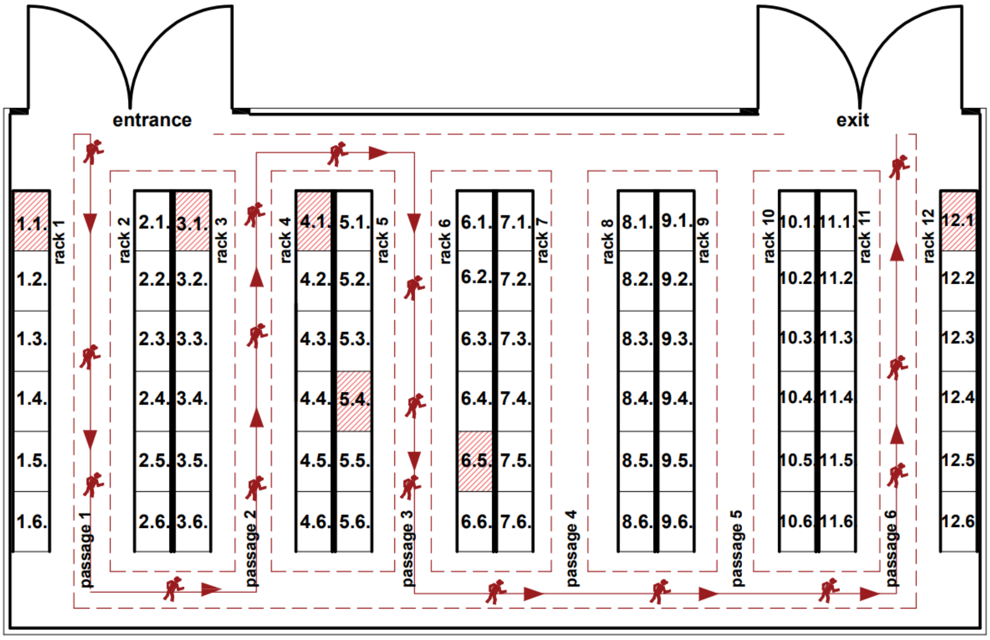


Fig. 2. S-shape method

b) *Return method*

The return method stands out as a simple and frequently employed approach in order picking. In this method, the order picker enters between the racks, exclusively from one side. After collecting the required goods, the order picker follows the same route for the return journey (Figure 3). It's important to note that this method might not always be practical, especially in situations where order picking is done with forklifts and there is not enough room to perform a 180˚ turn [7]. A further drawback of this method is its tendency to prolong the duration of the process compared to alternative methods, resulting in limited optimization of the time allocated for preparing the order for delivery.

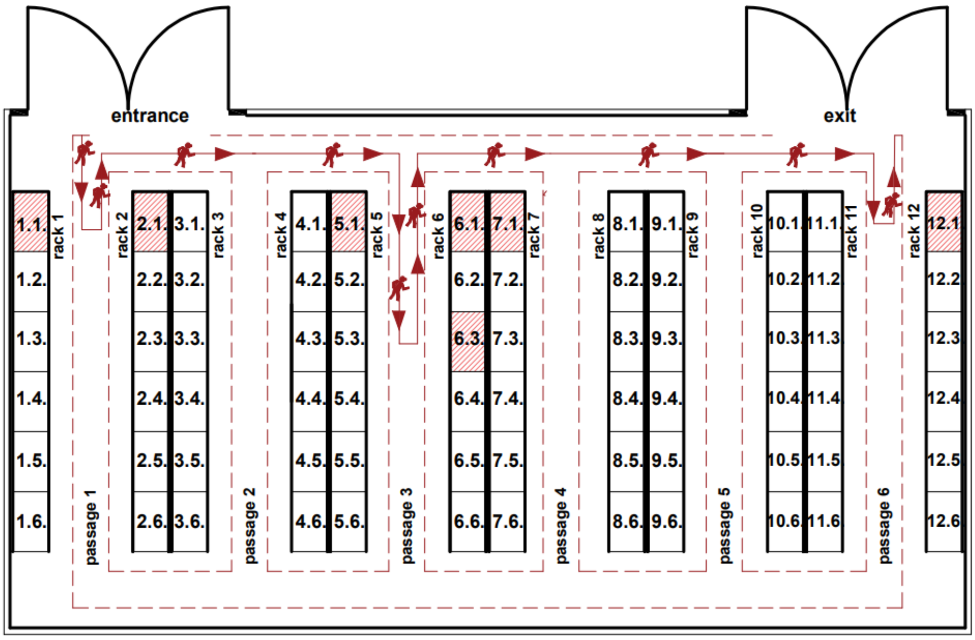


Fig. 3. Return method

c) *Midpoint method*

In this method, the warehouse is conceptually divided into two hypothetical halves. Thus, the completion of the order is done by entering from the first passage and only the first and last passage are traversed across their entire length. When passing through the remaining passages, an alternative approach is adopted. If the items to be picked are situated in either the first or second hypothetical half of the warehouse, the return method is applied. Access to these passages is determined by the corresponding side. For instance, when goods need to be retrieved from the second half of the warehouse (rack bays 4, 5, or 6), entry is made from that side (Figure 4). In contrast, when goods are to be picked from the first half of the warehouse (rack bays 1, 2, or 3), the access point for these passages is from the front side of the warehouse. When passages do not contain items for picking, they are simply bypassed. This approach is illustrated in Figure 4, showcasing how the return method is applied selectively depending on where the parts are located in the two hypothetical warehouse halves [8].

It's crucial to note that the midpoint method might not apply in all situations and could encounter challenges in cases where there's an odd number of rack bays in a sequence. In such cases, decisions must be made on how to divide the racks across the two warehouse halves.

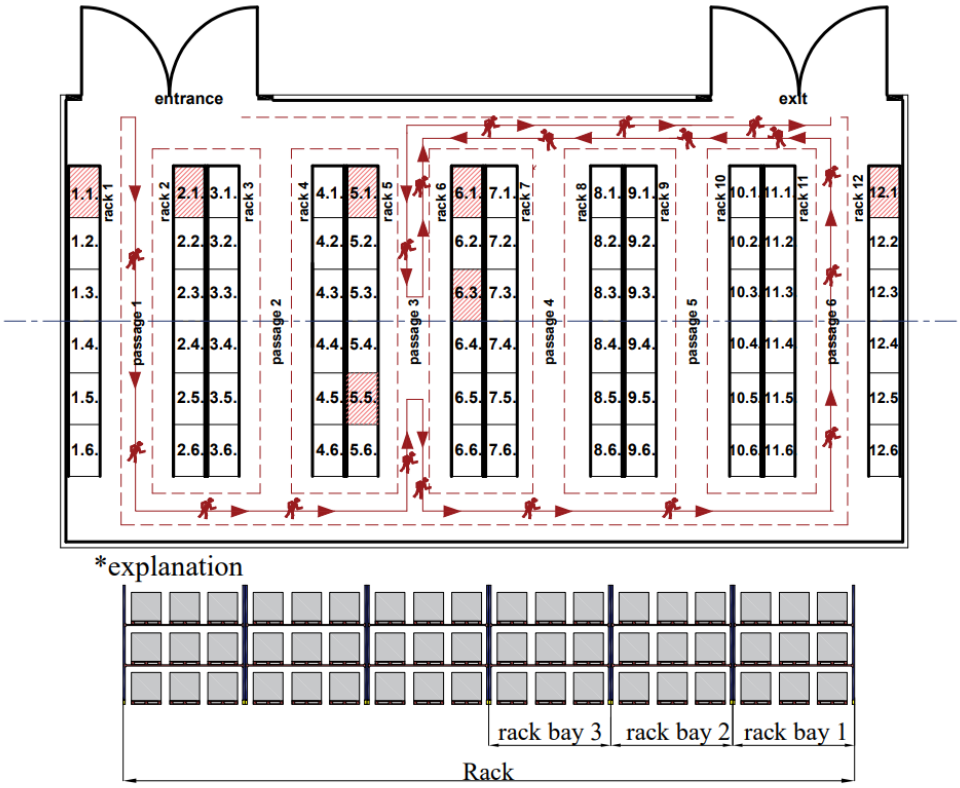


Fig. 4. Midpoint method

d) *Composite method*

As the name suggests, the composite method represents a new method that is a combination of the two existing methods (the s-shape method and the return method), which pulls out the best features of both methods and combines them into one composite version. The purpose of this method is to minimize the movement between two farthest locations and two adjacent crossings, so the aim is to use either the s-shape method or the return method [5, 14]. A composite method example is provided in Figure 5.

Since there are parts to be taken from the bays in the first and the second half (racks bays 3.6 and 4.3) the s-method is applied, for picking the parts in those two passages, the first and the second passage are passed in their entire length. The return method is applied in the third passage, because in that passage the only parts to be taken are the ones that are located in the first half of the warehouse (rack bays 5.1, 6.1 and 6.3). The passages 4 and 5 are bypassed, since there are no parts to be taken.

Unlike the s-method, in the composite method the last passage does not have to be passed in its entire length. Therefore, as shown in Figure 5, the last passage, passage 6, is not passed in its entire length, since it is necessary to take goods from the first bay of the rack (12.1).

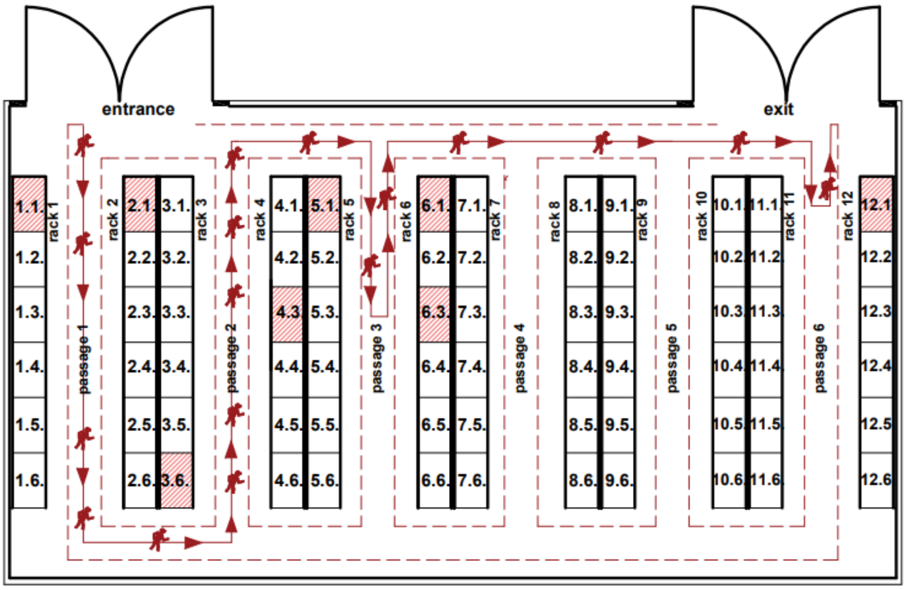


Fig. 5. Composite method

3.2. *Methods of pick path optimization*

The basic approach for calculating the direct distance between two given points, $A(x_1, y_1)$ and $B(x_2, y_2)$ or Euclidean distance, is calculated according to the equation (1):

$$d(A,B) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}. \qquad (1)$$

Manhattan distance is another way of distance calculation. According to the Manhattan distance, the distance between two points $A(x_1, y_1)$ и $B(x_2, y_2)$ is calculated using the expression (2) [15]:

$$d(A,B) = |x_1 - x_2| + |y_1 - y_2|. \qquad (2)$$

In the literature review on route optimization during the preparation of a delivery order, the Steiner Traveling Salesman Problem (STSP) is used, which is a subtype of the traditional TSP [13, 15]. The TSP deals with scenarios where a known number of locations $\{l_1, l_2,...,l_n\}$ are given, and the traveling salesman must visit each location, considering the distances between each pair of locations [2, 16, 17]. The objective is to find the shortest path along which the traveling salesman will visit all locations and return to the starting location. The spatial solution comprises the set of all permutations of the numbers 1, 2,...,n without repetition. Some of the methods for calculating TSP include the Brute-force method and the Branch and Bound method [18].

If the task involves determining routes for the movement of vehicles, it is known as the Vehicle Routing Problem (VRP) [19, 20]. This method expands upon the TSP. In the TSP, the goal is to visit a specific number of locations from the starting point and ultimately return to the starting point [1]. The fundamental form of the VRP focuses on optimizing the routes for vehicles originating from a central location, delivering goods to various destinations [21]. This could involve the use of several types of vehicles or a single vehicle making multiple trips [9, 22, 23]. The objectives of determining vehicle movement routes include:

- Minimizing the total distance traveled;
- Ensuring that the selected path passes through all locations only once;
- Ensuring that the chosen route starts and ends at the same location.

The objective of the Steiner Traveling Salesman Problem (STSP) [2, 7, 8, 10, 12, 24, 25] is, given a list of locations to be visited and the mutual distances between them, to find the shortest possible path. This path should encompass all locations, ultimately returning to the initial position [21, 26, 27].

4. MODEL DESCRIPTION

This section illustrates the warehouse model used in this research paper. First, the model under study is described in detail. To examine a real-world scenario, input parameters for an actual warehouse are employed. The layout of the warehouse under consideration is depicted in Figure 6. The dimensions of the warehouse are 31,900 mm in width and 11,000 mm in length. The warehouse consists of twelve racks, five of which being double-sided racks and two of which being single-sided racks. Each rack has six bays. The length of each rack is 6,000 mm, while each rack bay is 1,000 mm in length. The distance between the racks and the warehouse walls is 2,500 mm, and the gap between two adjacent racks is 2,800 mm. The width of the single-sided racks is 1,300 mm, and for the double-sided racks is 2,500 mm. The warehouse features a single entrance and exit, both located on the same side of the building. The entrance is positioned on the leftmost side, while the exit is on the right. Within the warehouse, six passages between the racks allow for the movement and manipulation of goods using a forklift. In Figure 6, the path anticipated during order creation is marked in red. In detail A of Figure 6, the 1,000 mm distance represents the space between two rack bays of one rack when collecting parts. In detail B of Figure 6, the 500 mm distance indicates the space from the beginning of the rack to the middle of the first rack bay.

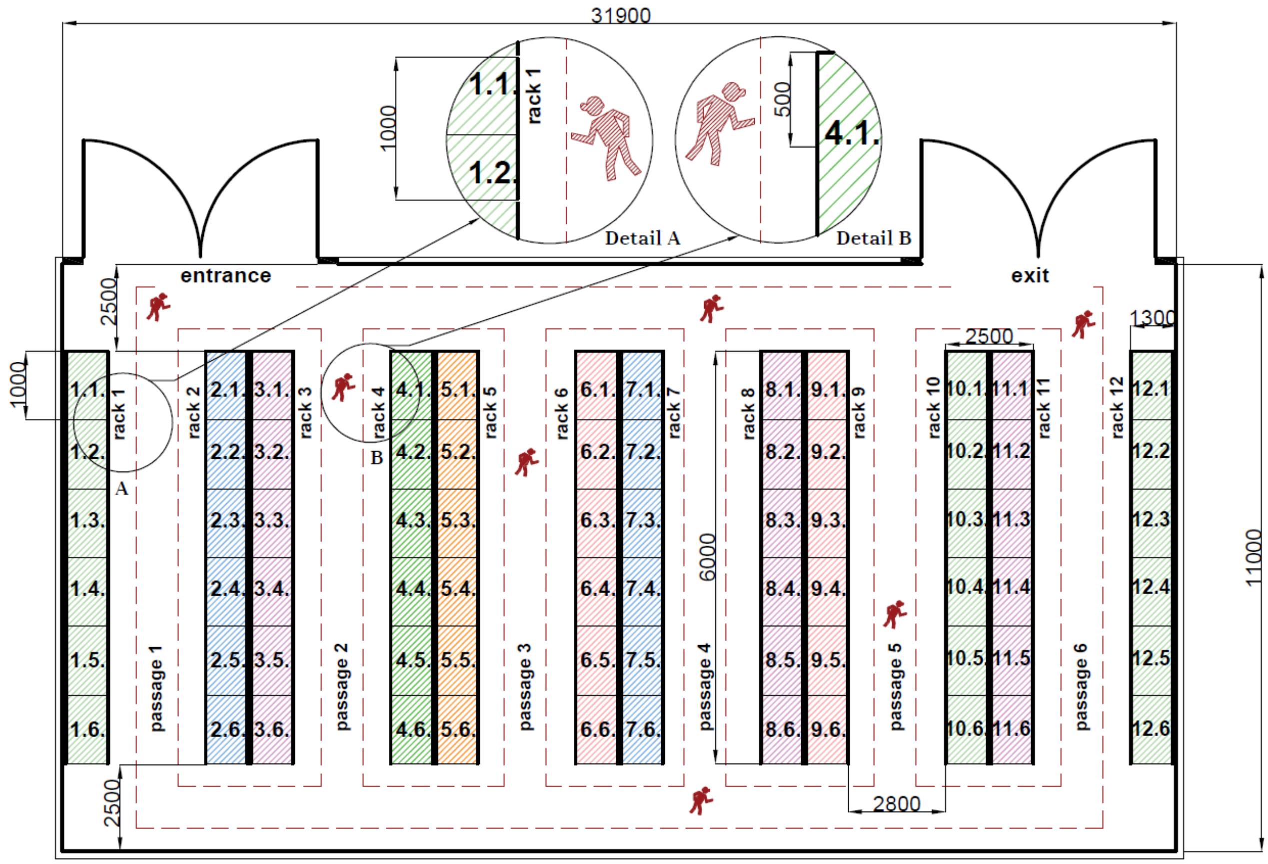


Fig. 6. Warehouse dimensions

For a simpler representation of the warehouse in Figure 6, the racks and rack bays are labeled. The racks are numbered from 1 to 12, and each rack bay is labeled from 1 to 6. Therefore, for rack 1, the rack bays are marked as 1.1, 1.2, 1.3, where the first number indicates the rack number, and the second number indicates the bay number on that rack.

The height of both the racks and the warehouse are not considered, since they are not taken into account in the calculation of the route for order picking.

Additionally, it is expected that the order picker will select boxes from the center of each rack bay to form the delivery order. This research paper omits the dimensions and mass of the boxes and there are no limits on capacity, i.e., on how many parts the order picker can carry.

4.1. *Presentation of the algorithm*

Figure 7 illustrates the block diagram of the algorithm for creating an executable program. The algorithm operates by calculating paths using four methods and choosing the best one. The first step of the algorithm is to create a matrix with 12 columns and 6 rows, where the number of columns corresponds to the number of racks, and the number of rows represents the bays of each rack.

In the next step, the code generates a matrix with all elements initialized to zero. To modify the matrix, the positions from which an order needs to be picked are changed from zero to one. This is achieved using the command 'change = 1:num_changes', where the variable ‘num_changes’ denotes the number of orders to be taken. The cycle iterates 'n' times, prompting the user to specify from which rack (column) and rack’s bay (row) packet need to be taken. After completing the ‘for’ operation, the matrix is formed, with ‘1’ representing the positions from which orders should be picked. Following this, the output matrix is displayed, highlighting the locations marked with '1' as the places from which goods should be retrieved.

After the completion of the previous steps, the algorithm proceeds to calculate the sub-processes for the entered parameters based on the four methods: the s-method, the return method, the midpoint method, and finally, the composite method. Following the execution of these four sub-processes, the algorithm compares the path lengths obtained from each method. If the length of the path according to the s-method is smaller than the lengths obtained from the other three methods, the output is printed: "The path according to the s-method is the shortest". However, if the path length according to the s-method is not smaller than at least one of the paths obtained from the other three methods, a comparison is made with the length of the path obtained according to the return method, the midpoint method, and the composite method. If the length obtained from the return method is the smallest compared to the other three methods, the output is: "The path according to the return method is the shortest". In case the length obtained from the midpoint method is the smallest compared to the other three methods, the output is: "The path according to the mid-point method is the shortest". Otherwise, the output is: "The path according to the composite method is the shortest".

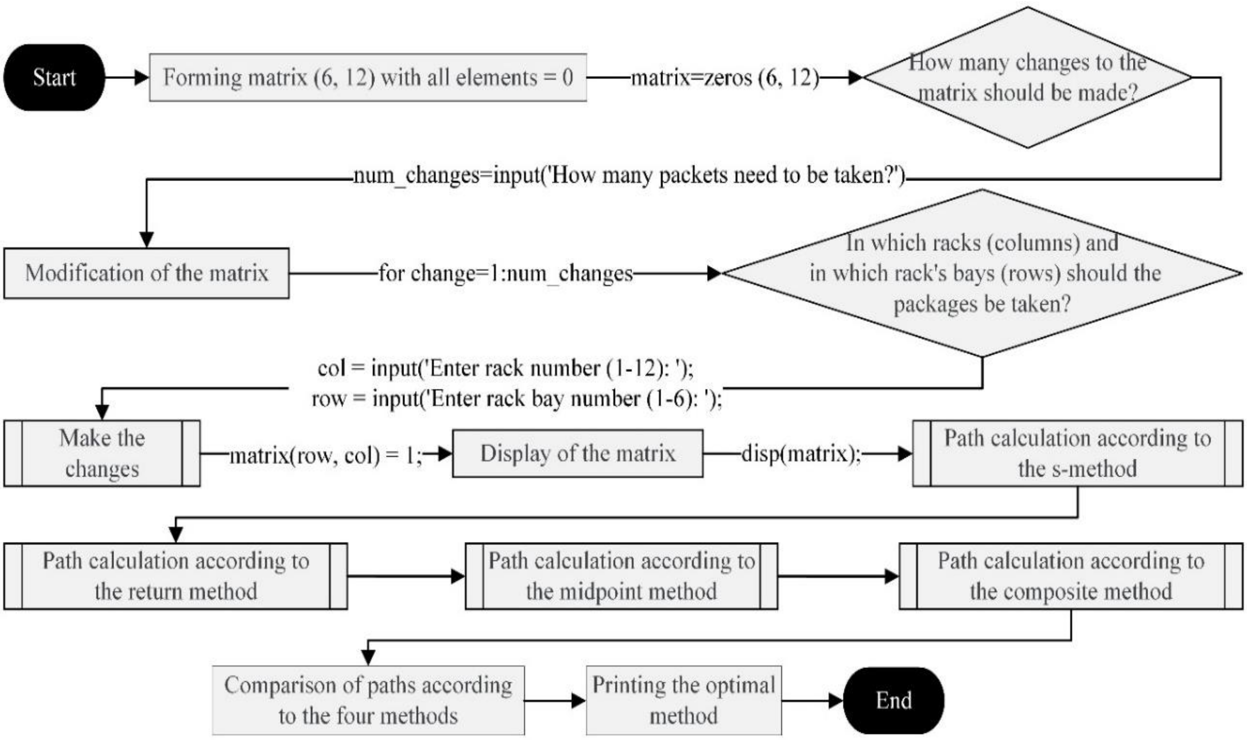


Fig. 7. Block diagram of the algorithm

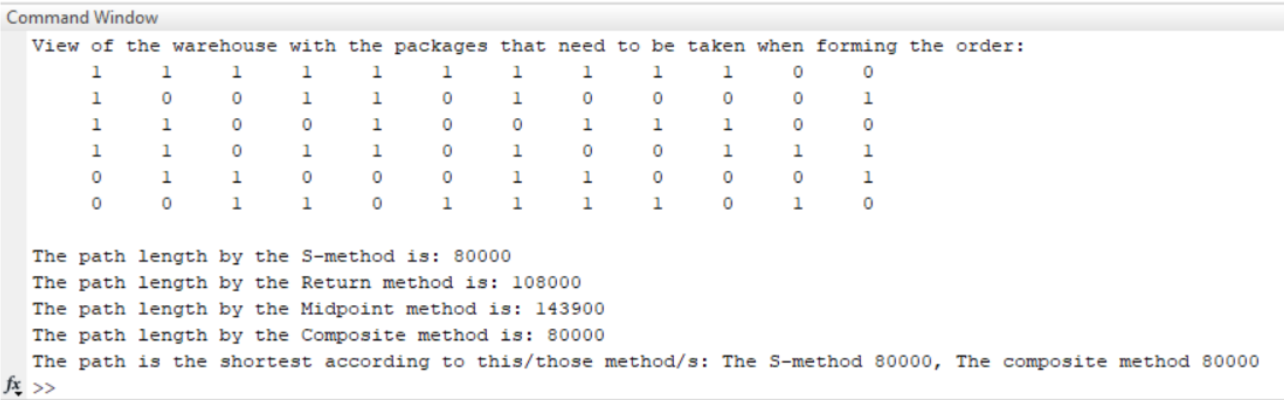
5. MODEL VALIDATION AND VERIFICATION

Results and discussion

Thirty distinct arbitrary order picking cases were generated to evaluate the reliability of the Matlab code. To validate the code, three cases were randomly selected from the total of thirty and manually calculated. In Figure 8, the slice window for case 1 is displayed, while Figure 9 shows the paths generated according to the four methods for the input data of case 1.

In Figure 10, the slice window for case 2 is shown, while Figure 11 presents the paths generated according to the four methods for the input data of case 2.

In Figure 12, the slice window for case 3 is shown, while Figure 13 presents the paths generated according to the four methods for the input data of case 3.



```
Command Window
View of the warehouse with the packages that need to be taken when forming the order:
     1     1     1     1     1     1     1     1     1     1     0     0
     1     0     0     1     1     0     1     0     0     0     0     1
     1     1     0     0     1     0     0     1     1     1     0     0
     1     1     0     1     1     0     1     0     0     1     1     1
     0     1     1     0     0     0     1     1     0     0     0     1
     0     0     1     1     0     1     1     1     1     0     1     0


The path length by the S-method is: 80000
The path length by the Return method is: 108000
The path length by the Midpoint method is: 143900
The path length by the Composite method is: 80000
The path is the shortest according to this/those method/s: The S-method 80000, The composite method 80000
fx >>
```

Fig. 8. Case 1

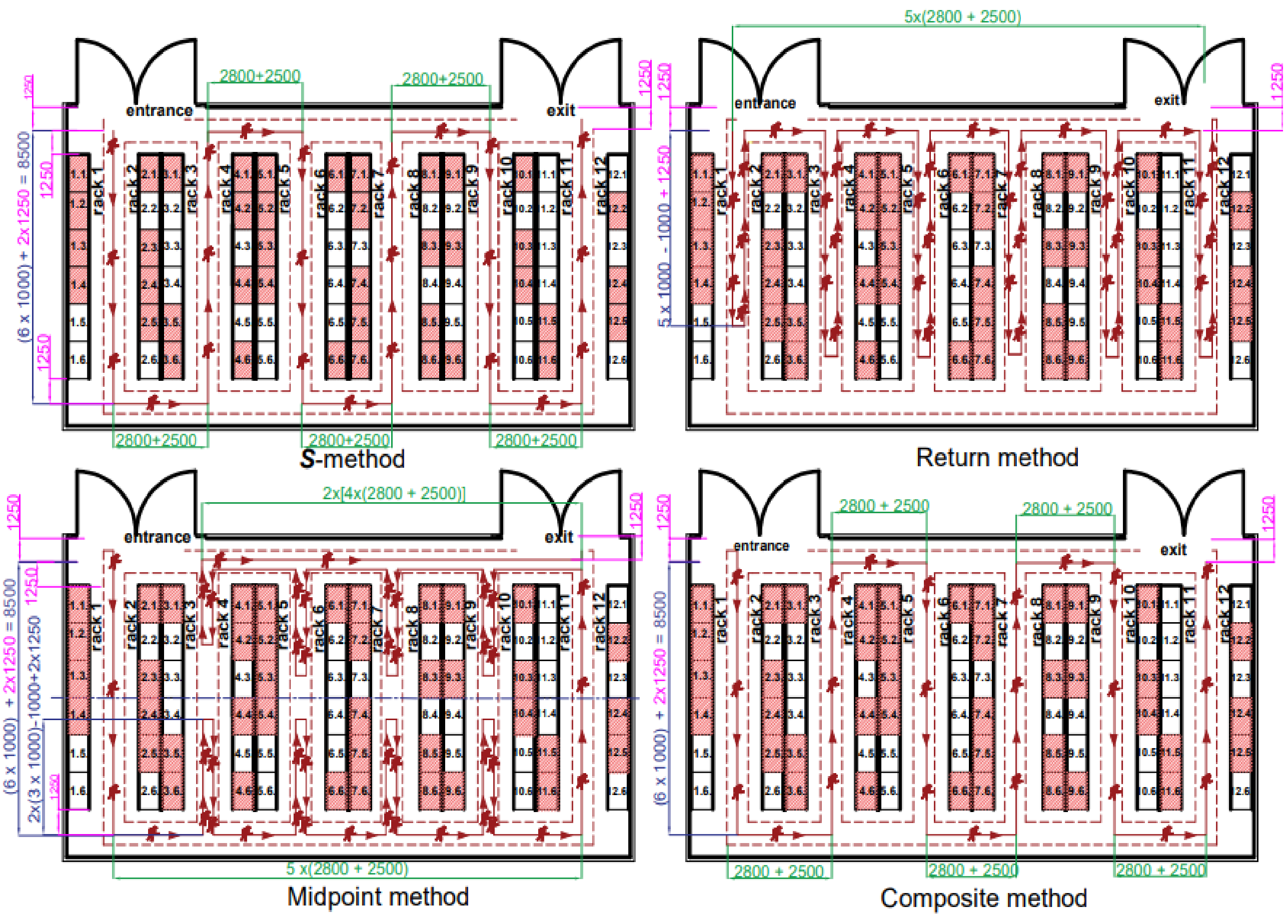
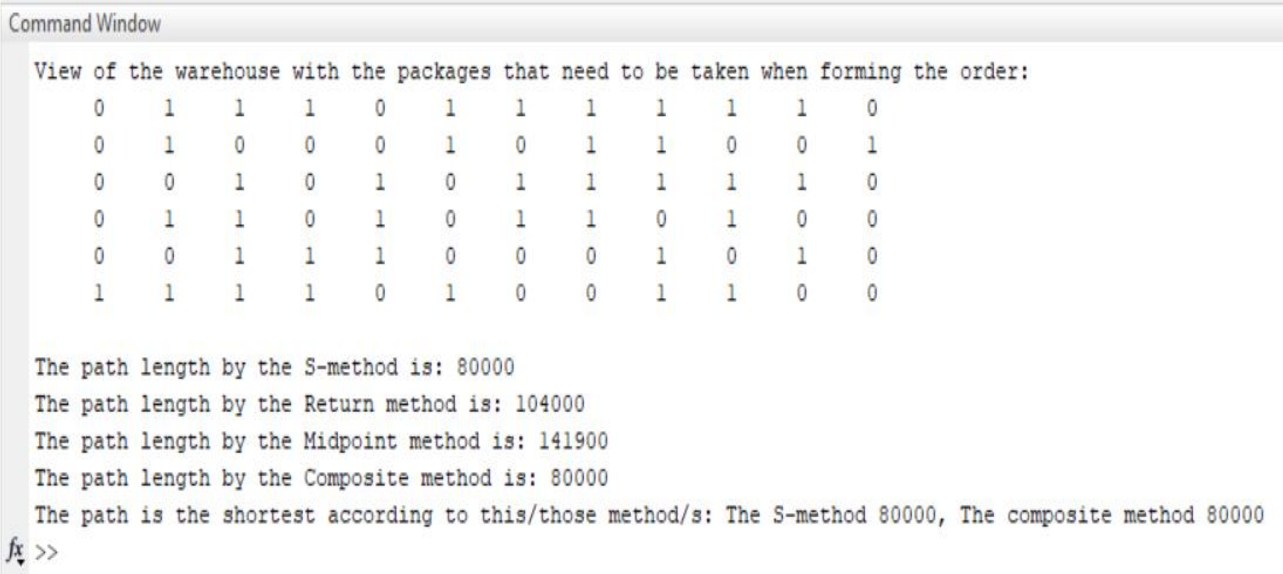


Fig. 9. Comparison of path lengths according to the four methods (Case 1)



```
Command Window
View of the warehouse with the packages that need to be taken when forming the order:
     0     1     1     1     0     1     1     1     1     1     1     0
     0     1     0     0     0     1     0     1     1     0     0     1
     0     0     1     0     1     0     1     1     1     1     1     0
     0     1     1     0     1     0     1     1     0     1     0     0
     0     0     1     1     1     0     0     0     1     0     1     0
     1     1     1     1     0     1     0     0     1     1     0     0

The path length by the S-method is: 80000
The path length by the Return method is: 104000
The path length by the Midpoint method is: 141900
The path length by the Composite method is: 80000
The path is the shortest according to this/those method/s: The S-method 80000, The composite method 80000
>>
```

Fig. 10. Case 2

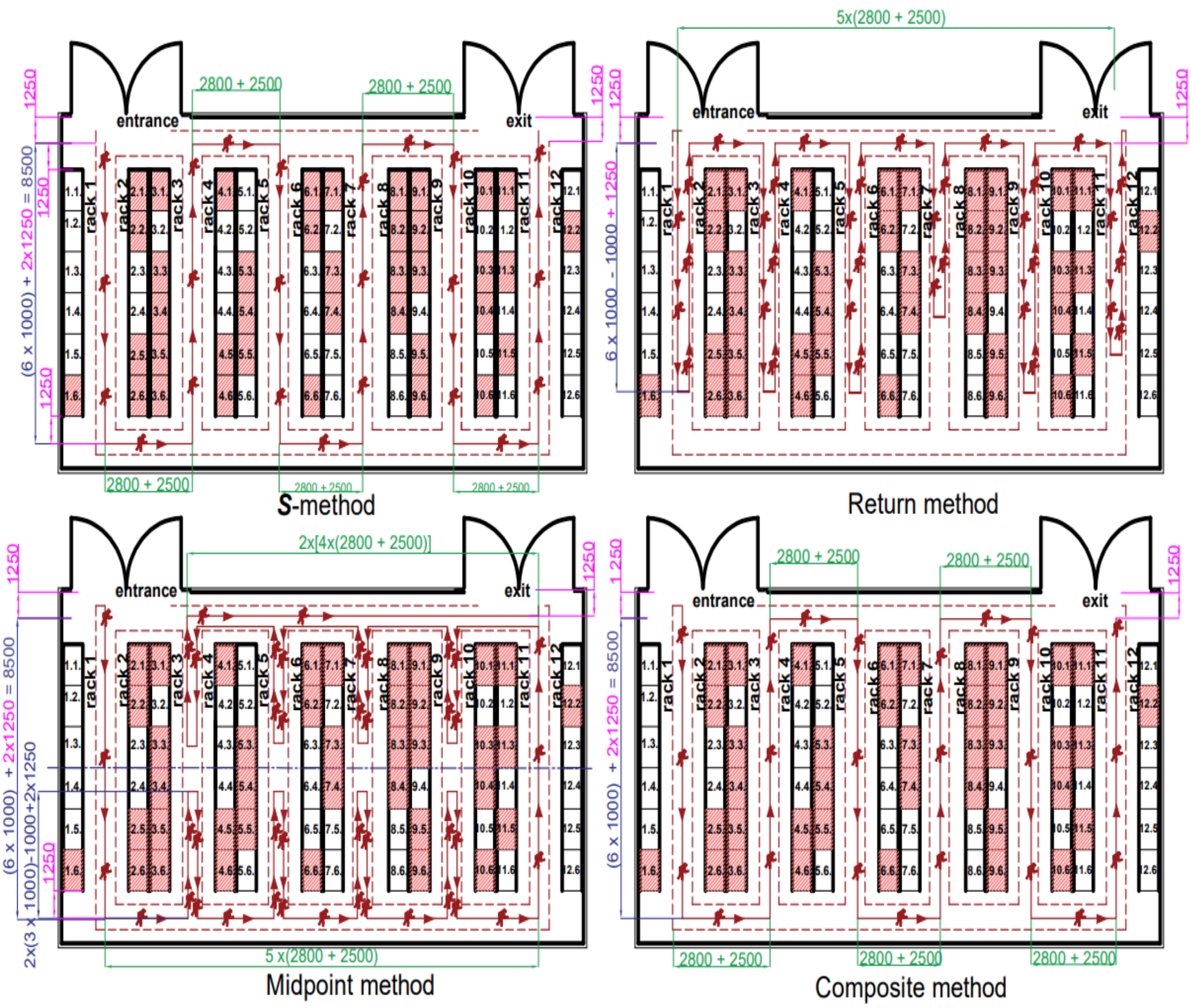


Fig. 11. Comparison of path lengths according to the four methods (Case 2)

```
View of the warehouse with the packages that need to be taken when forming the order:
      0      0      1      0      0      0      1      0      0      0      0      1
      1      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0      0      0

The path length by the S-method is: 53000
The path length by the Midpoint is: 44000
The path lengh by the Midpoint method is: 90400
The path length by the Composite method is: 44000
The path is the shortest according to this/those method/s: The return method 44000, The composite method 44000
```

Fig. 12. Case 3

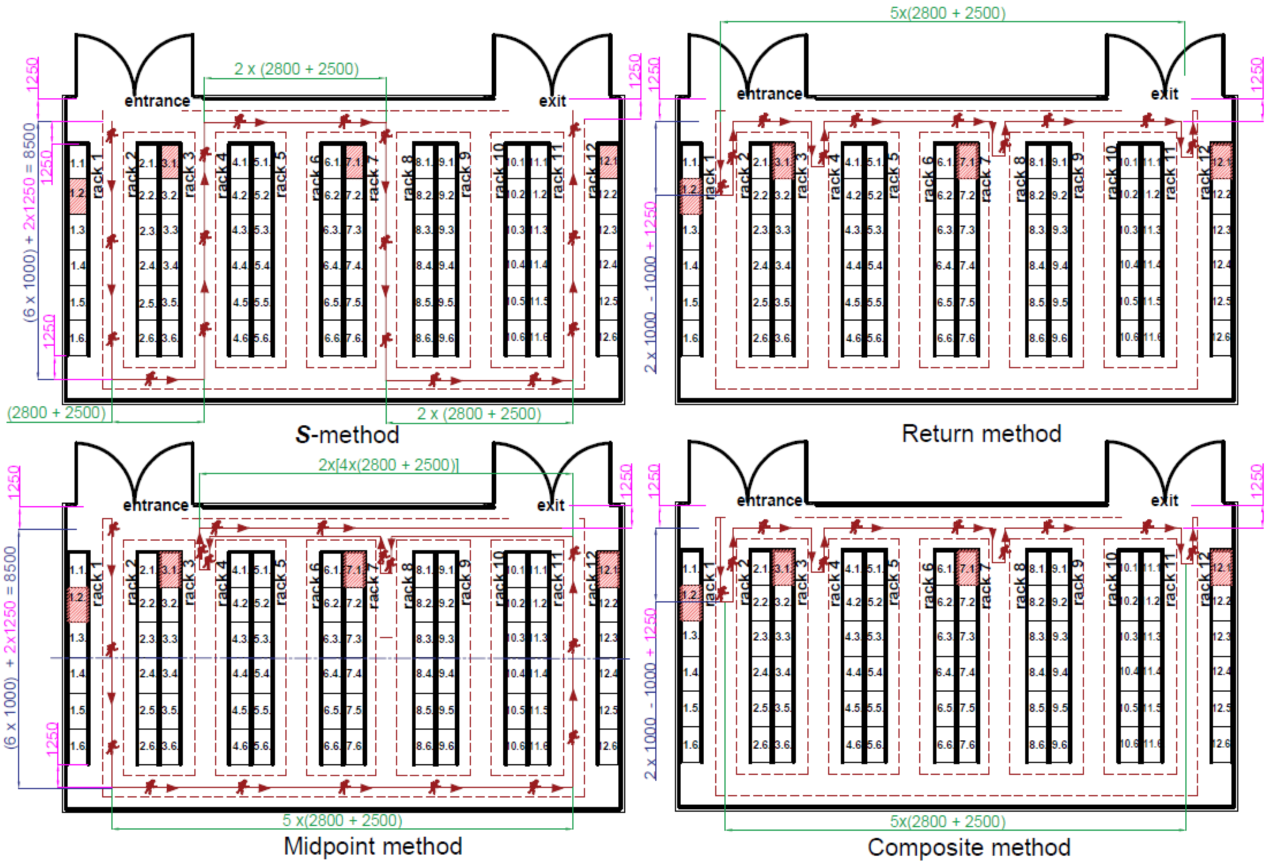


Fig. 13. Comparison of path lengths according to the four methods (Case 3)

Based on the results obtained, the formation of paths for order picking using the composite method and the s-method consistently outperformed in all of the test cases compared to the other methods. The identical values of the paths for the composite method and the s-method arise from the nature of the orders in the illustrated cases. These cases require retrieving a significant number of parts/boxes from nearly every bay of the racks, resulting in the formation of the same path for both the composite method and the s-method. In all cases, it is worth noting that the lengths according to the s-method are consistently 80,000 mm. This uniformity in path lengths for different orders stems from the necessity to retrieve a box from each rack, requiring passage through all the passages to enable access to each rack bay. After the composite method and the s-method, the next best-performing method is the return method. The longest paths in all thirty cases, are observed with the midpoint method. For the given warehouse and its entry and exit layout, the midpoint method fails to provide an adequate path formation in order picking. In scenarios where only a small number of boxes need to be retrieved from the first bays of the racks, the return method, as well as composite method, yields the shortest path.

6. CONCLUSIONS

The selection of the shortest delivery path is a logistical challenge that has been extensively studied since the second half of the 20th century. In logistics, the preference for the shortest path is primarily applied during the delivery of shipments within the borders of a country, for intercity or city deliveries. The issue of choosing the shortest path when preparing goods for delivery within the warehouse, as part of the logistics chain, is a problem that is not as thoroughly researched, and few executable programs are available. The varying shapes and internal layouts of warehouses add to the difficulty of solving the issue of choosing the shortest path within a warehouse. This suggests that a software solution needs to be tailored to the placement of input and output, as well as the layout of the racks where the items are stored. Selecting the optimal path when preparing an order for delivery in a warehouse is essential for optimizing logistics processes. In this regard, this research paper addresses the specific problem of calculating the shortest path in a rack warehouse with given dimensions and layout.

The verification of the executable code is demonstrated through thirty arbitrary order-picking cases. The simulation results show that for varying numbers of racks and rack's bays from which part/boxes need to be picked, the composite method and the s-method show superior performance among the four methods. As expected, the composite method outperforms the other techniques and provides optimal solutions by combining and addressing the limitations of alternative methods. In scenarios where numerous boxes are to be picked up from almost all racks, the paths formed by the composite method and the s-method are identical.

When it comes to retrieving parts/boxes from a smaller number of racks, particularly from the first or the second rack bays in the first half of the warehouse, the return method yields better results than the s-method. As the number of racks increases, and there is a need to collect boxes from more distant rack bays like 4, 5, and 6, the s-method proves more effective. In the given case, the longest paths during order formation in all examples were observed using the midpoint method. In conclusion, the values obtained from the conducted research underscore the importance of calculating the shortest path in warehouses when preparing a delivery order.

Future directions for refining, expanding, and advancing the research would involve a comparative analysis examining how changes in input and output parameters affect path lengths. Additionally, the objective is to develop an executable algorithm capable of mapping the shortest path as an output, enabling the code to find more practical applications. Developing an algorithm to calculate the shortest path for warehouses with varying dimensions and spatial layouts is a substantial challenge.

A major improvement to the algorithm in the future would involve incorporating capacity considerations into the calculation of the optimal path during the process of preparing a delivery order. This entails including the quantity of items retrieved from a particular rack and considering the limited capacity of the asset, such as a cart or a box, into which the order picker will place the ordered pieces.

REFERENCES

[1] Ratliff, H. D., Rosenthal, A. S. (1983): Order-picking in a rectangular warehouse: a solvable case of the traveling salesman problem. *Operations Research* **31** (3), 507–521.

[2] Kruithof, M. W. (2012): *Traveling Salesman Problem. Comparisons between heuristics, linear and semidefinite programming approximations,* Master's thesis in applied mathematics, University of Groningen, Faculty of Mathematics and Sciences.

[3] Wang, P. G., Qi, X. M., Zong, X. P., Zhu, L. L. (2013): Picking route optimization of automated warehouse based on improved genetic algorithms. *Applied Mechanics and Materials* **411**, 2694–2697.

[4] Puka, R., Duda, J., Karkula, M. (2019, June): Improving of selected routing strategies for order picking. In: *International Scientific Conference Transport of the 21st Century* (pp. 363–373). Cham: Springer International Publishing.

[5] Liu, H., Wang, F., Zhao, J., Yang, J., Tan, C., Zhou, L. (2022): Performance analysis of picking path strategies in chevron layout warehouse. *Mathematics* **10** (3), 395.

[6] Esra, B. O. Z., Nil, A. R. A. S. (2022): Order picker routing problem in a single block warehouse. *Journal of Turkish Operations Management* **6** (1), 1113–1120.

[7] Lanza, G., Passacantando, M., Scutellà, M. G. (2022): Sequencing and routing in a large warehouse with high degree of product rotation. *Flexible Services and Manufacturing Journal*, 1–50.

[8] Korbacher, L., Heßler, K., Irnich, S. (2023): *The single picker routing problem with scattered storage: Modeling and evaluation of routing and storage policies,* Discussion papers No. 2302, Johannes Gutenberg Universität, Mainz.

[9] Shetty, N., Sah, B., Chung, S. H. (2020): Route optimization for warehouse order picking operations via vehicle routing and simulation. *SN Applied Sciences*, **2**, article number 311, pp. 1–18.

[10] Burinskiene, A. (2010): Order picking process at warehouses. *International Journal of Logistics Systems and Management* **6** (2), 162–178.

[11] Cano, J. A., Correa-Espinal, A. A., Gómez-Montoya, R. A. (2017): An evaluation of picking routing policies to improve warehouse efficiency. *International Journal of Industrial Engineering and Management* **8** (4), 229.

[12] Goeke, D., Schneider, M. (2021): Modeling single-picker routing problems in classical and modern warehouses. meritorious paper awardee. *INFORMS Journal on Computing* **33** (2), 436–451.

[13] Zhou, L., Zhao, J., Liu, H., Wang, F., Yang, J., Wang, S. (2022): Stochastic models of routing strategies under the class-based storage policy in fishbone layout warehouses. *Scientific Reports* **12** (1), 12876.

[14] Merkuryev, Y., Burinskiene, A., Merkuryeva, G. (2009): Warehouse order picking process. *Simulation-Based Case Studies in Logistics: Education and Applied Research*, 147–165, Technical University, Riga (Latvia).

[15] Birge, J. R., Louveaux, F. (2010): *Introduction to Stochastic Programming* (Second Edition), Springer. DOI 10.1007/978-1-4614-0237-4.

[16] Lu, W., McFarlane, D., Giannikas, V., Zhang, Q. (2016): An algorithm for dynamic order-picking in warehouse operations. *European Journal of Operational Research* **248** (1), 107–122.

[17] Theys, C., Bräysy, O., Dullaert, W., Raa, B. (2010): Using a TSP heuristic for routing order pickers in warehouses. *European Journal of Operational Research* **200** (3), 755–763.

[18] Brucato, C. (2013): *The Traveling Salesman Problem*. Master's thesis, University of Pittsburgh (Unpublished).

[19] Burkard, R. E., Fruhwirth, B., Rote, G. (1995): Vehicle routing in an automated warehouse: Analysis and optimization. *Annals of Operations Research* **57**, 29–44.

[20] Yang, J., Zhou, L., Liu, H. (2021): Hybrid genetic algorithm-based optimisation of the batch order picking in a dense mobile rack warehouse. *PLoS ONE* **16** (4), e0249543, doi: 10.1371/journal.pone.0249543

[21] Namany, S., Kissani, I. (2017): *Capacitated Vehicle Routing Problem with Variable Fleet of Delivery Vehicles of Uniform Capacity*. Capstone report, University of Al Akhawayn, Morocco.

[22] Roodbergen, K. J., Koster, R. (2001): Routing methods for warehouses with multiple cross aisles. *International Journal of Production Research* **39** (9), 1865–1883.

[23] Shen, X., Yi, H., Wang, J. (2021, March): Optimization of picking in the warehouse. In: *Journal of Physics: Conference Series* Vol. **1861**, No. 1, p. 012100. IOP Publishing.

[24] Bottani, E., Montanari, R., Rinaldi, M., Vignali, G. (2015): *Intelligent algorithms for warehouse management*. Intelligent techniques in engineering management: Theory and applications. 645–667, Springer.

[25] Ivanov, D., Tsipoulanidis, A., Schönberger (2019): *Global Supply Chain and Operations Management*, Second Edition. Springer.

[26] Pinkam, N., Bonnet, F., Chong, N. Y. (2016, October): Robot collaboration in warehouse. In *2016 16th International Conference on Control, Automation and Systems (ICCAS)* (pp. 269–272). IEEE.

[27] Vivaldini, K. C. T., Becker, M., Caurin, G. A. (2009, November): Automatic routing of forklift robots in warehouse applications. In: *Proceedings of the 20th International Congress of Mechanical Engineering*, Gramado-RS, Brazil.

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Original scientific paper

DEVELOPMENT OF CURRENT MEASURING INSTRUMENT USING HALL EFFECT

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A b s t r a c t: Isolated current sensing is fundamental in several contexts, including power electronics, automotive, and smart buildings. To meet the requirements of modern applications, current sensors should feature ever larger bandwidth and dynamic range, as well as reduced power consumption and dimension. There are different ways for current measurement like using current transformers or using the Rogowski coils which are not precise enough in many applications and not suitable for use in power electronic measurement systems. For that reason, the Hall effect-based sensor can be used as a very precise alternative with minimum external components. Many modern electronic devices utilize linear Hall sensors to measure current and the magnetic field, as well as to perform switching and latching operations. Within this paper a focus is on the analysis and creation of a current measuring device using the Hall effect sensor SS495A. The mathematical model of the device is calculated experimentally, which then is connected to a microcontroller. The device is connected to the internet and using an IoT platform, an app is created which allows for real time monitoring through the web or a smartphone.

Key words: current sensing; Hall effect; Arduino microcontroller

РАЗВОЈ НА ИНСТРУМЕНТ ЗА МЕРЕЊЕ ЈАЧИНА НА СТРУЈА КОРИСТЕЈЌИ ХАЛОВ ЕФЕКТ

А п с т р а к т: Мерењето на струја е од фундаментално значење во неколку контексти, вклучувајќи ја енергетската електроника, автомобилската индустрија и паметните згради. Со цел да се задоволат барањата на современите апликации, тековните сензори треба да имаат динамичен и зголемен опсег, како и намалена потрошувачка на енергија и димензии. Постојат различни начини за мерење на струјата, на пример користење струјни трансформатори или користење намотки, кои не се доволно прецизни во многу апликации и не се погодни за употреба во електронски мерни системи за напојување. Од таа причина, сензорот заснован на Халов ефект може да се користи како многу прецизна алтернатива со минимални надворешни компоненти. Многу современи електронски уреди користат линеарни Халови сензори за мерење на струјата и магнетното поле, како и за извршување операции на прекинувачи. Во рамките на овој труд фокусот е ставен на анализа и создавање уред за мерење струја со помош на сензорот со Халов ефект SS495A. Експериментално се пресметува математички модел на уред кој потоа се поврзува со микроконтролер. Уредот е поврзан на интернет и со користење на платформата IoT се креира апликација која овозможува следење на податоците во реално време преку веб или преку паметен телефон.

Клучни зборови: мерење на струја; Халов ефект; Ардуинов микроконтролер

1. INTRODUCTION

Current sensing circuits are needed for measurement, monitoring and control of various applications. These circuits are used largely in automotive and power electronics which require current sensing to estimate electrical power and energy. This demand is driven by the recent trends and policies towards smart energy efficient cities, creation, conversion and storage of energy as well as in smart electric vehicles [1–4]. Another relevant use for current sensing is in power modules, in the current-mode loop control of DC-DC converters [5, 6], protection from over current and current leakage.

In several of these applications, the current sensor should satisfy many requirements including low insertion loss, high dynamic range, robustness, high speed, low cost, and reduced physical dimensions. Therefore, it is essential to develop miniaturized and high-performance sensing devices to be possibly embedded within the power system. In this context one of the more widely used techniques for current sensing is the use of the Hall effect. These sensors are sensitive to the magnetic field generated by the current to be detected. Using this effect the current flow which is monitored in the power circuit is kept electrically isolated from the sensor [7]. This isolation of the Hall effect sensors ensures that it is not affected by conducted interference generated by the power system which is monitored which ensures effective use in electromagnetically polluted environment. Sasti et al. [8] have used the Hall effect to develop a high current DC sensor with the ability to measure at 128 amps, while in [9] an educational laboratory was set up using national instruments LabView and an acquisition card and the use of a closed loop Hall effect sensor.

Most magnetic sensors available commercially are so-called Hall devices, which are based on the Hall effect. The Hall effect is the appearance of an electric potential difference in a probe or semiconductor, when there is a magnetic field nearby, perpendicular to the plane of the probe. The original experiment consisted of a metal sheet attached to a glass substrate through which an electric current was conducted (Figure 1). By connecting a galvanometer to the ends of the sheet, at equipotential points, and placing the sheet between the poles of an electromagnet, it was seen that at certain positions of the basic electromotive force and the magnetic field, a suppression of the electric current appeared towards one end of the sheet.

With further tests, it was confirmed that the newly created electromotive force is directly proportional to the product of the magnetic field strength *B* and the current speed *v*.

$$E_H \sim [v \times B] \quad (1)$$

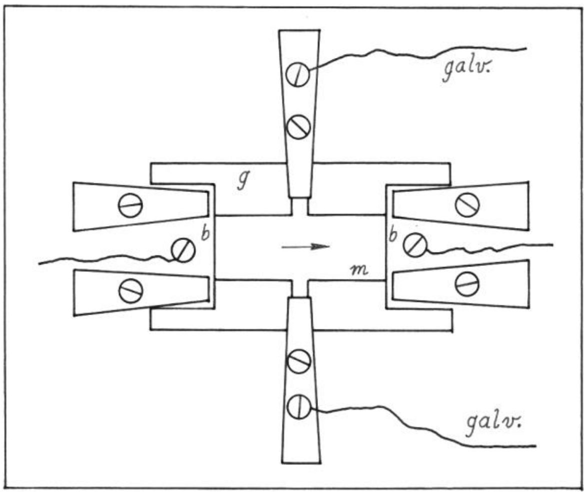

Fig. 1. A sketch of Hall's original experimental arrangement [10]

2. DEVELOPMENT OF CURRENT MEASURING DEVICE

The aim of this work is the development of a device that can measure current flow and send data to a database which can be accessed from anywhere. The use case of the device is mainly focused in household appliances since they are the main power consumers in any home. By connecting to a cloud service, where data processing and collection of real time power consumption data will take place, an application can be created where a statistical overview can be seen of where and how much power is consumed on a daily/monthly basis. In addition, the device for measuring the flow of electric current can serve as a security measure in homes, by sending a predefined notification to the user (example: a certain device has been switched on longer than the specified time, the occurrence of higher consumption than usual when using a certain device, a reminder to turn off the device, a warning about current exceeding the specified limit, etc.). The need of such a device arises since on the market most of the available devices only give information on whether the appliance is turned on or off and they usually come prebuilt into the appliance.

The functional block diagram for this device can be seen on Figure 2.

Fig. 2. Development of current measuring device with cloud connection

2.1. *Measuring and amplification of magnetic field*

In order to approach the realization of the idea of creating a device for measuring the flow and strength of electric current, we firstly need to select an element, i.e., a sensor, from which we will receive data that is directly dependent on the strength of the electric current. Since a magnetic field is created around every conductor through which electric current flows, a suitable solution would be to choose a magnetic sensor. For this purpose the analog Hall sensor Honeywell SS495A is selected, which is a magnetic sensor and at the output it generates a voltage that is directly connected and depends strictly on the strength of the electric current. The SS495A sensor is suitable for its small size, low power consumption, built-in resistors for greater accuracy and temperature compensation, stable output signal and the ability to respond to positive and negative magnetic fields.

The next step in the process is the amplification of the magnetic field in order to obtain a larger range of values that the sensor can detect, which would also increase the accuracy of the output signal. We perform the amplification with a metal part in the shape of a toroid (Figure 3), on which, for additional amplification, we coil up the wire of the conductor where we want to measure the current flow.

Fig. 3. Hall sensor inside a toroid for amplification of magnetic field

A notch in the toroid is made, with the dimensions of the sensor. By inserting the sensor into the notch of the toroid, its position is fixed. The stable position of the sensor is an important factor for obtaining accurate and precise data, because even the slightest change in position can result in a completely different mathematical model.

2.2. *Mathematical model*

Modeling a system means establishing a mathematical model for the behavior of the constituent components of the system itself. Mathematical models represent a set of mathematical relations. They can be obtained analytically or experimentally, i.e., identification of a system. Due to the insufficient amount of available information about the toroid material, we cannot determine the mathematical model for the device analytically. The system for which a mathematical model is developed is shown on Figure 4. The magnetic field which is created when current flows through the conductor is given by the following equation.

$$B = \frac{\mu_0 \mu_r I}{2\pi r}, \tag{2}$$

where B is the magnetic flux density, μ_0, μ_r are the vacuum and relative permeability, respectively, and I is the current. The magnetic flux is measured by the Hall sensor but this value is very low hence it is required to be amplified by a material with high permeability, which is the toroid where the sensor is placed. Since there is a notch in the toroid where the sensor is placed the magnetic flux has a different value which considers the air gap between the sensor and the field concentrator, denoted in the equation as d. This relationship is given by equation 3.

$$B = \frac{\mu_0 \mu_r I}{2\pi(r-d) + d\mu r}. \tag{3}$$

Equation 3 can be rewritten in the same order as equation 2 if an effective permeability is considered.

$$B = \frac{\mu_0 \mu_e I}{2\pi r}, \tag{4}$$

where the effective permeability can be calculated as:

$$\mu_e = \frac{\mu_r}{1 + \frac{\mu_r d}{2\pi r} - \frac{d}{r}}. \tag{5}$$

The Hall sensor outputs a voltage whose relation can be described with the following equation, (eq. 6). Further explanation and a deep dive in current measurement in power electronic can be found in [11].

$$V_{\mathrm{out}} = \left(\frac{s\mu_0\mu_e}{2\pi r}\right) I + V_{\mathrm{offset}} \tag{6}$$

The value of the offset is directly affected by the input voltage of the sensor, where $V_{\mathrm{offset}} = \frac{V_{\mathrm{cc}}}{2}$. The value of the constant that directly connects the current in the conductor and the output voltage from the sensor $\left(\frac{s\mu_0\mu_e}{2\pi r}\right)$ needs to be experimentally determined. This is achieved by connecting the sensor with a generator and an oscilloscope and generating a set of input values for the voltage and current and recording the output values of the sensor. The connection diagram can be seen on Figure 4.

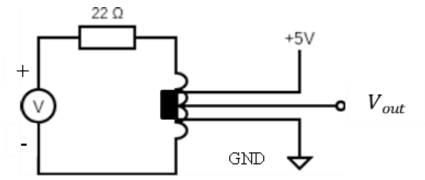

Fig. 4. Electrical scheme for determining mathematical model

We control the strength of the current flowing through the conductor through the generator, and we display and read the signal which we receive from the sensor on the oscilloscope. The experiment was done for current values from 0 to 1.4 Amps, and we write down the values for the corresponding generated voltage (Table 1), and with the help of software, in this case MATLAB, through the linear regression method we determine the dependence that best describes them. The expected dependence is the shape $y = ax + b$.

Table 1

V_{in} (V)	I (A)	V_{out} (V)
0	0	2.49
2.24	0.1	2.51
4.57	0.2	2.53
6.8	0.3	2.54
8.96	0.4	2.55
11.14	0.5	2.57
13.44	0.6	2.58
15.71	0.7	2.6
17.9	0.8	2.62
20.7	0.9	2.63
22.17	1	2.64
24.2	1.1	2.66
26.32	1.2	2.68
28.44	1.3	2.69
30.77	1.4	2.71

The obtained data from the software is graphically shown in Figure 5. The coefficient $\left(\frac{s\mu_0\mu_e}{2\pi r}\right)$ is calculated to be 0.15286 and the offset voltage to be 2.493, which is half of the input voltage as stated previously.

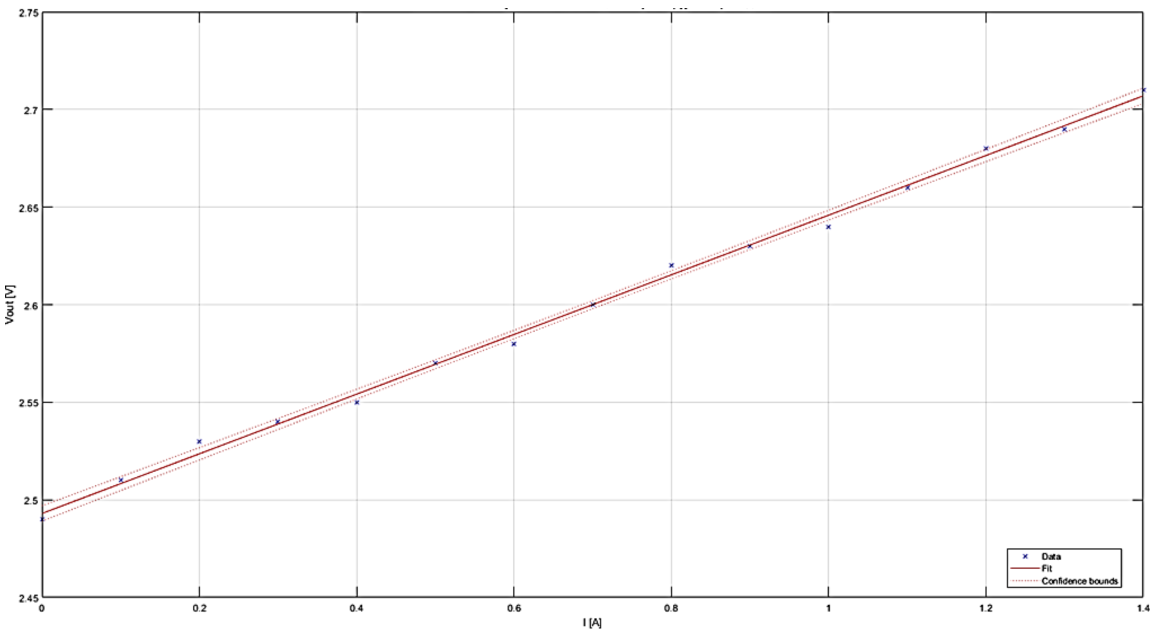

Fig. 5. Relation between the output voltage of the sensor and the current of the conductor

The final mathematical model for this system is described by equation 7.

$$V_{\text{out}} = 0.153 * I + 2.493. \quad (7)$$

3. RESULTS AND DISCUSSION

After determining the coefficients of the mathematical model, the system is connected with a microcontroller which enables reading and writing of the data received from the sensor. The choice of microcontroller has a big role in the resolution of the system, i.e., the smallest possible change that can be detected depends on the microcontroller. Arduino UNO WiFi Rev.2 is be used for this project, which, as the name suggests, has a built-in WiFi module and can easily be connected to the Internet. The resolution of the system, or rather of the converter from analog to digital signal, can be determined by the equation 8:

$$ADC_{res} = \frac{V_{\text{ref}}}{2^{10}-1} = \frac{5}{1023} = 4.89\,\frac{\text{mV}}{\text{bit}}, \quad (8)$$

where the value of V_{ref} indicates the power supply of the sensor and also the range of the output signal. The resolution of the sensor in the system is ~5 mV.

The system connection is the same as when determining the mathematical model (Figure 4), with the only difference that we do not connect the output signal to an oscilloscope, but to one of the analog pins of the Arduino, A0 shown in Figure 6.

After the device is connected to the Arduino, a program is created which will read the values from the sensor and transform them into useful data about the current passing through the conductor. We connect the Arduino to the Internet, and we upgrade the existing program with additional functions for sending the data to a cloud service. The cloud service we use is Blynk, an IoT (Internet of Things) platform for smartphones that is used to control various microcontrollers such as Arduino, Raspberry Pi and similar. The advantage of Blynk compared to other cloud services is the direct and easy connection to Arduino and the possibility of creating a simple user interface. To create a new application, it is necessary to create a template, i.e., template for how it would look, but existing ones can also be used. Templates mainly consist of dashboards, information about the connected system, assigning virtual pins, and of course, the appearance of the application. The appearance of the application is given in Figure 7.

The application can be accessed via a smartphone or the web. It shows the current measurement for the current and voltage, and values can be seen for hourly, daily, and monthly consumption. The program can be upgraded with conditions for sending notification to the user, as can be seen in Figure 8.

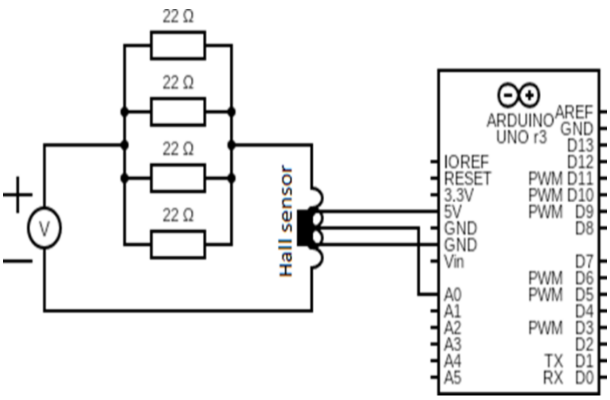

Fig. 6. Connection diagram of the current measuring system

Fig. 7. Blink application for the system

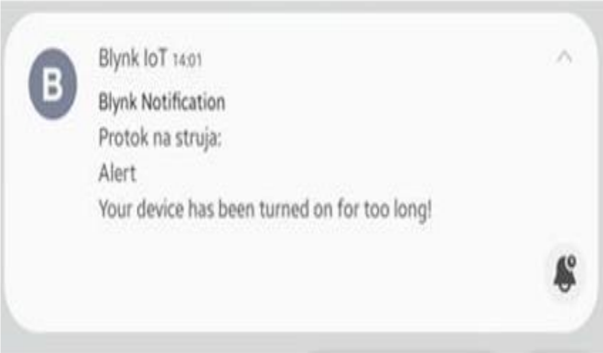

Fig. 8. Notification from Blink application to smartphone

Emphasizing the rational use of electricity, the condition was set that when the device is turned on for a long period of time a notification is sent to the user. These conditions can be varied based on the need, for example a notification to be sent when exceeding a certain current consumption.

4. CONCLUSION

The aim of this work was to create a system for measuring flow and strength of electric current in conductors using a Hall sensor and it was successful realized. During the analysis and realization of the system, it was shown that the Hall sensor is a good option for this application, but not ideal, since an additional power supply is needed. The system is suitable for use in conjunction with a large number of devices. The created system, although functional, has its drawbacks. The main disadvantage is that it needs to be integrated within the device. This would make it difficult to change the sensor from one device to another however by integrating some of the elements in a smaller assembly, and powered by a battery, it is possible to significantly reduce the dimensions of the system, and at the same time to allowing the system to become portable. Upgrading the device will mean coming closer to the standard current clamp for measurements only having smaller dimensions as well as an IoT application for real time monitoring of the devices we connect too.

REFERENCES

[1] Adamo, F., Attivissimo, F., Di Nisio, A., Carducci, C. G. C., Spadavecchia, M., Guagnano, A., Goh, M. K. (2017): Comparison of current sensors for power consumption assessment of wireless sensors network nodes. In: *2017 IEEE International Workshop on Measurement and Networking (M&N)* (pp. 1–4).

[2] Ouyang, Y., He, J., Hu, J., Zhao, G., Wang, Z., Wang, S. X. (2015): Contactless current sensors based on magnetic tunnel junction for smart grid applications. *IEEE Transactions on Magnetics* **51** (11), pp. 1–4.

[3] Mota, L., Mota, A., Coiado, L. C. (2015): Non-destructive current sensing for energy efficiency monitoring in buildings with environmental certification. *Sensors* **15** (7), pp. 16740–16762.

[4] Tamburini, C., Pizzotti, M., Dini, M., Crescentini, M., Tartagni, M., Romani, A., Alimenti, F., Virili, M., Mezzanotte, P., Roselli, L. (2018): A CMOS RF-powered tag with sensing and localization capabilities. In: *2018 IEEE 23rd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)* (pp. 1–5).

[5] Tong, Q., Chen, C., Zhang, Q., Zou, X. (2015): A sensorless predictive current controlled boost converter by using an EKF with load variation effect elimination function. *Sensors* **15** (5), pp. 9986–10003.

[6] Huang, K., Liu, Z., Zhu, F., Zheng, Z., Cheng, Y. (2017): Evaluation scheme for EMI of train body voltage fluctuation on the BCU speed sensor measurement. *IEEE Transactions on Instrumentation and Measurement* **66** (5), pp. 1046–1057.

[7] Popovic, R. S. (2003): *Hall Effect Devices*. CRC Press.

[8] Sasti Dwi Tungga Dewi, C. Paratarani, I. Made Joni, (2016): Design and development of DC high current sensor using Hall-effect method. In: *AIP Conference Proceedings*, Vol. **1712**, No. 1. AIP Publishing.

[9] Luković, M., Koprivica, B., Milovanović, A. (2018): Educational laboratory setup for electric current measurement using hall effect current sensors. In: *Proceedings of 7th International Conference Technics and Informatics in Education-TIE2018* – Čačak, Faculty of Technical Sciences, Serbia (pp. 340–346).

[10] Mareš, J. J., Špička, V., Hubík, P. (2023): Thought experiments in electromagnetic theory and the ordinary Hall effect. *The European Physical Journal Special Topics* **232** (20–22), pp. 3529–3544.
DOI: 10.1140/epjs/s11734-023-00978-3

[11] Patel, A. (2007): *Current measurement in power electronic and motor drive applications – a comprehensive study*. Master thesis. 4581.
https://scholarsmine.mst.edu/masters_theses/4581

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Original scientific paper

OVERCOMING INDUSTRIAL ROBOTICS CHALLENGES AND THE ROLE OF OFFLINE PROGRAMMING

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A b s t r a c t: Industrial robots play a pivotal role in modern industrial production, with robotic welding standing out as a crucial application. This paper analyzes the utilization of online and offline programming methods to optimize robotic welding processes, with an application of Gas Metal Arc Welding (GMAW) techniques. GMAW offers exceptional versatility, including adaptability to various plate thicknesses, high productivity rates, compatibility with diverse materials, and the ability to weld coated metals. The synchronization of robotic movements and positioners plays a crucial role in ensuring precise welding execution. This complexity is particularly evident in scenarios involving welding complex curves, where coordinated movement between the robotic arm and positioner is essential for successful outcomes. In this study, an experiment involving the welding of a pipe-pipe joint using a robot with 6 and positioner with 2 degree of freedom is presented. By applying synchronized movement, seamless welding operations are achieved, highlighting the importance of advanced programming techniques and synchronized operations in enhancing the efficiency and precision of robotic welding in industrial production.

Key words: welding robot; robot programing; OLP; GMAW; MIG/MAG

НАДМИНУВАЊЕ НА ПРЕДИЗВИЦИТЕ НА ИНДУСТРИСКАТА РОБОТИКА И УЛОГАТА НА ПРОГРАМИРАЊЕТО ОФЛАЈН

А п с т р а к т: Индустриските роботи играат клучна улога во современото индустриско производство, при што роботското заварување се издвојува како клучна примена. Овој труд го истражува користењето на методите за онлајн и офлајн програмирање за оптимизирање на процесите на роботско заварување, со примена на електролачно заварување со топлива електрода во заштитна атмосфера од инертен/активен гас. GMAW нуди исклучителна разновидност, вклучувајќи приспособливост на различни дебелини на плочи, високи стапки на продуктивност, компатибилност со различни материјали и способност за заварување обложени метали. Синхронизацијата на движењата на роботот и позиционерот игра клучна улога за обезбедување прецизно извршување на заварувањето. Оваа комплексност е особено видлива кај предмети кои вклучуваат сложени просторни криви за заварување, каде што координираното движење помеѓу роботската рака и позиционерот е од суштинско значење за добивање квалитетни резултати. Во оваа студија е претставен експеримент кој вклучува заварување на спој цевка-цевка со помош на робот со 6 и позиционер со 2 степени слобода на движење. Преку употреба на нивно синхронизирано движење се постигна квалитетно заварување, што ја истакнува важноста на напредните техники на програмирање и синхронизираните операции со цел подобрување на ефикасноста и прецизноста на роботското заварување во индустриското производство.

Клучни зборови: роботско заварување; програмирање на роботи; OLP; GMAW; MIG/MAG

1. INTRODUCTION

Welding is the process of joining two or more pieces, usually metallic, with or without the use of additional material, applying a combination of thermal and/or mechanical energy. Numerous factors, such as carbon migration from the low alloy side, microstructure gradient, and residual stress across various regions of the weld metal, influence the properties of the welded joints and the feasibility of the welding processes [1]. Welding techniques are commonly observed and analyzed from several points of view such as: structural, metallurgical, chemical, physical and electrical. Accordingly, this activity overlaps with several disciplines from technology and science, which gives it a multidisciplinary character. It enables and requires the engagement of more profiles of experts in the research and application of this activity. From a sustainability standpoint, welding has not received much attention. Instead, research on welding has been more dedicated on developing welding processes, studying applications on different metals, and improving weld performance and quality, meanwhile, society, economy, and the environment were rarely considered [2].

The most significant advantage of welding is undoubtedly that it provides exceptional structural integrity, producing joints with very high efficiency [3]. The disadvantage is that there is a lot of heating and consequent changes in thermal-deformation cycle. Welding as a technique is often presented as a difficult discipline. Welders are part of a heterogeneous workforce employed in a variety of workplace settings. Well-ventilated indoor and outdoor locations, as well as small, inadequately ventilated interiors like ship hulls, pipelines, and basements of buildings, may be included. As a result, various exposure concentrations have been measured in welding-related workplaces [4]. Experienced welders are highly valued because they control the welding process, and it is not easy to practice. The traditional method of production uses labor, necessitates a large number of welders to ensure progress, and the welding quality varies. Additionally, labor costs have been rising annually, and the difficulty of recruiting and labor shortages in high-risk occupations like welders and grinders have grown in prominence. There is an urgent need to use automated equipment to improve quality and efficiency. Advancements in robotic automation and intelligent welding represent significant innovations [5].

The development of welding techniques has led to the fact that the worker is not able to perform the welding in which a high-quality welded joint should be obtained in a sufficiently short time and at a sufficiently low cost. Consequently, the development of the welding procedure is in automation and robots. Their accuracy, speed and repeatability of processes is beyond human ability. The bigger problem with welding robots is to be programmed for complex welded joints. Industrial robots are an essential segment of today's industrial production. The demands for high quality, low cost and flexibility simply compel the development of robots. Nevertheless, the focus of the intelligent welding manufacturing technology is mainly related to three key elements: sensing welding process for imitating welder’s sense organ function, knowledge extraction and modeling of welding process for imitating welder’s experience reasoning function, and intelligent control of welding process for imitating welder’s decision-making operation function [6].

The development of robotized welding, which is now one of the main applications for industrial robots, has been truly remarkable since the introduction of the first industrial robots in the early 1960s. Robot welding is mainly concerned with the use of mechanized programmable tools, known as robots, which completely automate a welding process by both performing the weld and handling the part [7]. For the reason that they are so adaptable, robots have been used for resistance and arc welding among other types of welding. Robotic welding has great advantages over any other method. Precision and reproducibility, consistent weld quality, welding at optimal speed, without delays results in a quick return on investment, consistent product quality, reduced predictability and duration of the operation and cost. Additionally, makes the process quite flexible and can be utilized for other modern manufacturing processes, and also adaptation of variation in production line with variation in production volume [8]. Manual welding has many sources of injury at work, it produces harmful gases that have a harmful effect on man and his health. Most of the time, labor costs make up the majority of the total cost. Robotic welding is harmless and allows to avoid injuries and other possible inconveniences. A single robot can perform a large number of welding operations, including welding different elements and shapes. The integration of welding robots brings numerous advantages to various industrial welding tasks since most of the drawbacks attributed to the human factors are eliminated as a result [9].

By combining offline programming with an 8 degree of freedom (DOF) system, manufacturers can address various challenges in industrial robotics effectively. The virtual simulation environment provided by offline programming helps in optimizing robot programs and ensuring seamless integration into the production line. Meanwhile, the enhanced capabilities of an 8 DOF system enable robots to handle intricate tasks and navigate challenging workspaces more effectively, leading to improved productivity and quality in manufacturing operations. In the following, Section 2 introduces Gas Metal Arc Welding, considering its advantages and disadvantages. Section 3 examines the programming methods essential for optimizing efficiency and precision in manufacturing. Within this section, we explore both online and offline programming approaches for robotic welding. Welding robot characteristics and workspace considerations, as crucial factors in optimizing performance within manufacturing environments are mentioned in Section 4. Furthermore, Section 5 delves into the robotic welding process and the conducted experiment of welding a pipe-pipe joint via the utilization of a 6 DOF robot and a 2 DOF positioner. Finally, Section 6 is dedicated to the conclusion that synthesizes the insights gathered from our exploration, emphasizing the significance of the presented robot-based welding system for advancing modern manufacturing practices.

2. GAS METAL ARC WELDING

Gas Metal Arc Welding (GMAW) is one of the most widely used welding techniques and is also known as MIG/MAG welding. GMAW is valued for its versatility, making it a widely used welding process in industries ranging from automotive manufacturing to construction. Belongs to the fusion welding processes that utilizes a consumable wire electrode and a shielding gas to create an arc between the electrode and the workpiece. The wire electrode is fed continuously from a spool, and the arc created melts the wire and the base metals, forming a weld pool that solidifies to create the weld joint. The shielding gas protects the weld from atmospheric contamination. Figure 1 depicts this process, providing a visual representation of the GMAW [10]. The density of the shielding gas used in welding is critical for ensuring proper protection of the welding area from atmospheric contamination. Gases like argon and carbon dioxide, due to their high density, provide excellent shielding, while gases like hydrogen and helium, with lower densities, are less efficient in shielding and can lead to turbulent flow issues. The presence of metal vapors in the gas plasma, combined with the characteristics of the shielding gas, affects the stability and ignitability of the welding arc in MIG/MAG welding. Argon typically forms a soft and stable arc, while helium forms a less stable arc that is also harder to ignite [11].

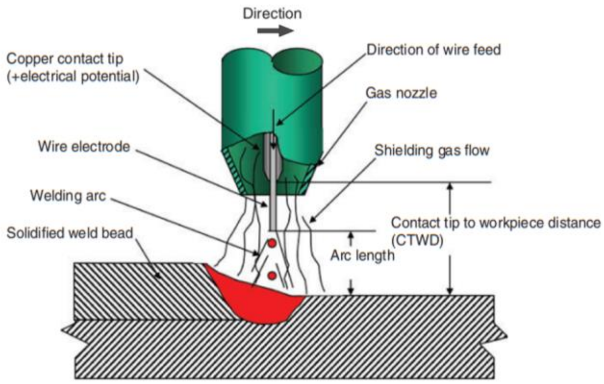


Fig. 1. Gas metal arc welding process

During welding, harmful gases are emitted, affecting human health. Greater consumption of shielding gas correlates with higher impacts on human health indicators. However, these harmful gases can be controlled and removed, minimizing their impact on workers. Measures such as mandatory gas filter masks and designated welding areas with extractors help mitigate health risks in welding workshops [12].

MIG and MAG welding methods are highly flexible and widely applicable, offering benefits such as suitability for various plate thicknesses, high productivity, compatibility with a wide range of materials, capability to weld coated metals, and versatility in welding positions. While MIG/MAG welding offers numerous advantages, it also has limitations compared to Manual Metal Arc (MMA) welding, including more complex equipment and a more restricted application outdoors due to the need to protect the shielding gas from draughts [13]. In conventional MIG/MAG welding, the productive capacity is constrained by the maximum current that can be used. This limitation arises because when the current reaches a certain level, the metal transfer process shifts to a mode known as rotating-spray transfer. Despite its advantages in terms of productive capacity, high strength and ductility with low hydrogen and nitrogen contents [14], submerged-arc welding is not always a suitable replacement for MIG/MAG welding in various applications. This is because submerged-arc welding may lack the versatility or practicality needed for certain welding tasks. Double-wire MIG/MAG welding offers a solution to enhance the productivity of the welding process while preserving its versatility. By utilizing two wires and maintaining operational flexibility, this method overcomes the limitations of conventional MIG/MAG welding, resulting in higher deposition rates, increased travel speeds, and stable metal transfer [15].

3. PROGRAMMING METHODS

The robotic welding process to be of high quality which is essential, and the robot can adapt to certain changes in the welding conditions or environment through making an appropriate response to the movement correction or other process parameters, can be achieved by adaptive process control. The structure of adaptive control is made up of modules that have specific tasks and that interact with each other. Industrial robots can be programmed in different ways, i.e., offline, online, and hybrid programming [16].

3.1. *Online programming*

The online programming method is performed at the robot's workplace and therefore they should be excluded from production. Conventional online programming is a completely manual process [17]. Direct and indirect teach-in programming are the two primary types of online programming. Direct teach-in takes place in a way that the operator guides the robot manually along the path. Physically along the path, where key points or positions are stored in memory, allowing the robot to repeat the movement later. As lead-through programming [18] is the simplest of all robot teaching methods. This programming method is outdated and therefore rarely used in welding programming.

The indirect way of programming as pendant programming [19] is when the operator, with the help of the control panel, follows the desired path by saving the positions in the memory as well as other process parameters such as voltage, current, welding speed, and so on. After the teach-in, the program is tested, in order to see if the robot will interpret well and whether it will execute the assigned program. The advantage of this programming method is that it does not require additional purchases of hardware and software. Moreover, the teaching can be done by an operator who has no competencies in robotics easily and intuitively [20]. The robot cannot perform a production function during programming, which is one of its disadvantages.

3.2. *Offline programing*

Programming according to offline method is performed on a computer and does not require physical movement of the robot, therefore it is not excluded in the production process, which is economically feasible and is the main advantage over teach-in programming. Offline programming may be considered as the process by which robot programs are developed, partially or completely, without requiring the use of the robot itself [21]. Due to deviations in machining tolerances in the robot linkages, robot arm compliance and elasticity, encoder resolution, and the lack of repeatability during calibration, significant errors can occur in an offline generated tool path. The meaning of offline programming is to project as many technological processes as possible at a separate workplace, independently of the robot and in the shortest possible time. In some instances, the programming time during which the facility is ineffective may last for days or even weeks. Therefore, reducing set-up time is the primary benefit of using an offline programming system [22]. The programming time in which the facility cannot be used productively may in some cases last days or even weeks. Hence, the primary motivation for utilizing an offline programming system is to minimize the set-up time. Offline programming method systematically combining CAD-based, vision-based, and vision & CAD interactive activities can overcome the limitations of current automatic program generation methods for robotic welding systems [23]. Through programmatic use of CAD, i.e., knowledge-based engineering system (KBE) as a phase in the evolution of CAD leads to possibility of automating the engineering task of marking a weld path, by logically defining weld locations in code. The paths may be extracted and exported for generating robot code for a welding robot [24].

The high cost of the offline programming package and the programming overhead required for software customization for specific applications make it uneconomical to justify offline programming implementation, especially for smaller product values. Furthermore, the development of customized software for offline programming is a time-consuming process that demands high-level programming skills that are often not available from process engineers and operators who typically perform robot programming [25]. Additionally, the hybrid programming method offers efficiency in robotic welding by combining online and offline processes. During the online phase, the method controls the welding path in real-time, memorizing key position points. In the subsequent offline stage, a welding program is generated based on these memorized points, incorporating parameters like welding current and other necessary characteristics. This dual-phase approach significantly reduces programming time and minimizes production losses.

Synchronized programming in robotic welding involves the meticulous coordination of the welding process through the integration of positioners. A typical welding positioner consists of a rotating platform or fixture on which the workpiece is securely mounted. This platform can be rotated, tilted, or both, allowing for precise control over the orientation of the workpiece during welding. In this method, the programming ensures a harmonized movement of both the robotic arm and the positioner, optimizing the welding position for efficiency and quality. Non-synchronized programming, on the other hand, deviates from the use of positioners and relies solely on the robotic arm to execute the welding motion along a predetermined trajectory. The programming involves defining a set path for the robotic arm without the added coordination with a positioner. While non-synchronized programming may be simpler in setup, it may not optimize the welding position to the same extent as synchronized programming.

Different robot manufacturers use different programming languages for their controllers. This lack of standardization means that there is no universal language that all robots use for programming. Due to the diversity in programming languages, achieving standardization across the robotics industry becomes challenging. Many robot programming languages are in use across the industry, making it complex for operators and programmers who need to work with different robots. A procedure that utilizes forward and inverse kinematics, applies to different types of robots and is STEP-NC-compliant, can significantly cut down the time needed for setting up and integrating robots in manufacturing operations [26]. The focus is on improving the efficiency and standardization of the programming and control processes for robotic systems.

4. ROBOTIC WELDING SYSTEM

Since there are many parameters and a limited knowledge of how the process works, today's welding techniques are sophisticated. Users and customers have specific weldment requirements and dynamic work environments. Therefore, welding is moving towards more customized production by leveraging next-generation welding systems capable of intelligently adapting to evolving welding requirements while maintaining high quality [27]. The robotic welding system integrates several key components essential for efficient welding operations. The welding torch serves as the primary tool for generating the welding arc and directing the flow of shielding gas. Supported by a wire feeding mechanism and tray, it ensures a continuous supply of welding wire for seamless operation. Fixtures and positioners provide stability and adjustability to secure and orient the workpiece for precise welding from various angles. The gas cylinder contains shielding gas, crucial for protecting the weld from atmospheric contamination. A water chiller system maintains optimal temperatures, particularly for the welding torch, to prevent overheating during prolonged usage. The power supply provides the necessary electrical energy to sustain the welding arc, while the control unit manages parameters such as arc voltage, wire feed speed, and travel speed to ensure consistent weld quality. Additionally, the teach pendant offers a handheld interface for operators to program and control the robotic welding system with desired accuracy. These components, shown in Figure 2, collectively contribute to the functionality and effectiveness of the robotic welding system.

4.1. *Welding robot characteristics*

In this study 6 DOF industrial robot Panasonic YA-1 TA-1400 was utilized for performing welds. With a repeatable precision of 0.1 mm, the robotic arm ensures accurate and consistent weld placements. Its payload capacity of 6.0 kg and an arm reach of 1374 mm highlight its versatility in handling various welding requirements. The main control unit serves as the system's core, processing data for seamless coordination of the positioner and robotic manipulator. A 2 DOF positioner supports the robotic arm, with a maximum load capacity of 500 kg, along with torque specifications of 1470 Nm and a rotation speed of 16 r/min. The welding torch attached to the end of the robotic arm serves as both a wire transmitter and gas conductor, ensuring stable arcs for producing high-quality welding joints. Furthermore, it is equipped with water cooling to avoid overheating during operation. In Figure 3 detailed dimensions of the 6 DOF manipulator are shown, outlining its physical extents including height, width, and depth, crucial for spatial planning and integration within a given welding station. Additionally, it delineates the manipulator's range of movement, showing its DOF, essential for task feasibility assessment and workspace design. Points P and O within the work envelope denote critical locations where the manipulator can effectively execute tasks important for trajectory planning and operational analysis.

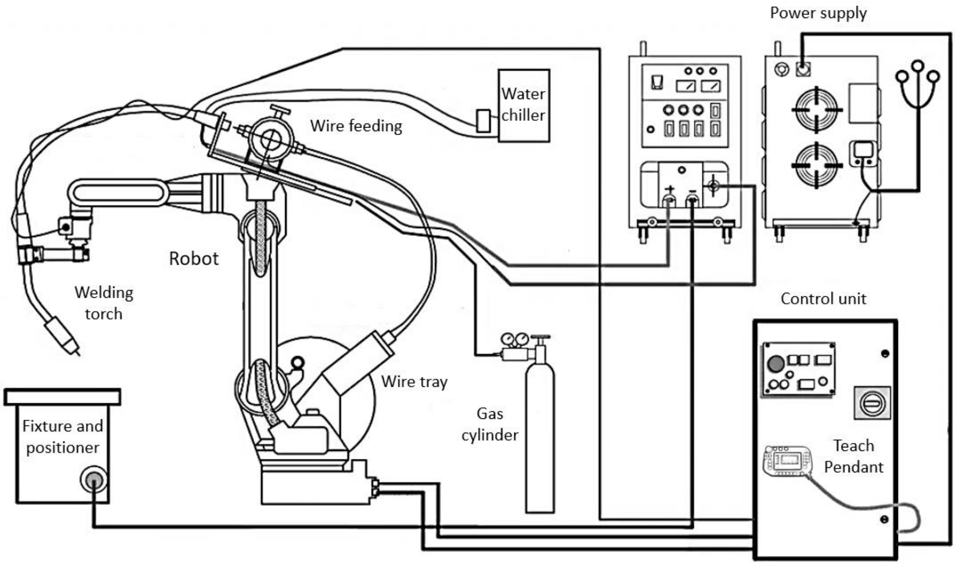
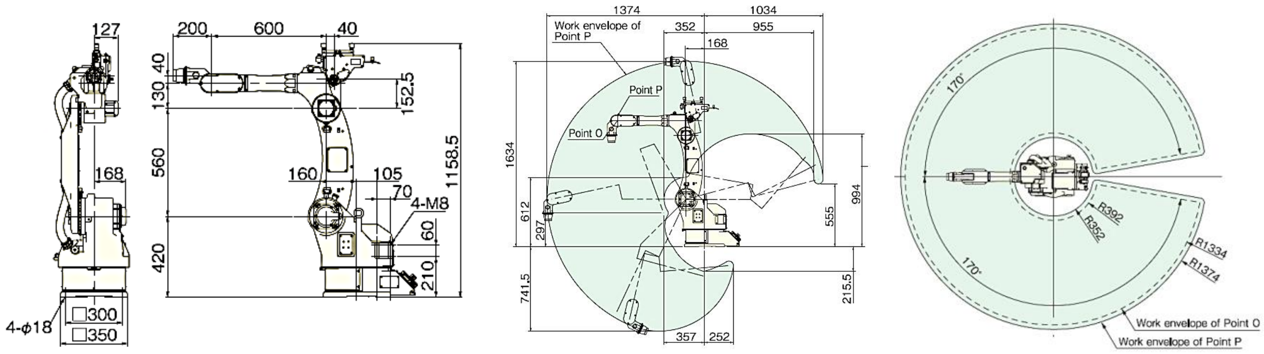


Fig. 2. Scheme of the robot-based welding system



a) b) c)

Fig. 3. 6 DOF manipulator: a) dimensions, b) range of movement, c) work envelope points P and O

4.2. *Robot workspace*

The workspace is determined by the geometry of the manipulator and the limits of the joint motions. It is more specific to define the reachable workspace as the total locus of points at which the end-effector can be placed and the dexterous workspace as the subset of those points at which the end-effector can be placed while having an arbitrary orientation. Dexterous workspaces exist only for certain idealized geometries, so real industrial manipulators with joint motion limit almost never possess dexterous workspaces [28]. As well as reaching the weld, the robot must be able to achieve the torch postures necessary for a quality weld, which means that the sets of joint angles determined by inverse kinematics must be within the robot's range [29].

Depicted as a point cloud, the robot's operational workspace utilized in our study is shown in Figure 4. The method for determining the reachable workspace of a robot includes four steps. It starts by randomly selecting combinations of joint angles for the robot within specified limits, considering physical constraints from welding cell. Each joint angle determines a unique configuration of the robot's arm. Once the joint angles are chosen, forward kinematics is used to calculate the position and orientation of the robot's end-effector in space for each configuration. In the third step, the positions and orientations of the end-effector obtained from forward kinematics are extracted and recorded. These positions represent points in space that the end-effector can reach. Lastly, by repeating this process for a large number of randomly sampled joint angles, the entire reachable workspace of the robot can be comprehensively delineated. To facilitate better visualization, i.e., to clearly observe the robot and positioner with the workpiece, the number of points in this specific view is not maximized. The limitations that arise from both the physical characteristics of the robot itself and the constraints imposed by the fencing in the work cell are noticeable.

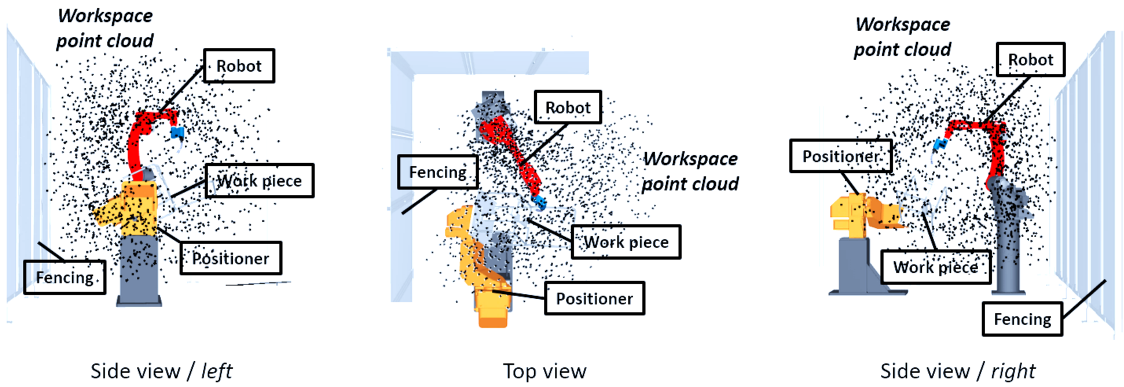


Fig. 4. Workspace point cloud and welding cell

5. ROBOTIC WELDING PROCESS

The robotic welding process can be divided into a few procedures. It begins with preparation which involves determining the welding parameters such as voltage, current, wire feed speed, and shielding gas. Additionally, to program the robotic welding system with the appropriate welding path and parameters. This involves defining the weld joint geometry, specifying the welding sequence, and setting the sensors for vision-based seam tracking. The setup follows, involving the positioning of the workpiece and calibration of the robotic arm for ensuring accurate positioning and alignment with the clamped workpiece. Touch sensing and seam tracking play a crucial role in ensuring accurate alignment of the welding torch before the actual welding process begins. Initiation marks the start of welding as the robotic arm moves to the starting position. During execution, the arm follows the programmed path, depositing filler material and applying heat. Monitoring occurs throughout, ensuring key parameters are maintained and the weld quality is high. Upon completion, the arm returns to its home position, and the finished workpiece can be removed. Post-welding operations may be performed, and maintenance is crucial for optimal system performance. Throughout this process, safety measures are paramount to protect both the robot operator and the equipment. The welding task in our case was welding pipe-pipe joint, and the time key frames are presented in Figure 5. The welding parameters consist of a welding current of 80-85 A, a welding voltage of 14.5–14.8 V, and a welding speed of 10 m/min.

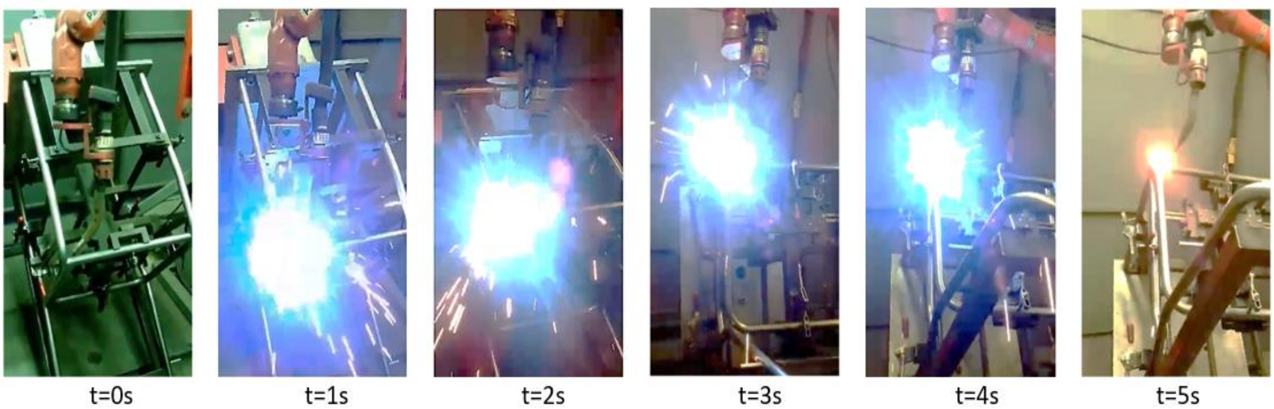


Fig. 5. Welding task key frames

Since this joint is a complex curve, within the frame of the constructive concept of the chair as a workpiece, a synchronized movement of the robotic arm and the positioner was applied. By applying synchronized movement, successful welding was achieved. In Figure 6 the touch sensing and seam tracking, as part of the procedure related to the preparation step, as well as a display of the finished weld, are presented.

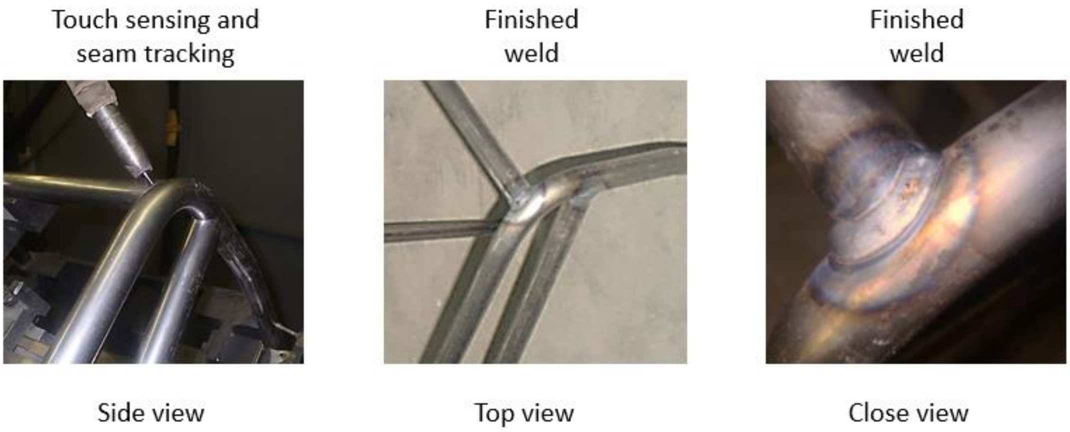


Fig. 6. Touch sensing and finished weld

6. CONCLUSION

The innovation of robot welding has been impressive since the introduction of the first industrial robots, making it a major application for industrial robots. Creating an automated robotic welding system is difficult because of its adaptable nature and requires preparation, welding, and assessment. Developing such a system requires a combination of mechanical and software engineering expertise to ensure the reliable production of high-quality welds in a variety of situations.

The robot must move along the programmed path precisely, maintain proper torch angles, and adjust welding parameters as needed to achieve the desired results. To increase productivity, offline programming is essential as it combines programming and regular robot operation and reducing the setup time for the robotics system. Offline programming allows for better production anticipation, estimation, and minimization of robot cycle times, resulting in more repeatable and compliant welding procedure qualification records. Offline programming also enhances safety by taking place in a comfortable environment away from hazardous workshop conditions.

The presented approach and simulation model are based on a real case of industrial welding process. To complete welding tasks along a space-curved path, a robot and a positioner as an 8-DOF system were used and analyzed. The virtual experiments were used to analyze the robot welding path planning, collision analysis, and reachability of the industrial robot before welding. The simulation environment offered by offline programming aids in refining robot programs and ensuring smooth integration into the production line. Our approach offers to save time and to increase productivity in the welding process, leading to a quick return on investment. Additionally, allows for rapid reconfiguration of robotic welding systems to adapt to changing production requirements, further increasing flexibility and competitiveness.

REFERENCES

[1] Mvola, B., Kah, P., Martikainen, J., Suoranta, R. (2015): State-of-the-art of advanced gas metal arc welding processes: Dissimilar metal welding. Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture* **229** (10), 1694–1710.

[2] Jamal, J., Darras, B., Kishawy, H. (2020): A study on sustainability assessment of welding processes. Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture* **234** (3), 501–512.

[3] Messler Jr, Robert, W. (2008): *Principles of Welding: Processes, Physics, Chemistry, and Metallurgy*. John Wiley & Sons.

[4] Zeidler-Erdely, P. C., Erdely, A., Antonini, J. M. (2012): Immunotoxicology of arc welding fume: Worker and experimental animal studies, *Journal of Immunotoxicology* **9** (4), 411–425.

[5] Lan, H., Zhang, H., Fu, J., Gao, L., Wei, L. (2021): Teaching-free intelligent robotic welding of heterocyclic medium and thick plates based on vision. In: Chen, S., Zhang, Y., Feng, Z. (eds) *Transactions on Intelligent Welding Manufacturing*. Springer.

[6] Chen, S. B., Lv, N. (2014): Research evolution on intelligentized technologies for arc welding process. *Journal of Manufacturing Processes* **16** (1), 109–122.

[7] Hong, T. S., Ghobakhloo, M., Khaksar, W. (2014) 6.04 – Robotic Welding Technology, *Comprehensive Materials Processing*, Saleem Hashmi, Gilmar Ferreira Batalha, Chester J. Van Tyne, Bekir Yilbas (eds). Elsevier, pp. 77–99. ISBN 9780080965338.

[8] Xu, F., Xu, Y., Zhang, H., Chen, S. (2022): Application of sensing technology in intelligent robotic arc welding: A review. *Journal of Manufacturing Processes* **79**, 854–880.

[9] Lin, W., Luo, H. (2015): Robotic Welding. In: Nee, A. (ed.): *Handbook of Manufacturing Engineering and Technology*. Springer, London.

[10] Marcus, M., Harwig, D., Gould, J., Lindamood, L. (eds.) (2024): Welding. In: *Kirk-Othmer Encyclopedia of Chemical Technology*.

[11] Suban, M., Tušek, J. (2001): Dependence of melting rate in MIG/MAG welding on the type of shielding gas used. *Journal of Materials Processing Technology* **119** (1–3), 185–192.

[12] González-González, C., Los Santos-Ortega, J., Fraile-García, E., Ferreiro-Cabello, J. (2023): Environmental and economic analyses of TIG, MIG, MAG and SMAW welding processes. *Metals* **13** (6), 1094.

[13] Weman, K. (2012): MIG/MAG welding. *Welding Processes Handbook*, 75–97, Elsevier.

[14] Sharma, H., Rajput, B., Singh, R. P. (2020): A review paper on effect of input welding process parameters on structure and properties of weld in submerged arc welding process. *Materials Today*: *Proceedings* **26**, 1931–1935.

[15] Mishchenko, A., Caimacan, D., Scotti, A. (2015): Assessment of the use of negative polarity in double-wire MIG/MAG-welding filling passes. *Soldagem & Inspeção* **20**, 48–58.

[16] Kuts, V., Sarkans, M., Otto, T., Tähemaa, T., Bondarenko, Y. (2019, November): Digital twin: concept of hybrid programming for industrial robots – use case. In: *ASME International Mechanical Engineering Congress and Exposition* (Vol. **59384**, p. V02BT02A005). American Society of Mechanical Engineers.

[17] Pan, Z., Polden, J., Larkin, N., Van Duin, S., Norrish, J. (2012): Recent progress on programming methods for industrial robots. *Robotics and Computer-Integrated Manufacturing* **28** (2), 87–94.

[18] Bascetta, L., Ferretti, G., Magnani, G., & Rocco, P. (2013): Walk-through programming for robotic manipulators based on admittance control. *Robotica* **31** (7), 1143–1153.

[19] Deisenroth, M. P., Krishnan, K. K. (1999): On-line programming. In: Nof, S. Y. (ed.): *Handbook of Industrial Robotics*.

[20] Massa, D., Callegari, M., Cristalli, C. (2015): Manual guidance for industrial robot programming. *Industrial Robot: An International Journal* **42**. 457–465.

[21] Yong, Y. F., Bonney, M. C. (1999): Off-line programming. In: Nof, S. Y. (ed.), *Handbook of Industrial Robotics*.

[22] Roos, E., Behrens, A. (1997): Offline programming of industrial robots – Adaptation of simulated user programs to the real environment. *Computers in Industry* **33** (1), 139–150.

[23] Zheng, C., An, Y., Wang, Z., Wu, H., Qin, X., Eynard, B., Zhang, Y. (2022): Hybrid offline programming method for robotic welding systems. *Robotics and Computer-Integrated Manufacturing* **73**, 102238.

[24] Sarah Ann Oxman Prescott, Tuan Anh Tran, Andrei Lobov (2020): Automatic weld path definition in CAD, *Procedia Manufacturing*, Volume **51**, 478–484.

[25] Kah, P., Shrestha, M., Hiltunen, E. et al. (2015): Robotic arc welding sensors and programming in industrial applications. *Int J Mech Mater Eng* **10**, 13.

[26] Sylvia Nathaly Rea Minango, Joao Carlos Espindola Ferreira (2017): Combining the STEP-NC standard and forward and inverse kinematics methods for generating manufacturing tool paths for serial and hybrid robots, *International Journal of Computer Integrated Manufacturing* **30**, 11, 1203–1223.

[27] Wang, B., Hu, S. J., Sun, L., Freiheit, T. (2020): Intelligent welding system technologies: State-of-the-art review and perspectives. *Journal of Manufacturing Systems* **56**, 373–391.

[28] Waldron, K. J., Schmiedeler, J. (2016): Kinematics. In: Siciliano, B., Khatib, O. (eds.), *Springer Handbook of Robotics*. Springer Handbooks. Springer, Cham.

[29] Ryu, Lh., Kim, Tw., Oh, Mj. et al. (2009): Workspace analysis to generate a collision-free torch path for a ship welding robot. *J Mar Sci Technol* **14**, 345–358.

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KINEMATICS ANALYSIS OF 6 DOF INDUSTRIAL MANIPULATOR AND TRAJECTORY PLANNING FOR ROBOTIC WELDING OPERATION

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A b s t r a c t: Robotic manipulators are commonly used in the manufacturing industry for tasks such as assembly, welding, painting, and palletizing. In these applications, precise control over the position and orientation of the robot's end-effector is crucial for efficient and accurate operation. Both inverse and forward kinematics play crucial roles in the design, programming, and operation of industrial robotic manipulators, helping to ensure their effectiveness, efficiency, and safety in various manufacturing environments. In this paper the forward and inverse kinematic model of 6 degrees of freedom (DOF) industrial manipulator are presented. Additionally, the study focuses on analyzing single pass welding across a range of different scenarios. These cases involve welding paths that have different geometric shapes, with a goal to join the materials together and form a closed shape. Maintaining a vertical orientation of the welding torch was achieved, because it is important for realizing uniform heat distribution, consistent weld bead geometry, and better control over the welding process, ultimately contributing to the effectiveness of the robotic welding operation.

Key words: robotic manipulator; forward kinematics; inverse kinematics; welding robot; manufacturing

КИНЕМАТСКА АНАЛИЗА НА ИНДУСТРИСКИ МАНИПУЛАТОР СО 6 СТЕПЕНИ СЛОБОДА НА ДВИЖЕЊЕ И ПЛАНИРАЊЕ НА ТРАЕКТОРИЈА ПРИ ПРОЦЕСОТ НА РОБОТСКО ЗАВАРУВАЊЕ

А п с т р а к т: Индустриските роботски манипулатори обично се користат во производствените процеси со задача да се реализира склопување, заварување, бојадисување и складирање. За вакви примена, прецизната контрола на положбата и ориентацијата на крајниот член на роботот е клучна за ефикасно и прецизно работење. Инверзната и директната кинематика играат клучна улога во дизајнот, програмирањето и работата на индустриските роботи, помагајќи да се обезбеди нивна ефективност, ефикасност и безбедност во различни производствени капацитети. Во овој труд се претставени директна и инверзна кинематика на индустриски манипулатор со 6 степени слобода на движење (DOF). Дополнително, истражувањето се фокусира на заварување со поединечно поминување за различни сценарија. Овие случаи вклучуваат навари, односно траектории со различна геометриска форма, со цел спојување на материјалите и формирање затворени патеки. Одржувањето на вертикалната ориентација на пламенот за заварување беше постигнато, бидејќи тоа е важно за остварување рамномерна дистрибуција на топлината, конзистентна геометрија на заварот и подобра контрола врз процесот на заварување, што на крајот придонесува за ефективноста на процесот на роботско заварување.

Клучни зборови: роботски манипулатор; директна кинематика; инверзна кинематика; роботско заварување; производство

1. INTRODUCTION

The demand for precise positioning and tracking accuracy in industrial robots continues to increase as industries strive for higher efficiency, quality, and safety standards in their manufacturing processes [1]. Correct positioning allows robots to perform tasks more efficiently by minimizing the need for additional adjustments or rework, which improves overall productivity and reduces production time and costs. In industries where robots work alongside human operators, precise positioning helps prevent accidents and injuries [2]. Robots can avoid collisions with other equipment or workers by precisely tracking their movements [3]. Industrial robots are often employed for repetitive tasks where consistency is crucial [4]. Precise robot controlling ensures that each cycle of the operation is performed identically, leading to uniformity in output [5, 6]. As automation technologies advance, the integration of robots with other automated systems becomes more common [7], therefore seamless coordination between different robotic and machinery components within an automated workflow is necessity. In manufacturing processes such as welding and assembly, even minor deviations in positioning can lead to defects in the final product [8]. Robotic welding needs to ensure that components are joined correctly and that tolerances are met, resulting in higher quality products. Moreover, in fields such as robotics-assisted surgery [9] or high-precision manufacturing [10], where even slight errors can have significant consequences, ultra-precise positioning is imperative. This ensures that delicate operations are performed accurately and safely.

Robot kinematics determines how accurately the robot can move its joints to reach a desired position and orientation in its workspace. By understanding the kinematics of the robot, engineers can calculate the required joint angles or end-effector positions to achieve the given desired task [11]. Kinematics plays a role in optimizing the robot's motion to accomplish tasks efficiently. Through kinematic analysis and optimization, engineers can minimize the time and energy required [12] for the robot to move between different positions, leading to improved productivity. Kinematics is essential for ensuring that the robot's movements are within safe limits. By understanding the kinematic constraints of the robot, the motion trajectories that avoid collisions with obstacles or other machinery in the workspace can be designed and programed, contributing to enhance safety for human operators and equipment. Furthermore, by precisely controlling the robot's joint motions for consistent performance of repetitive tasks, the variations in task execution can be minimized that leads towards greater consistency in product quality. Kinematics is fundamental for coordinating the motions of multiple robots or robotic systems within an automated manufacturing environment [13]. By understanding the kinematic relationships between different robotic components, engineers can synchronize their motions to achieve seamless operation. Robot kinematics is central to achieving precise positioning, efficient motion, and safe operation of industrial robots across a wide range of applications. It provides the foundation to design and control robotic systems that meet the demanding requirements of modern manufacturing environments.

In robotics, the inverse kinematics problem involves finding the joint configurations or angles of a robotic manipulator to achieve a desired position and orientation of its end-effector. Conversely, the forward kinematics problem involves determining the end-effector pose based on the joint variables. Solving the inverse kinematics problem is essential in robotics, particularly in fields such as robot kinematics, motion planning, and control theory. Different approaches can be used to solve this problem, and each has its own strengths and weaknesses. Numerical methods use iterative techniques to approximate solutions. They are more versatile and can handle a wider range of manipulators and end-effector poses. However, they tend to have higher computational costs, longer execution times, and may encounter issues such as local minima and numerical errors. The most common approach is Jacobian-based methods [14], which use the Jacobian matrix to iteratively update joint configurations until a desired end-effector pose is reached. Closed-form methods provide solutions in explicit mathematical forms, often based on the geometry of the robotic manipulator. They have advantages such as lower computational cost and faster execution time compared to numerical methods. However, they may not be applicable to all types of manipulators and end-effector poses. These methods include strategies based on matrix manipulations, arm angle parameter definitions, and geometric methods [15] or soft computing approaches [16].

In the manufacturing industry, robotic arc welding has grown in popularity because it provides a fast return on investment, increases productivity and weld quality, reduces production costs, and saves time. Numerous industries have found success with robotic welding due to its advanced features, which include welding process control, workpiece handling, sensors, and programming. Welding processes are the most popular joining techniques in today's industry. It is used for joining metal materials permanently, with or without the additional material by using heat and, or pressure. It is also thought to be the most economical technique in terms of material use and fabrication, producing a welded joint that is homogenous and stronger than the parent metal. These benefits make this process perfect for the production and restoration of structures across various industries, including but not limited to automotive, construction, agriculture, food processing, marine and offshore, power generation, and aerospace [17, 18].

In the following, Section 2 is dedicated to robot kinematics, including both forward and inverse kinematics. Effective trajectory planning for industrial robot welding operations plays a crucial role in optimizing productivity, ensuring quality welds, and maintaining a safe working environment. Hence, in Section 3 modeling and simulation are included, considering manipulator characteristics and defining different welding cases. In these instances, welding is utilized to connect materials along various geometric paths, with the objective of creating a unified closed shape. Section 4 presents the results and analysis, followed by Section 5 that refers to the conclusions.

2. ROBOT KINEMATICS

For modeling robotic manipulators, the Denavit-Hartenberg (DH) method provides a systematic way to describe the geometry and kinematics of a manipulator. Frames are assigned to each joint of the manipulator, starting from the base frame and progressing towards the end-effector frame. The DH parameters used in this method include: θ_i as joint angle about the Z_{i-1} axis; α_i as angle of rotation about the X_{i-1} axis; d_i as the length of the link along the Z_{i-1} axis; and a_i as distance between the Z_{i-1} and Z_i axes, measured along the X_{i-1} axis [19]. Figure 1 shows intermediate links in the chain.

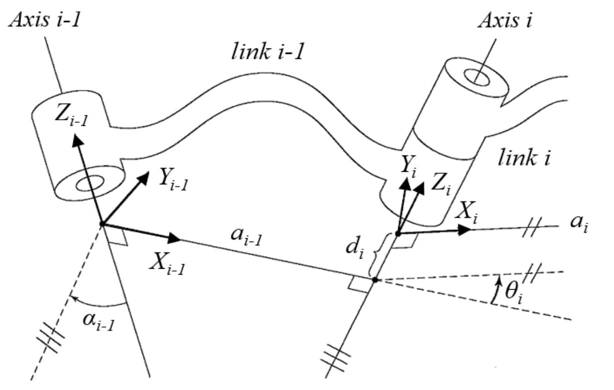

Fig. 1. Link frames

The Z-axis of frame {i}, called Z_i, is coincident with the joint axis i. The origin of frame {i} is located where the a_i perpendicular intersects the joint axis i. X_i points along a_i in the direction from joint i to joint i+1. In the case of $a_i = 0$, X_i is normal to the plane of Z_i and Z_{i+1}. As being measured in the right-hand sense about X_i, the α_i is defined and the freedom of choosing the sign of α_i in this case corresponds to two choices for the direction of X_i. Also, Y_i is formed by the right-hand rule to complete the i-th frame [20]. These DH parameters are essential for defining the transformation between adjacent frames in the manipulator. By appropriately choosing and assigning these parameters, the kinematics of the manipulator can be accurately represented, allowing for control and trajectory planning. In DH parameterization, each joint of the robotic manipulator is assigned a sequential number starting from 1 to n, where 1 represents the first joint nearest to the base and n represents the last joint of the manipulator, which is typically located at the end-effector. The robotic manipulator with 6 rotational axes is presented in Figure 2.

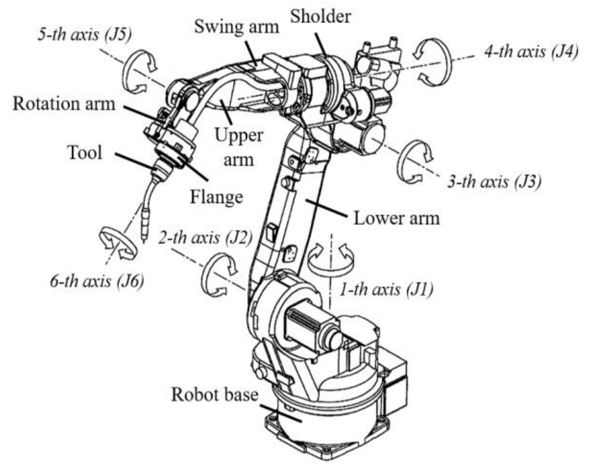

Fig. 2. Industrial robot with 6 rotational axes

2.1. *Forward kinematics*

Forward kinematics as one of the fundamental concepts in robotics deals with the determination of the position and the orientation of the end-effector, the tool or end point of a robotic arm given the joint variables, such as angles of its individual joints and the link length. To achieve forward kinematics, one typically defines a series of homogeneous transformation matrices for each joint of the robot. These matrices describe the transformation from one coordinate system to another as the robot moves through its various joint configurations. By combining these transformations, the position and orientation of the end-effector relative to a fixed reference frame can be calculated.

The position and orientation of the tool frame in relation to the base frame are determined by combining the transformations (both translation and rotation) between each intermediate frame and the base frame using homogeneous transformation matrices. Each intermediate frame provides information about how much the robot has translated and rotated from the base frame. By combining these transformations using homogeneous transformation matrices, we can accurately determine the position and alignment of the tool frame relative to the base frame.

These matrices are typically 4×4 matrices T_i^{i-1} $(i = 1,..6)$:

$$T_i^{i-1} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The process of calculating the position and orientation of the tool frame in relation to the base frame involves multiplying the homogeneous transformation matrices of each intermediate frame with respect to the base frame. This multiplication effectively combines the translation and rotation information from each frame to determine the overall position and orientation of the tool frame.

$$T_6^0 = T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \quad (2)$$

$$T_6^0 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The rotation matrix *R* (3 × 3) is formed by the first three columns with notation *r*, and the translation vector *T* (3 × 1) is represented by the elements in the last column, with notation *t*. The submatrix *R* represents the rotation, while *T* is the translation part of the homogeneous transformation matrices.

2.2. *Inverse kinematics*

Finding the position and orientation of the end-effector given the joint angles of the robot, i.e., calculating how the robot's joints move the end-effector in space is a task for forward kinematics. On the other hand, finding the joint angles required to place the end-effector at a specific position and orientation in space is a task related to inverse kinematics. Robots typically operate in joint space, where movements are defined by the angles of the robot's joints. However, tasks are often specified in Cartesian space, where positions and orientations are described in terms of coordinates and orientation matrices. Converting from Cartesian space to joint space involves solving the inverse kinematics problem. This requires finding the joint angles that achieve the desired end-effector position and orientation [21].

The general problem of inverse kinematics can be stated via the desired position and orientation of the end-effector T_d and 4 × 4 homogeneous transformations [22], namely, to find (one or all) solutions of the equation:

$$T_n^0(q_1, \dots q_n) = T_d \quad (4)$$

Among the most challenging issues in robotics is inverse kinematics. The task is to find the values for the joint variables $q_1, \dots q_n$ that satisfied the equation. Because each link in the robotic manipulator has a transformation matrix that describes how it moves relative to the previous link or the robot's base, by taking the inverses of these transformation matrices and premultiplying them [23, 24], it can be combine the effects of each link's movement to find the joint angles required to achieve the desired end-effector pose. Consequently, for:

$$[T_1^0(\theta_1)]^{-1} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = [T_1^0]^{-1}\, T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \quad (5)$$

$$\begin{bmatrix} c_1 & s_1 & 0 & 0 \\ -s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \quad (6)$$

it follows:

$$\theta_1 = \text{atan2}(t_y, t_x) - \text{atan2}(-s_1 t_x + c_1 t_y, \pm\sqrt{t_x^2 + t_y^2 + (-s_1 t_x + c_1 t_y)^2}) \tag{7}$$

$$(\theta_3 = \text{atan2}(a_3, d_4) - \text{atan2}(K, \pm\sqrt{a_3^2 + d_4^2 - K^2}) \tag{8}$$

where simplify notations are c_i for $\cos(\theta_i)$, and s_i for $\sin(\theta_i)$, and

$$K = [t_x^2 + t_y^2 + t_x^2 - a_2^2 - a_3^2 (-s_1 t_x + c_1 t_y)^2 - d_4^2] / 2a_2 \tag{9}$$

Taking into consideration that:

$$[T_3^0(\theta_2)]^{-1} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = [T_1^0\, T_2^1\, T_3^2]^{-1}\, T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \tag{10}$$

$$\begin{bmatrix} c_1 c_{23} & s_1 c_{23} & -s_{23} & -a_2 c_3 \\ -c_1 s_{23} & -s_1 s_{23} & -c_{23} & a_2 s_3 \\ -s_1 & c_1 & 0 & -d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_4^3(\theta_4)\, T_5^4(\theta_5)\, T_6^5(\theta_6) \tag{11}$$

it follows:

$$\theta_2 = \text{atan2}[(-a_3 - a_2 c_3) t_z - (c_1 t_x + s_1 t_y)(d_4 - a_2 s_3), (a_2 s_3 - d_4) t_z - (a_3 + a_2 c_3)(c_1 t_x + s_1 t_y)] - \theta_3 \tag{12}$$

$$\theta_4 = \text{atan2}(-r_{13} s_1 + r_{23} c_1, - r_{13} c_1 c_{23} - r_{23} s_1 c_{23} + r_{33} s_{23}), \tag{13}$$

where simplify notations are c_{ij} for $\cos(\theta_i + \theta_j)$, and s_{ij} for $\sin(\theta_i + \theta_j)$. If $\theta_5 = 0$, the joint axes 4 and 6 line up and cause the same motion of the last link of the robot, it means that the manipulator is in a singular configuration. Furthermore, considering that:

$$[T_4^0(\theta_4)]^{-1} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = [T_1^0\, T_2^1\, T_3^2\, T_4^3]^{-1}\, T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \tag{14}$$

$$\begin{bmatrix} c_1 c_{23} c_4 + s_1 s_4 & s_1 c_{23} c_4 - c_1 s_4 & -s_{23} c_4 & -a_2 c_3 c_4 + d_3 s_4 - a_3 c_4 \\ -c_1 c_{23} s_4 + s_1 c_4 & -s_1 c_{23} s_4 - c_1 c_4 & s_{23} s_4 & a_2 c_3 s_4 + d_3 c_4 + a_3 s_4 \\ -c_1 s_{23} & -s_1 s_{23} & -c_{23} & a_2 s_3 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_5^4(\theta_5)\, T_6^5(\theta_6) \tag{15}$$

it follows:

$$\begin{aligned} \theta_5 = \text{atan2}[&- r_{13}(c_1 c_{23} c_4 + s_1 s_4) - r_{23}(s_1 c_{23} c_4 - c_1 s_4) + r_{33}(s_{23} c_4), \\ & r_{13}(- c_1 s_{23}) + r_{23}(- s_1 s_{23}) + r_{33}(- c_{23})] \end{aligned} \tag{16}$$

At last, since:

$$[T_5^0]^{-1} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = [T_1^0\, T_2^1\, T_3^2\, T_4^3]^{-1}\, T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 = T_6^5(\theta_6) \tag{17}$$

The following angle is obtained:

$$\begin{aligned} \theta_6 = \text{atan2}[& -r_{11}(c_1 c_{23} s_4 + s_1 c_4) - r_{21}(s_1 c_{23} s_4 + c_1 c_4) = \\ & = +r_{31}(s_{23} s_4), r_{11}[(c_1 c_{23} c_4 + s_1 s_4) c_5 - c_1 s_{23} s_5] + \\ & + r_{21}[(s_1 c_{23} c_4 - c_1 s_4) c_5 - s_1 s_{23} s_5] - r_{31}(s_{23} c_4 c_5 + c_{23} s_5)] \end{aligned} \tag{18}$$

In this manner, solving the inverse kinematics of the 6 DOF manipulator needs addressing twelve sets of nonlinear equations. The primary unknown is θ_1 that appears on the left side of the equation (5). Furthermore, the twelve nonlinear matrix elements on the right side of the equation can be either zero, constant, or functions of θ_2 through θ_6. Therefore, by equating the elements on both sides of the equation, the joint variable θ_1 is solved as functions of $r_{11}, r_{12}, \ldots, r_{33}, t_x, t_y, t_z$, and fixed link parameters. Once θ_1 is determined, subsequently the remaining joint variables can be solved using this procedure.

3. TRAJECTORY PLANNING

3.1. *Modeling and simulation*

Modeling and simulation play crucial roles in industrial robot path planning by providing a structured approach to designing and optimizing motion trajectories in complex environments. Through describing the physical structure of the robot and developing mathematical equations that describe the relationship between the joint angles and the position and orientation of the end-effector in space, these models provide a simplified yet accurate description of the robot's capabilities, allowing to understand how it will move and interact with its environment. The process begins with importing a CAD model of the robot into the software environment. This model includes the geometrical and mechanical information about the robot, such as its links, joints, and end-effector. It is followed by configuring the virtual environment within the software by setting up the workspace, defining any obstacles or constraints, and specifying the task requirements. Establishing the kinematic model of the robot in this kind of environment includes defining the joint types, ranges of motion, and kinematic constraints based on the physical characteristics of a real robot. When these steps are complete, programing the desired tasks with motions that the robot needs to perform can be done. This could involve defining trajectories, and sequences of movements in the direction of accomplishing specific objectives. The key features of the simulation approach are its ability to demonstrate the robot's movements within the virtual environment and to visualize how the robot will execute the programmed tasks, identify potential issues, and refine the robot's movements as needed. Analyzing the simulation can result in verification of the programmed tasks, meeting the desired criteria and performance objectives, optimizing the efficiency, accuracy, and safety.

3.2. *Robotic manipulator characteristics*

Robotic systems possess diverse characteristics, encompassing factors such as robot size, its load capacity and range of motion, which are governed by joint limits that define the allowable range of motion for each articulated joint. As discussed previously, their kinematics are further described by DH parameters, crucial for precise trajectory planning and control. Table 1 represents the characteristics of the 6 DOF manipulator used for this study, related to parameters α, a, d, and the corresponding six joint limits.

T a b l e 1

6 DOF manipulator characteristics

i	α_i *d* (degree)	a_i (mm)	d_i (mm)	Joint limits (degree)
1	–90	160	430	–60 / 60
2	180	580	0	0 / 90
3	90	125	0	–80 / 80
4	–90	0	239	–180 / 180
5	90	0	0	–80 / 80
6	0	0	411	–270 / 270

3.3. *Weld seam trajectories*

Single-pass welding involves making a single weld pass to fill the joint, while multi-pass welding involves making multiple passes to fill larger or deeper joints. The choice between single and multi-pass welding depends on factors such as the thickness of the material and the desired strength of the weld. In this study we consider the single pass welding in 3 different cases, as shown in Figure 3. These cases involve welding paths that have different geometric shapes, with a goal to join the materials together and form a closed shape. The welding torch moves along the edges of a triangle, rectangle and curved edge of a semicircle, i.e., creating welding seams along straight and curved paths. Case 1 has one path length of 243 mm and two of 172 mm. Case 2 has four straight lines, each with a length of 120 mm, and Case 3 has one straight line with a length of 243 mm and a curved path of 382 mm. The starting and ending positions of the welding torch are 10 mm above the *xy*-plane, and each case has its own starting and ending position. The positions of the robot base and the work bench do not change during the execution of these three cases.

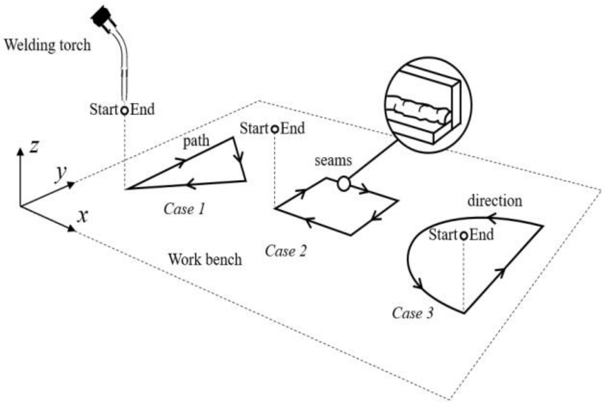

Fig. 3. Welding seams trajectories

4. RESULTS AND ANALYSIS

The results obtained from these three setups, i.e. for the different welding paths and robot movements, are presented in Figures 4, 5 and 6. It is notable the changes in the angles of each of the 6 joints during the realization of the sated goals, which is to pass the entire path to form a closed trajectory, i.e., welding seams. The change in angles is obvious for each of the 6 joints, but it is smooth and without sudden variations, and it is within the set joint limit values. The biggest change in the angles is observed for case 3, where in addition to moving in a straight line, moving along a path in the form of a semicircle is also needed. When movement along a curve is performed, it is observed that there are greater changes in the angles of joints 4 and 6 compared to other joints. This is due to the fact that these are robot joints associated with rotating the welding torch attached to the robot, while keeping it constantly in a vertical direction for the purpose of effective welding. The vertical dashed lines separate the time when the robot performs welding and moving along the given trajectory. The time intervals on the left and far right refer to the robot approaching and retracting, moving towards and away from the workpiece, respectively. Therefore, the change of the angles when the robot begins to move from the marked start point to the point where the welding is, also when it has reached the last point of the path and retracting from the work piece to the point marked as the end, is presented. The angles of the robot's joints evolve during the entire process, from initial movement to welding, welding itself and to retraction, reflecting the dynamic nature of robotic motion in industrial applications.

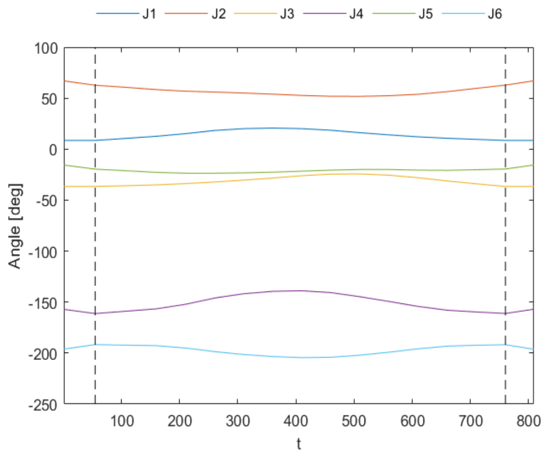

Fig. 4. Joint angles case 1

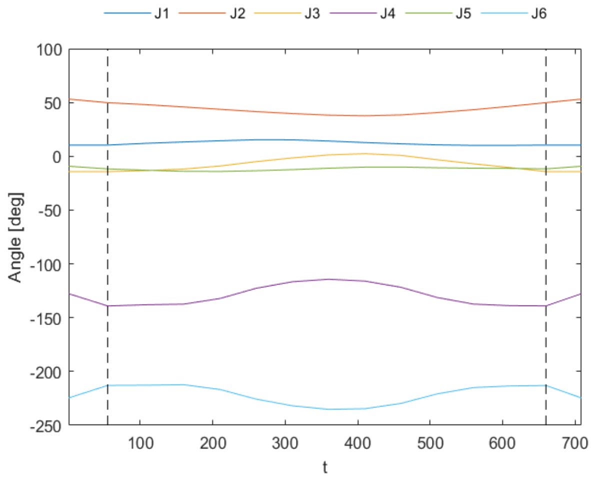

Fig. 5. Joint angles case 2

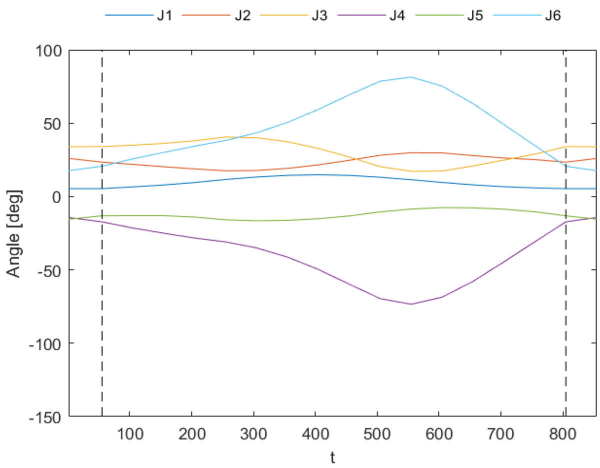

Fig. 6. Joint angles case 3

5. CONCLUSIONS

Comprehensive understanding of the kinematics of an industrial manipulator is important for accurate controlling its movements, programing it to perform various tasks, to optimize its performance, and for ensuring safe operation in industrial environments. Each joint of the manipulator can be rotated to different angles, allowing the end-effector to reach various positions and orientations in the workspace. Forward kinematics involves determining the position and orientation of the end-effector given the joint angles, using mathematical models, often based on transformation matrices or DH parameters. On the other hand, inverse kinematics deals with determining the joint angles required to achieve a desired position and orientation of the end-effector. Solving inverse kinematics problems can be more complex and time-consuming considering manipulators with more degrees of freedom. As the number of degrees of freedom increases, the number of equations needed to solve the inverse kinematics problem also increases. This leads to more complex mathematical relationships between the joint angles or positions and the desired end-effector pose.

In our study we considered 3 cases related to 3 different welding operations where materials are joined together along different specific paths to create a unified, closed shape. This could be a necessary step in various manufacturing processes, such as fabricating metal components for machinery, or building structural frameworks. When the 6 DOF manipulator is used to move the welding torch along a curve path, is observed that there are greater changes in the value of the angles of joints 4 and 6. More significant changes in their angles compared to other joints during the movement along the curve occur because they are joints associated with the rotation of the welding torch attached to the robot. For the purpose of effective welding, the aim of keeping the tool oriented vertically as much as possible during the welding process was achieved. This vertical orientation is crucial for ensuring proper weld penetration and quality. The adoption of robotic arc welding in the manufacturing industry offers numerous benefits, including cost savings, improved productivity, enhanced weld quality, and shorter lead times, making it an attractive investment for many companies. Besides increasing the efficiency, repeatability, and precision, the manufacturers can consistently produce high-quality welds across a wide range of products and materials.

REFERENCES

[1] Gao, G., Sun, G., Na, J., Guo, Y., & Wu, X. (2018): Structural parameter identification for 6 DOF industrial robots. *Mechanical Systems and Signal Processing* **113**, 145–155.

[2] Robla-Gómez, S., Becerra, V. M., Llata, J. R., Gonzalez-Sarabia, E., Torre-Ferrero, C., Perez-Oria, J. (2017): Working together: A review on safe human-robot collaboration in industrial environments. *Ieee Access* **5**, 26754–26773.

[3] Haddadin, S., De Luca, A., Albu-Schäffer, A. (2017): Robot collisions: A survey on detection, isolation, and identification. *IEEE Transactions on Robotics* **33** (6), 1292–1312.

[4] Appleton, E., Williams, D. J. (2012): *Industrial Robot Applications*. Springer Science & Business Media.

[5] Bilancia, P., Schmidt, J., Raffaeli, R., Peruzzini, M., Pellicciari, M. (2023): An overview of industrial robots control and programming approaches. *Applied Sciences* **13** (4), 2582.

[6] Rawat, D., Gupta, M. K., Sharma, A. (2023): Intelligent control of robotic manipulators: a comprehensive review. *Spatial Information Research* **31** (3), 345–357.

[7] Bock, T. (2015): The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction* **59**, 113–121.

[8] Söderberg, R., Wärmefjord, K., Lindkvist, L., Berlin, R. (2012): The influence of spot weld position variation on geometrical quality. *CIRP Annals* **61** (1), 13–16.

[9] Biswas, P., Sikander, S., Kulkarni, P. (2023): Recent advances in robot-assisted surgical systems. *Biomedical Engineering Advances*, 100109.

[10] Avram, O., Valente, A. (2016): Trajectory planning for reconfigurable industrial robots designed to operate in a high precision manufacturing industry. *Procedia CIRp* **57**, 461–466.

[11] Yang, C., Ma, H., Fu, M. (2016): Robot kinematics and dynamics modeling. In: *Advanced Technologies in Modern Robotic Applications*. Springer, Singapore.

[12] Gadaleta, M., Pellicciari, M., Berselli, G. (2019): Optimization of the energy consumption of industrial robots for automatic code generation. *Robotics and Computer-Integrated Manufacturing* **57**, 452–464.

[13] Gogouvitis, X. V., Vosniakos, G. C. (2015): Construction of a virtual reality environment for robotic manufacturing cells. *International Journal of Computer Applications in Technology* **51** (3), 173–184.

[14] Park, S. O., Lee, M. C., Kim, J. (2020): Trajectory planning with collision avoidance for redundant robots using jacobian and artificial potential field-based real-time inverse kinematics. *International Journal of Control, Automation and Systems* **18** (8), 2095–2107.

[15] Zaplana, I., Hadfield, H., Lasenby, J. (2022): Closed-form solutions for the inverse kinematics of serial robots using conformal geometric algebra. *Mechanism and Machine Theory* **173**, 104835.

[16] El-Sherbiny, A., Elhosseini, M. A., Haikal, A. Y. (2018): A comparative study of soft computing methods to solve

inverse kinematics problem. *Ain Shams Engineering Journal* **9** (4), 2535–2548.

[17] Lin, W., Luo, H. (2014): Robotic welding. In: Nee, A. (ed.), *Handbook of Manufacturing Engineering and Technology*. Springer, London.

[18] Hong, T. S., Ghobakhloo, M., Khaksar, W. (2014): 6.04 – Robotic welding technology. In: *Comprehensive Materials Processing*, Elsevier, pp. 77–99.

[19] Garnayak, O. P., Soumyaranjan, S., Choudhury, B. B. (2020): Kinematics analysis of a 6-DOF industrial robot. In: Nayak, J., Balas, V., Favorskaya, M., Choudhury, B., Rao, S., Naik, B. (eds.), *Applications of Robotics in Industry Using Advanced Mechanisms. ARIAM 2019*. *Learning and Analytics in Intelligent Systems*, Vol **5**. Springer, Cham.

[20] Kucuk, S., Bingul, Z. (2010): An off-line robot simulation toolbox. *Computer Applications in Engineering Education* **18** (1), 41–52.

[21] Craig, J. J. (2006): *Introduction to Robotics*. Pearson Educacion.

[22] Spong, M. W., Hutchinson, S., Vidyasagar, M. (2020): *Robot Modeling and Control*. John Wiley & Sons.

[23] Kucuk, S., Bingul, Z. (2014): Inverse kinematics solutions for industrial robot manipulators with offset wrists. *Applied Mathematical Modelling* **38** (7–8), 1983–1999.

[24] Zhang, L., Zuo, J., Zhang, X., Yao, X., Shuai, L. (2015): A new approach to inverse kinematic solution for a partially decoupled robot. In: *2015 International Conference on Control, Automation and Robotics* (pp. 55–59). IEEE.

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Original scientific paper

NEEDS ASSESSMENT OF AMBIENT CO_2 MONITORING SOLUTION

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A b s t r a c t: Monitoring exhaled CO_2 levels in indoor working spaces is crucial for maintaining employees' quality of performance. Hence, preventing excessive levels of exhaled CO_2 in any working environment is a key factor relevant for increased cognitive capacity, decreased occurrence of headaches, sleepiness, etc. This paper addresses the need for CO_2 monitoring by proposing a novel design of a CO_2 monitoring solution, consisting of a device and an appropriate client-oriented data acquisition and presentation software platform. A Needs Assessment is performed to examine the necessity of such a solution on the market. The outcomes of the performed Needs Assessment show that commercial products using WiFi, 4G, standalone with rechargeable battery power supply, and comparable available technologies are missing on the market. Due to the fact that exhaled CO_2 concentration acts as an indicator for diseases such as COVID-19, tuberculosis, influenza, SARS, etc., from the perspective of the challenges posed by the COVID-19 pandemic, the novel CO_2 monitoring solution can effectively be used for indicative risk prevention of airborne infectious diseases.

Key words: monitoring ambient CO_2; needs assessment; risk prevention; monitoring device

ПРОЦЕНА НА ПОТРЕБИТЕ ОД РЕШЕНИЕ НА СЛЕДЕЊЕ НА АМБИЕНТАЛНИОТ CO_2

А п с т р а к т: Следењето на нивото на амбиенталниот издишан CO_2 во работни простории е од клучно значење за одржување на квалитетот на работниот учинок кај вработените. Оттука, спречувањето на прекумерно ниво на издишан CO_2 во која било работна средина е клучен фактор релевантен за зголемен капацитет на когнитивните способности, намалена појава на главоболки, поспаност итн. Овој труд ја посочува потребата од следење на CO_2 преку ново решение за мониторинг на CO_2, кое се состои од уред и соодветна клиентски ориентирана софтверска платформа за аквизиција и приказ на податоци. За таа цел е спроведена процена на потребите од такво решение на пазарот. Резултатите од процената на потребите покажуваат дека на пазарот недостигаат комерцијални производи кои користат технологии споредливи со WiFi, 4G, а се напојувани преку батерија со репетитивно полнење. Имајќи превид дека концентрацијата на амбиенталниот издишан CO_2 може да служи како прокси индикатор за заболувања како што се КОВИД-19 (COVID-19), туберкулоза, грип, САРС итн., а навраќајќи се на предизвиците што ги донесе пандемијата КОВИД-19, новото решение за следење на CO_2 може ефикасно да се користи за индикативна превенција на ризици од заразни болести кои се пренесуваат преку воздухот.

Клучни зборови: следење на амбиенталниот CO_2; процена на потребите; превенција на ризик; уред за следење

1. INTRODUCTION

Indoor air quality, in particular, levels of exhaled CO_2, is one of the key factors influencing the quality of working performance, not only related to general physical activity, but specifically, related to cognitive and intellectual activities. In that sense, addressing the challenges to maintain the quality of indoor air is in compliance with:

(1) the health and safety requirements of any working environment, including their standardization via e.g. standards from the family of ISO 16000, Indoor air quality [1–3]; ISO 45001:2018, Occupational health and safety management systems [4];

thus, preventing risks from injuries, low cognitive performance and mental concentration caused by increased CO_2 levels therein;

(2) the related national and/or international environmental protection legislation, including other requirements;

(3) the synergy between energy efficiency and energy management and corresponding national and/or international legal or other requirements and standardization via, e.g., the Energy Efficiency Directive (*EU acquis communautaire*) (EU/2023/1791) [5] and ISO 50001:2018 [6];

(4) the overarching sustainable development paradigm [7], via direct or indirect compliance with the following Sustainable Development Goals (SDGs): SDG3 (good health and wellbeing), SDG7 (affordable and clean energy), SDG8 (decent work and economic growth), SDG12 (responsible consumption and production), SDG13 (climate action), and SDG17 (partnership for the goals).

In line with the aforestated, the focus of this paper sets on the assessment of the needs that led to offering a novel solution for monitoring exhaled ambient CO_2 concentrations (levels) on the market, which consists of a device and a software platform. This solution is applicable for various working environments, where intellectual and cognitive activities are being delivered/performed.

2. METHODOLOGY

The process of delivering a new product on the market, *inter alia*, requires a thorough market analysis including a comprehensive and profound assessment of needs (incl. gaps) for such a product from all relevant perspectives, whereby the proposed product is identified as the bridge between the identified gaps and the solution that firmly addresses those gaps.

As per Watkins, West Meiers, Visser (2012) [8], needs assessment is a tool that facilitates delivering better decisions, thereby encompassing identifying the problems, and weighing the alternative solutions in order to deliver informed decisions about which actions (parts of the solutions) must be performed first. E.g., it may incorporate selecting an appropriate product for the market, defining and prioritizing critical aspects (incl. gaps in results/ solutions [9]) of that product for the market, delivering an informed decision relating to that particular product, defining the steps necessary to deliver that particular decision from the perspective of what is the status of the problem in the presence, and in turn, what is planned to be achieved in the future, etc.

The needs assessment protocol utilized in this paper combines the Japan International Cooperation Agency (JICA) [10] and the Australian Institute of Family Studies (AIFS) [11] recommendations. The protocol based on the methodology is presented on Figure 1, whilst Table 1 matches the steps with the corresponding indicators' sets deriving thereby.

Table 1

Needs assessment methodology [8, 10, 11] combined with the corresponding indicators' sets

Step #	Action	Corresponding indicators' set
1st:	Identifying the problem and needs	IPN
2nd:	Determining the design of the needs assessment	A
3rd:	Collecting the necessary data	CD
4th:	Analyzing the collected data	AD
5th:	Providing feedback and proposing adequate solution	AS

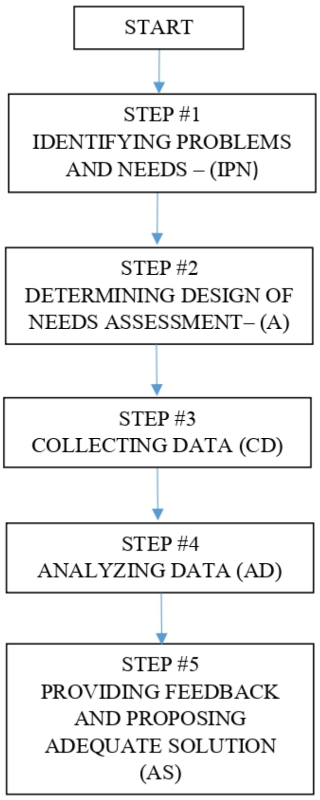

Fig. 1. Needs assessment protocol [8, 10, 11]

3. EXPERIMENTAL CASE STUDY:
Solution for monitoring ambient CO_2 concentrations – DamaLUFT

Conforming to the 5 steps needs assessment protocol presented in Section 2, this Section focuses on elaborating the performed assessement of needs in relation to monitoring ambient CO_2 concentrations, including the already existing solutions [12, 13], thus to provide a clear distinction among those and the novel approach of the solution proposed therein, which in turn, addresses the identified gaps. The implemented protocol explained in the following subsections is concisely presented on Figure 2.

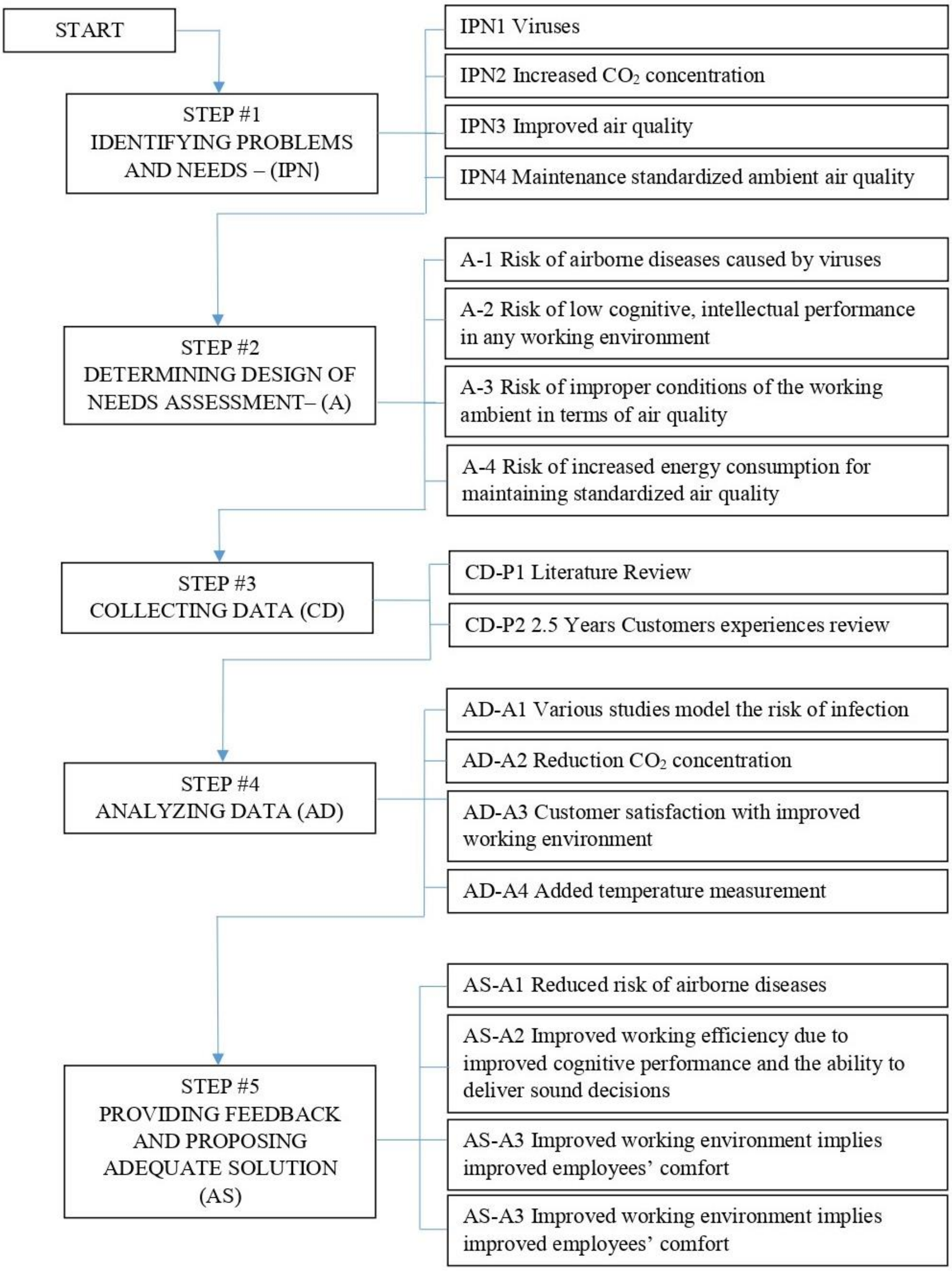

Fig. 2. Needs assessment procedure implemented for the experimental case study. Solution for monitoring ambient CO_2 concentrations – DamaLUFT

3.1. *Step 1: Identifying problems and needs (IPN).*

IPN-1. Due to the fact that viruses (such as COVID-19, influenza, etc.) are spread via respiratory droplets – aerosols in the air exhaled by those present in the room [14] (Figure 3), higher ambient CO_2 concentrations may act as a proxy indicator for increased incidence of such airborne diseases [15].

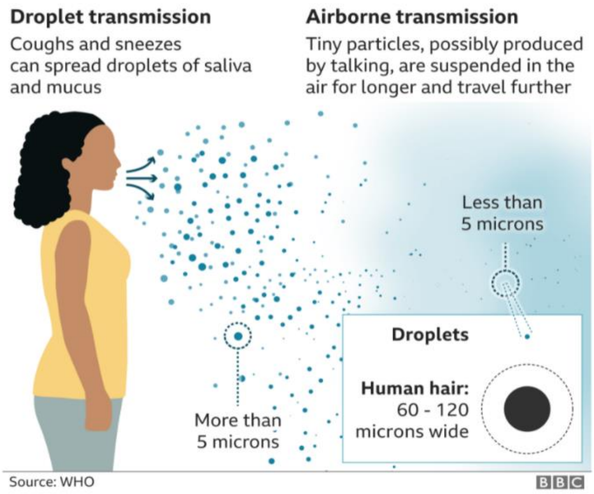

Fig. 3. Difference between droplet and airborne transmision (Source: BBC https://www.bbc.com/news/health-54435240) [17]

IPN-2. Increased/high CO_2 concentrations in working environments imply reduced working efficiency, poorer cognitive performance and decreased ability to deliver sound decisions. Namely, in their study, Wargocki et al. (2020) [16] estimated that reducing CO_2 concentration from 2100 ppm to 900 ppm improves students' scores on psychological tests and school assignments by 12% in terms of the speed at which tasks are performed and by 2% in terms of making errors. Reduction in CO_2 concentrations from 2300 ppm to 900 ppm improves learning achievement test scores by 5%, while reduction of CO_2 from 4100 ppm to 1000 ppm increases students' daily school attendance by 2.5%.

IPN-3. Better air quality throughout the working environment not only infers improved comfort of the employees thus, their improved contentment, satisfaction, sense of wellbeing, but as well, reduced occurrence of headaches, dizziness, confusedness among them.

IPN-4. Optimizing the process of maintaining standardized air quality implies optimizing costs of energy consumed to operate the system for ventilation and/or air-conditioning.

3.2. *Step 2: Determining design of needs assessment (A)*

Having the listed issues in Step 1 in perspective, the needs assessment in this paper is focusing around the overall goal to find a solution that addresses the identified issues, i.e., the following four aspects (A):

A-1. Risk of airborne diseases caused by viruses;

A-2. Risk of low cognitive, intellectual performance in any working/dwelling environment;

A-3. Risk of improper conditions of the working ambient in terms of air quality, implying reduced contentment and satisfaction among employees and increased occurrence of headaches, disorientation, dizziness, etc.;

A-4. Risk of increased energy consumption for maintaining standardized air quality that has a potential to be optimized.

3.3. *Step 3: Collecting data (CD)*

In view of the four aspects (A-1 to A-4) identified in Steps 1 and 2, conducted are two separate processes of collecting data (CD), i.e.:

Literature review, which main goal is to collect notion of the status-quo with reference to experiences (both positive and negative) and recommendations deriving thereafter.

Customers experiences/review of the solution implemented (in real life) to addresses the identified needs in Step 1, in a period of approximately 2.5 years, with a frequency of 3–6 months.

3.4. *Step 4: Analyzing data (AD)*

The data collected in Step 3, thus, the corresponding needs analysis is performed with respect to the four aspects (A-1 to A-4) identified in Step 2, as follows:

AD-A1. Various studies [14, 15, 18] model the risk of infection depending on the volume of the closed spaces/rooms, the type of ventilation, the number of present persons and the infectors among them. The outcomes deriving thereby follow the recommendations and actions in the context of coping with the COVID-19 pandemic taken by governments of Great Britain [19], Ireland

[20], Australia [21], Canada [22], France [23], Belgium [24], etc. Namely, one of the main measures recommended by the governments in the listed countries is installing CO_2 meters in classrooms as a proxy to detect increased risk of airborne diseases caused by viruses.

AD-A2. In their study, Wargotzki et al. (2020) [16] estimate that reducing CO_2 concentration from 2100 ppm to 900 ppm improves students' scores on psychological tests and school assignments by 12% in terms of the speed at which tasks are performed and by 2% in terms of making errors. Reduction in CO_2 concentrations from 2300 ppm to 900 ppm improves learning achievement test scores by 5%, while reduction of CO_2 from 4100 ppm to 1000 ppm increases students' daily school attendance by 2.5%. The aforementioned results represent a solid argumentation for any corporate management to strive for improved air quality in companies' working environment, thus for the benefits derived thereby, including compliance with health and safety standards.

AD-A3. In a period of 2.5 years, the proposed solution DamaLUFT has been offered to a pool of 30 clients, whereby more than 200 devices have been installed. To date, the number of clients and devices is steadily increasing. In order to keep track of Dama LUFT proper operation, thus to maintain customers' satisfaction, clients are communicated quarterly to obtain feedback and overall experience, hence covering monitored parameters variations throughout all four seasons. Thus far, due to its novelty, customers' generally expressed positive attitude and enthusiasm in using the device/solution, in particular, attributable to the following benefits with respect to increased comfort and better working environment:

- regular monitoring of the CO_2 levels at immediate customer's disposal/visibility;
- facilitating maintenance of CO_2 levels below a predefined critical level;
- offering the end-users a tool for self-health-prevention.

Thus far, customers' satisfaction level steadily rises, leading to increased number of installed devices within one network, as well as increased number of clients.

AD-A4. Following the first quartal of DamaLUFT emergence on the market in Sep 2021, several clients inquired whether monitoring temperature levels can be added as a service. The rationale behind this request was: based on employees' presence that can simply be identified via measuring exhaled CO_2, to enable/provide a tool to monitor, control and plan actions for optimizing heating and/or cooling of the working environment. An immediate consequence from adding temperature measurement, is optimizing the related power consumption via scheduling company operations based on planned employees' presence/absence.

3.5. *Step 5: Providing feedback and proposing adequate solution (AS)*

A properly ventilated room implies and, with an appropriate/adequate solution (AS), facilitates/enables achieving low and controlled CO_2 concentrations in closed spaces/working environment, which in turn, as per the identified aspects in Step 2, provide as follows:

AS-A1. Reduced risk of airborne diseases caused by viruses such as: COVID-19, influenza, etc. whereby, viruses are spread via respiratory droplets-aerosols in the air exhaled by those present in the room.

AS-A2. Improved working efficiency due to improved cognitive performance and the ability to deliver sound decisions, which in turn, is negatively affected by the increased/high CO_2 concentrations in working environments.

AS-A3. Improved working environment, implying improved employees' comfort thus, improved contentment, satisfaction and sense of wellbeing for those present in the closed spaces/areas, and prevention/reduced appearance of headaches, dizziness, confusedness due poor air quality.

AS-A4. Added value of measuring temperature in correlation/combination with CO_2 concentrations.

Having the afore mentioned in perspective, DamaLUFT is proposed as a novel solution which provides measurement of CO_2 concentrations in closed room/spaces/areas, thus, measurement of the exhaled air of those present in the room. Such measurements act as indicator of potential risk deriving from airborne diseases transmitted via respiratory aerosols.

4. RESULTS AND DISCUSSION

The DamaLUFT solution consists of a software platform and a measuring device via which, ambient CO_2 concentrations (closed spaces e.g. classrooms, offices, meeting rooms, waiting rooms, shops, sports gym, etc.) are measured indicatively and are reported to the clients and administrator. The platform provides a crucial contribution to improved indoor air quality, enabling room occupants and building managers to deliver appropriate decisions relating to ventilation not only in separate offices/rooms, but as well of the overall building/facility.

The performed Needs assessment, elaborated in the previous Sections, points out that the proposed DamaLUFT solution addresses the identified gaps in Step 2. The highlights of those outcomes are presented in Table 2.

Namely, via concurrent measurement of exhaled ambient CO_2 concentration levels and temperature, and by means of providing visual signalization of the critical levels of ambient CO_2 and graphical display of the measured values, whereas defined are two level ranges – preventive level defined at 800 ppm and critical level defined at 1200 ppm noting that 2% of the total air in the analyzed space is exhaled by the people present in that room – DamaLUFT acts as a preventive tool to reduce risk from infections caused by airborne diseases.

In line with the findings from Wargotzki et al. (2020) [16], DamaLUFT acts as a tool that has a direct impact on the cognitive and the intellectual performance of the employees present in the analyzed ambient, complemented by increased satisfaction and sense of comfortable working environment for the affected employees avoiding headaches, dizziness, sleepiness, etc.

Table 2

Solution for monitoring of the ambient CO_2 concenstrations – DamaLUFT: Overview of the identified needs and the proposed actions enabled/facilitated after implementing the proposed bridge resulting from the Needs assessment

	Identified needs corresponding aspects (A-#)	DamaLUFT solution (Bridge to solve the problem)	Addressed gaps via and proposed actions after utilizing the solution
A-1	Aerosols droplets less than 5 microns spread airborne diseases (e.g., COVID-19, influenza, etc.) over the air.	CO_2 measurements presented in a simple graphical diagram. Visual signaling for reaching critical CO_2 level.	Ventilation of the spaces: Manually: opening windows. (semi)Automatized: switching on the HVAC system automatically or manually.
A-2	Decreased cognitive performance of the persons (students/employees) present in the analyzed ambient. Decreased ability to make decisions. Reduced working efficiency.	CO_2 measurement presented in a simple graphical diagram. Visual signaling for reaching critical CO_2 level.	Ventilation of the spaces: Manually: opening windows. (semi)Automatized: switching on the HVAC system automatically or manually. Short brakes 10–15 minutes while ventilation is active.
A-3	Increased level of CO_2 causes unpleasant working environments and comfort: Adequate/optimal temperature in working environment is needed.	CO_2 measurement presented in a simple graphical diagram. Visual signaling for reaching critical CO_2 level. Temperature measurement in simple graphical diagram.	Ventilation of the spaces: Manually: opening windows. (semi)Automatized: switching on the HVAC system automatically or manually. Introducing adequate plants in the space/room/office that improve the air quality and reduce CO_2 concentrations. Setting up the heating/cooling system on adequate/optimal temperature.
A-4	Energy efficiency Optimizing power consumption based on the employees presence and needs for heating or cooling	Daily, weekly, monthly and yearly data for CO_2 and temperature could be presented in graphical and table format.	Based on CO_2 and temperature measurement, creating optimal working regime of HVAC system providing fresh air and adequate heating/cooling.

Having in mind the combination of registering temperature levels in parallel with CO_2 measurements in buildings equipped with HVAC systems, DamaLUFT can be combined with the Building management system (BMS) and thus, have a direct impact in optimizing power consumption and increased energy efficiency, without reducing the quality of the working environment.

5. CONCLUSIONS

This paper focuses on identifying market gaps and needs for a novel client-oriented solution consisting of a combination of a CO_2 monitoring device and a software platform for related data acquisition and presentation. The performed needs assessment, conducted via a 5 steps protocol – i.e., identifying problem and needs; determining design of needs assessment; collecting data; analyzing data; and providing feedback and proposing adequate solution – identified 4 aspects (risks) relevant for the addressed problem: A-1, Risk of airborne diseases caused by viruses; A-2, Risk of low cognitive, intellectual performance in any working/dwelling environment; A-3, Risk of improper conditions of the working ambient in terms of air quality, implying reduced contentment and satisfaction among employees and increased occurrence of headaches, disorientation, dizziness, etc.; and A-4, Risk of increased energy consumption for maintaining standardized air quality that has a potential to be optimized.

The results of the Needs assessment show that, thus far, commercial products using Wi-Fi, 4G, standalone with battery power supply, and similar available technologies are missing on the market. DamaLUFT solution acts as a standalone device that for communication purposes is using either Wi-Fi technology or 4G (where Wi-Fi is not available) with rechargeable battery lasting between 3–4 months with one charge. The second element of DamaLUFT solution is the software platform available on any widely used browser s.a. Microsoft Edge, Google Chrome, Firefox, and Safari, and it is highly client-oriented, i.e., implementing DamaLUFT does not require any technical knowledge. Accessing DamaLUFT platform is through any of mentioned browsers, whereby users can obtain numeric and visual presentation of the ambient CO_2 levels and temperature in various timeframes, e.g. 1 day, 3 days, and 7 days. The platform administrator can monitor the measured parameters globally, in a timeframe of 30 calendar days, and monthly for the past 12 months. Apart of the aforementioned, DamaLUFT platform includes tools for the end-user as well as the solution administrator, and various respective analyses.

Considering the challenges posed by the Covid-19 pandemic, this novel CO_2 monitoring device exhibited an effective use for indicative risk prevention of airborne infectious diseases (e.g., COVID-19, tuberculosis, influenza, SARS, etc.) due to the fact that exhaled CO_2 concentrations act as an indicator for potential presence of such diseases.

An added value that the DamaLUFT 2.5 years market presence clearly displayed, is the potential to be integrated with HVAC and/or integrated BMS to facilitate optimizing power consumption, thus contributing towards the clients' corporate social responsibility (CSR) (as an internal indicator) and their environmental social governance (ESG) (as an external indicator), in compliance with the sustainable development paradigm, in particular contributing to SDG3 (good health and wellbeing), SDG7 (affordable and clean energy), SDG8 (decent work and economic growth), SDG12 (responsible consumption and production), SDG13 (climate action) and SDG17 (partnership for the goals).

Having in perspective that humidity control, as well contributes to air quality management and energy management in line with internationaly recommended standards could be taken in consideration for future research.

REFERENCES

[1] ISO, *Indoor Air* – Part 26*: Sampling strategy for carbon dioxide (CO_2) & ISO 16000-26:2012*. https://www.iso.org/standard/52140.html

[2] ISO, *Indoor Air* – Part 40: *Indoor air quality management system & ISO 16000-40:2019*. https://www.iso.org/standard/70424.html

[3] Yua, C., Crump, D. (2011): Standards for Evaluating Indoor Air. In: *Indoor Built Environment* **20** (4) pp. 389–392. DOI:10.1177/1420326X11417330, http://ibe.sagepub.com

[4] ISO, *Occupational health and safety management systems – Requirements with guidance for use & ISO 45001:2018*. https://www.iso.org/standard/63787.html

[5] European Commission, *Energy Efficiency Directive (EU/ 2023/1791)*. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AJOL_2023_231_R_0001&qid=1695186598766

[6] ISO, *Energy Management Systems: Requirements with Guidance for Use & ISO 50001:2018*, https://www.iso.org/iso-50001-energy-management.html.

[7] UN Department of Economic and Social Affairs, *The 17 Goals | Sustainable Development*. https://sdgs.un.org/goals (accessed: April 30, 2024).

[8] Watkins, R., West Meiers, M., Visser, Y. L. (2012): *A Guide to Assessing Needs: Essential Tools for Collecting Information, Making Decisions, and Achieving Development Results*, International Bank for Reconstruction and Development /International Development Association or The World Bank, Washington, USA.

[9] Kaufman, R., Oakley-Brown, H., Watkins, R., Leigh, D. (2003): *Strategic Planning for Success: Aligning people, performance, and payoffs*. San Francisco, Jossey-Bass.

[10] Japan International Cooperation Agency (JICA): *Manual on Training Needs Assessment*, In: Project on Improvement of Local Administration in Cambodia (2007–2010). https://www.jica.go.jp/Resource/project/cambodia/0601331/pdf/english/3_TNA_01.pdf

[11] Smart, J. (2019): *Needs Assessment Families and Children Expert Panel Practice Resource*, Australian Institute of Family Studies (AIFS), © Commonwealth of Australia. https://aifs.gov.au/sites/default/files/publication-documents/1902_expp_needs_assessment_0_0.pdf

[12] Marques, G., Ferreira, C. R., Pitarma, R. (2019): Indoor air quality assessment using a CO_2 monitoring system based on Internet of Things, *J Med Syst* Vol. **43**, Issue 67. https://doi.org/10.1007/s10916-019-1184-x

[13] Mbarndouka Taamté, J., Folifack Signing, V. R., Bobbo, M. O., Noubé Michaux, K., Abba Hamadou, Y., Saïdou (2024): Air quality assessment based on a smart locally CO_2 monitoring system with validation by a reference instrument, *Sustainable Chemical Engineering*, Vol. **5**, Issue 1, pp. 259–278. https://doi.org/10.37256/sce.5120244286

[14] Yan, J., Grantham, M., Pantelic, J., Bueno de Mesquita, P. J., Albert, B., Liu, F., Ehrman, S., Milton, D. K., and EMIT Consortium (2018): Infectious virus in exhaled breath of symptomatic seasonal influenza cases from a college community, *Proc Natl Acad Sci USA*, **115** (5), pp. 1081–1086. https://doi.org/10.1073/pnas.1716561115

[15] Issarow, C. M., Mulder, N., Wood, R. (2015): Modelling the risk of airborne infectious disease using exhaled air, *Journal of Theoretical Biology*, **372,** pp.100–106. https://doi.org/10.1016/j.jtbi.2015.02.010

[16] Wargocki, P., Porras-Salazar, J. A., Contreras-Espinoza, S., Bahnfleth, W. (2020): The relationships between classroom air quality and children's performance in school, *Building and Environment*, Vol. **173**, 106749. https://doi.org/10.1016/j.buildenv.2020.106749

[17] Roberts, M. (6 October 2020): Covid can be airborne, US CDC guidelines now say, British Broadcasting Corporation (BBC) [accessed August 31, 2021]. https://www.bbc.com/news/health-54435240.

[18] Hayashi, M., Kobayashi, K., Kim, H., Kaihara, N. (2020): The state of the indoor air environment in buildings and related tasks in Japan, *Journal of National Institute of Public Health*, Vol. **69**, Issue 1, pp. 63–72, https://www.niph.go.jp/journal/data/69-1/202069010008.pdf

[19] Richardson, H. (21 August 2021): Covid: CO_2 monitors pledged to aid school ventilation, *BBC* [accessed August 31, 2021]. https://www.bbc.com/news/education-58285359

[20] O'Riordan, E. (August 30, 2021): CO_2 monitors to be delivered to all State schools by mid-September: Devices will help regulate ventilation levels and prevent spread of Covid-19, *Irish Times* [accessed August 31, 2021]. https://www.irishtimes.com/news/ireland/irish-news/co2-monitors-to-be-delivered-to-all-state-schools-by-mid-september-1.4660368

[21] Paynter, J.: Dan Andrews says plan to reopen Victorian schools being finalized, *The Australian NCA NEWSWIRE*, (September 3, 2021). https://www.theaustralian.com.au/breaking-news/dan-andrews-says-plan-to-reopen-victorian-schools-being-finalised/news-story/797e017e2b247fc3de0ae23 24f7884c8 [accessed September 05, 2021].

[22] Lofaro, J. (2021): Quebec to install CO_2 detectors in all classrooms by the end of the 2022 school year: letter, *CTVNewsMontreal.ca* (published July 10, 2021, updated July 12, 2021). https://montreal.ctvnews.ca/quebec-to-install-co2-detectors-in-all-classrooms-by-the-end-of-the-2022-school-year-letter-1.5504110 [accessed Aug 30, 2021].

[23] Elzas, S. (2021): How France will keep schools open for the second year under Covid, *Radio France Internationale (RFI)*, (August 26, 2021). https://www.rfi.fr/en/france/20210826-how-france-will-keep-schools-open-for-the-second-year-under-covid [accessed August 31, 2021].

[24] Glen, D. (2020): Province of Antwerp Supports Schools by Donating CO_2 Meters, *Interreg Nort Sea Region: 2imprezs* (October 21, 2020) https://northsearegion.eu/2imprezs/news/province-of-antwerp-supports-schools-by-donating-co2-meters/ [accessed August 31, 2021]

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Original scientific paper

BRIDGING THE GAP: QUALITATIVE COMPARATIVE ANALYSIS OF INDUSTRY 4.0 AND INDUSTRY 5.0

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A b s t r a c t: The fourth industrial revolution comes with a lot of promises for the future of effective and efficient manufacturing. However, in the light of the rapid change of the technology, smart manufacturing is undergoing transformation driven by two distinct paradigms: Industry 4.0 advocates for the shift to-wards digitization and automation, while the emerging Industry 5.0 prioritizes human-centric approaches. Currently, there is a need to consider sustainable development and the crucial role of humans in the assumptions of industry's future development. Concerns about the implementation of digital technologies became the basis for building the assumptions of Industry 5.0. This article will present a comparative qualitative compassion between Industry 4.0 and Industry 5.0 in order to precisely characterize both concepts.

Key words: Industry 4.0; Industry 5.0; digitalization; comparison

СПОЈУВАЊЕ НА РАЗЛИЧНОСТИТЕ: КВАЛИТАТИВНА СПОРЕДБЕНА АНАЛИЗА НА ИНДУСТРИЈАТА 4.0 И ИНДУСТРИЈАТА 5.0

А п с т р а к т: Четвртата индустриска револуција доаѓа со многу ветувања за иднината на ефективно и ефикасно производство. Сепак, во согласност со брзата промена на технологијата, паметното производство претрпува трансформација водена од две различни парадигми: Индустрија 4.0, која се залага за пренасочување кон дигитализација и автоматизација, и Индустрија 5.0, која им дава приоритет на човечкиот фактор и одржливоста. Во моментов постои потреба да се разгледаат одржливиот развој и клучната улога на луѓето во претпоставките за идниот развој на индустријата. Овој труд прикажува квалитативна споредба помеѓу Индустрија 4.0 и Индустрија 5.0 со цел прецизно да се карактеризираат двата концепта.

Клучни зборови: Индустрија 4.0; Индустрија 5.0; дигитализација; споредба

1. INTRODUCTION

The industrial revolution began in the early 1800s, transitioning agrarian societies to industrialization, driven by coal, water, and steam power. This period originated in Britain and spread globally, leading to the second industrial revolution in the late 1800s, characterized by mechanization and significant technological advancements. However, poor working conditions prompted the formation of labor unions and regulations. In the 1950s, the third industrial revolution began with the introduction of transistors and microprocessors, enabling automated production and improved working conditions. This era also brought challenges such as overcrowding and environmental issues. The ongoing fourth industrial revolution, known as Industry 4.0 (I4.0), emerged in 2011, focusing on digital transformation through technologies like IoT and CPS for automation and real-time optimization [1].

As the manufacturers struggle with implementing I4.0, discussions about the next industrial revolution, Industry 5.0 (I5.0), have already begun among industrialists and scholars. While I4.0 focuses on seamless data flow and optimization through digital machine connectivity, I5.0 is envisioned to reintroduce human collaboration and emphasize sustainable manufacturing alongside product personalization [2]. Amidst the continued adoption of I4.0 across diverse sectors and the raising popularity of I5.0 (especially in the scientific circles), this study aims to perform comparative analysis between the two terms. The study doesn't aim to select a better concept because essentially I5.0 is an upgrade of I4.0, but rather characterize and define them. The following chapters include short literature review on both topics, in order to define what are the pillars and the theoretical foundations of both concepts. The final chapter includes a qualitative comparison using the Qualitative Comparative Analysis (QCA) method for more concise and structured comparison of the concepts according to selected criteria.

2. METHODOLOGY

The methodology for this paper involves an extensive literature review on the concepts of Industry 4.0 and Industry 5.0. The reviewed literature spans approximately the past three years, from 2020 to 2024, reflecting the rapid technological advancements in this period. The analysis is conducted using the Qualitative Comparative Analysis (QCA) method. QCA is a research method employed in social sciences to systematically compare multiple cases to study complex phenomena. It integrates qualitative and quantitative techniques to identify patterns and causal relationships within small to medium-sized datasets. The method comprises the following steps shown in Figure 1.

Fig. 1. Research methodology

3. DEFINITIONS

The term I4.0 refers to the fourth industrial revolution, which represents a technological alongside an economic, sociological, and strategic revolution [3]. The advanced technologies of I4.0, enable the collection, storage, analysis, and exchange of massive data between the human and machine in a fast an efficient way [4]. I4.0 enables the design of smart products and services with features such as more insight into customer requirements, better connectivity with customers, and real-time monitoring for better performance [5].

I4.0 is the current vision shaping the future of many industries by creating business models through cyber-physical systems (CPS) [6]. Nowadays, when thinking of I4.0 technologies, we mostly think of the enabling technologies of this paradigm. These technologies are also referred to as pillars of I4.0. In literature, pillars, and technologies of I4.0 usually mean the same.

One of the questions that emerged during the literature review for this paper is the dilemma of what is the definitive list of the digital technologies that should be considered as enablers of I4.0. The answer is that there is no such definitive list considering that it was discovered that many authors propose adding or subtracting pillars from the list depending on the use or simply on the time when the list was created considering the fast development of the new digital technologies. A short literature review was performed to define the list of I4.0 pillars by reviewing relevant sources on this topic [1, 7 – 10]. It is fair to conclude that most of the authors (although sometimes with different names, for example "autonomous robots" sometimes is referred just as "robots", or "collaborative robots" etc.) include the list of pillars shown in Figure 2.

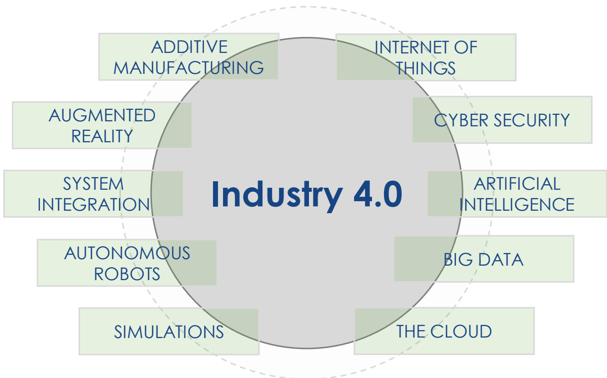

Fig. 2. Industry 4.0 pillars

While many authors and companies still struggle to implement most of the I4.0 pillars, and overall digital transformation [11], others are already researching the new emerging paradigm – I5.0 [12]. European commission defines I5.0 as a concept that complements the existing "Industry 4.0" approach by specifically putting research and innovation at the service of the transition to a sustainable, human-centric and resilient European industry. This approach provides a vison of industry that aims beyond efficiency and productivity as the sole goals and reinforces the role and the contribution of industry to society. It places the wellbeing of the worker at the center of the production process and uses new technologies to provide prosperity beyond jobs and growth while respecting the production limits of the planet [13].

While much more uniform, here once again, authors argue regarding the pillars of I5.0 [14 –17]. The most common model that shows the pillars of I5.0 is shown in Figure 3.

Even though many authors are pushing this I5.0 paradigm, where most of them agree that I5.0 is an extension of I4.0 where the human factor is playing a key role, the popularity of the terms is significantly different. Simple trend analysis based on web searches per quartal (Q) in the specific year is shown in Figure 4. In the context of science, the analysis has shown that I4.0 has 92% more searches than I5.0 on daily basis.

The trend analysis is showing results from January 2021 to March 2024, and it can be concluded that, although I4.0 popularity is declining, it is still significantly bigger than the slowly increasing popularity of the I5.0 concept.

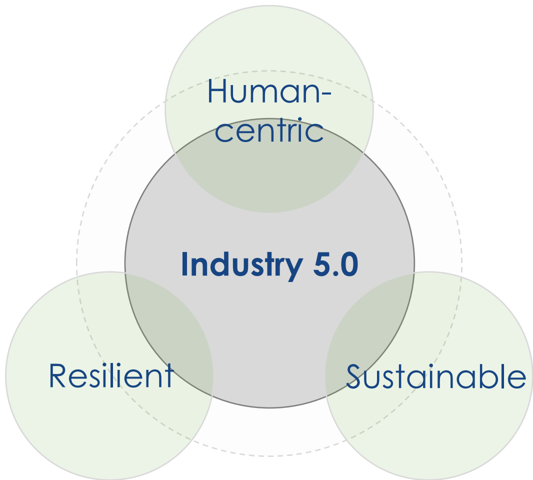

Fig. 3. Industry 5.0 pillars

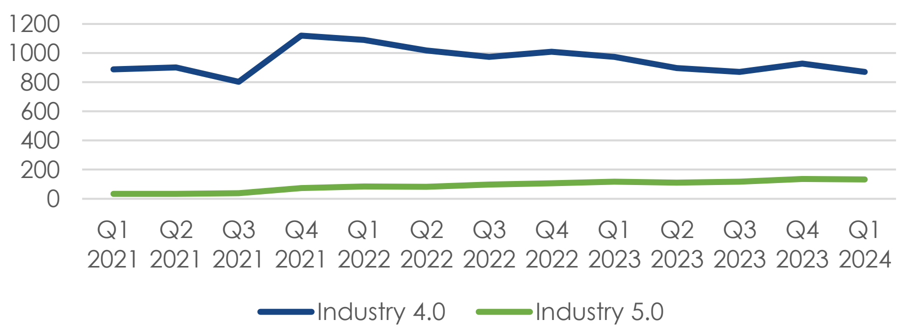

Fig. 4. Trend analysis: Industry 4.0 vs. Industry 5.0 (web searches)

4. QUALITATIVE COMPARATIVE ANALYSIS

For a more structured discussion, we will employ simplified Qualitative Comparative Analysis (QCA) method, as previously stated in the Methodology section of this paper.

4.1. *Case selection*

This specific case has been introduced in the preceding sections. The comparison will be conducted on two primary topics: **Industry 4.0** and **Industry 5.0**.

4.2. *Criteria identification and qualitative review*

Many authors already attempted to identify the commonalities and contrasts between the selected topics. When defining Industry 4.0 and Industry 5.0, and generally a technology disruption, in the literature there are several common factors that can describe these disruptions. According to different sources, authors have selected the most common criteria that will be utilized for the comparative analysis of the cases. The criteria are as following:

– Automation [18].

– Cultural readiness [11, 19].
– Customization & personalization [20].
– Data utilization & analytics [21].
– Economic impact [22, 23].
– Flexibility & adaptability [24].
– Human-centricity [25].
– High-tech products [26, 27].
– Social impact [25, 28].
– Sustainability & environment [28].
– Technology integration [24].

Qualitative review on each criterion was performed in order to find out more about the cases relation to each of these criteria. The results of the literature review that was conducted for both topics, with the key points is summarized in Table 1.

T a b l e1

Cases research

Criteria	Industry 4.0	Industry 5.0
Focus	Smart mass production and digitalization.	Sustainability, human-centricity, and resilience
Automation	Connecting the machines in an integrated system.	Automation enhanced human work.
Cultural readiness	Weak.	Weaker than Industry 4.0.
Customization	Mass customization.	Hyper customization.
Data utilization & analytics	Efforts on data collection and utilization. Automated decision-making uses algorithms and analytics to optimize processes, while humans handle high-level decisions and strategic planning.	Same efforts towards data collection and utilization. Introduction of AI in decision making on the shopfloor, while humans again handle high-level decisions and strategic planning.
Economic impact	Investment in digital equipment.	Investment in strategy and goverment.
Flexibility & adaptability	Adaptive manufacturing processes through real-time data and connectivity, enabling systems to adjust to changing conditions based on automated feedback.	Extends the concept of adaptability by emphasizing the flexibility of human workers.
Human-centricity	Digitalization/automation of as much manual processes as possible. Human has main role in strategic planning, innovation, and making complex decisions.	Human role centers on collaboration with advanced technologies to enhance creativity, innovation, and personalized solution. Manufacturers make efforts to incorporate human as much as possible.
High-tech products	Not in the focus.	Customer experience is the most important.
Social impact	Indirectly affects but it is not in the focus.	Significant emphasis on social implications, aiming to improve societal well-being.
Sustainability & environment	Indirectly affects but it is not in the focus.	Core principle.
Technology integration	The goal is to create a highly connected and data-driven manufacturing environment for improved efficiency and decision-making. Central roles are taken by IoT, CPS, and data analytics.	Continues to leverage advanced technologies but with a greater emphasis on using technology to augment human capabilities. Human and machine collaboration, and AI are in the focus.

4.3. *Calibration*

To facilitate the comparison, in accordance with the method, values are assigned to each condition for Industry 4.0 and Industry 5.0, based on the literature and the authors' expertise. For simplicity, binary values will be used, where 1 indicates the presence and 0 indicates the absence of the condition. The result of the analysis is shown in Table 2. The cells where one case excels against the other one are marked with yellow.

T a b l e 2

Scoring of the cases against the criteria

Condition	Industry 4.0	Industry 5.0
Automation	1	1
Cultural readiness	1	0
Customization	0	1
Data utilization & analytics	1	1
Economic impact	1	1
Flexibility & adaptability	1	1
Human-centricity	0	1
High-tech products	0	1
Social impact	0	1
Sustainability & environment	0	1
Technology integration	1	1

4.4. *Interpretation*

For clarification, this analysis does not determine the superiority of one concept over the other, as the list of comparison criteria is not exhaustive and could encompass additional aspects where each concept may excel. This comparison aims to elucidate the primary characteristics and provide a detailed description of the concepts based on the available data.

Industry 4.0 is predominately characterized by constant strive to automate the existing processes, while utilizing as much technology as possible. According to the research, Industry 4.0 excels only according to the criteria regarding the cultural readiness. And even though research shows that usually companies score poorly in the readiness surveys [29], they seem to be much more ready for I4.0 concepts that are around for a decade now, rather than the new concepts related to I5.0 [19].

Industry 5.0 is predominantly characterized by customization, human-centricity, high-tech products and high social and environmental impact leading to more expressed support for the need of sustainability. Considering the fact that I5.0 excels in all categories (except one) as I4.0, it is safe to assume that this concept is containing all the previously mentioned positive aspects of I4.0 and it is a human-centred and environmentally cautious addition to what I4.0 essentially wants to achieve.

Industry 5.0 demonstrates better performance across multiple criteria, notably customization, human-centric design, high-technology products, social impact, and sustainability and environmental considerations. Conversely, Industry 4.0 shows a marked proficiency in the dimension of cultural readiness, which is expected considering the time that Industry 4.0 concept has been around. Both Industry 4.0 and Industry 5.0 share similar attributes regarding their emphasis on data utilization and analytics, economic impact, technology integration and flexibility.

5. CONCLUSIONS

Industry 4.0 (I4.0) represents a significant evolution in industrial practices, blending advanced technologies with economic, sociological, and strategic transformations. By leveraging the capabilities of cyber-physical systems, I4.0 facilitates the seamless integration of humans and machines, enabling efficient data exchange, real-time monitoring, and the creation of smart products and services tailored to customer needs. However, defining a definitive list of I4.0 enabling technologies remains challenging due to the continuous and rapid development of new digital innovations. While the industry struggles with the full implementation of I4.0, the emerging Industry 5.0 paradigm is gaining attention. I5.0 aims to transcend the goals of efficiency and productivity by focusing on sustainability, human-centric processes, and social responsibility. Despite the growing interest in I5.0, I4.0 continues to dominate in popularity and implementation readiness, reflecting its decade-long presence and the industry's familiarity with its principles.

This paper presented Qualitative Comparative Analysis (QCA) of Industry 4.0 and Industry 5.0 based on several selected criteria that were identified in the literature as the most usual factors to compare these technological shifts. Industry 5.0 excelled according to most of these criteria including customization, human centricity, high-tech products, social impact and sustainability & environment. On the other hand, Industry 4.0 excelled in the cultural readiness dimension. It is noticeable that Industry 4.0 and Industry 5.0 have similar characteristics when it comes to the focus in data utilization & analytics, economic impact, flexibility, etc.

REFERENCES

[1] Erboz, G. (2017): How to define Industry 4.0: The main pillars of Industry 4.0. In: *Managerial Trends in the Development of Enterprises in Gglobalization era*. At: Slovak University of Agriculture, Nitra, Slovakia.

[2] Golovianko, M., Terziyan,V., Branytskyi, V., Malyk, D. (2023): Industry 4.0 vs. Industry 5.0: Co-existence, transition, or a hybrid. *Procedia Computer Science*, Vol. **217**, pp. 102–113.

[3] Skalli, D., Charkaoui. A., Cherrafi, A., Garza-Reyes, J. A., Antonyd, J., Shokri, A. (2023): Industry 4.0 and Lean Six Sigma integration in manufacturing: A literature review, an integrated framework and proposed research perspectives, *Quality Management Journal*, Vol. **30**, Issue 1, pp. 16–40. Integration of Lean Six Sigma with Industry 4.0 for Organisational Excellence.

[4] Salma, L., Vijaya, A., Wicaksono, H. (2020): Systematic literature review of Industry 4.0 maturity model for manufacturing and logistics sectors., *Procedia Manufacturing*.

[5] Koh, L., Orzes, G., Jia, F. (2019): The fourth industrial revolution (Industry 4.0): technologies disruption on operations and supply chain management. *International Journal of Operations & Production Management*, Vol **39**, No. 6/7/8, pp. 817–828. https://doi.org/10.1108/IJOPM-08-2019-788

[6] Zhou, K., Liu, T., Liang, L. (2016): From cyber-physical systems to Industry 4.0: Make future manufacturing become possible. *International Jurnal of Manufacturing Research* **11** (2), 167. DOI:10.1504/IJMR.2016.078251

[7] Ortiz, J. H. (editor) (2020): *Industry 4.0: Current Status and Future Trends.* http://dx.doi.org/10.5772/intechopen.86000

[8] Rehman, S., Ejaz, S. (2020): An implementation of the 9 pillars of Industry 4.0 in conventional footwear industry model. *International Journal of Engineering Applied Sciences and Technology* **4** (12), pp. 283–286.

[9] Polestar (2021): *The nine pillars of Industry 4.0: Technological achievement* [Online]. Available: www.polestarllp.com

[10] Akman, E., Karaman, A. S. (2021): Pillars in the making, Industry 4.0 on the horizon. *International Journal of the Analytic Hierarchy Process* **13** (2). DOI:10.13033/ijahp.v13i2.839

[11] Argilovski, A., Jovanoski, B., Minovski, R. (2023): An overview of the Digital Transformation and Industry 4.0 technologies implementation frameworks. In: *Conference: IS'23 – 19th International Scientific Conference on Industrial Systems*, Novi Sad, Serbia. DOI:10.24867/IS-2023-T1.1-7_03841

[12] Metcalf, G. S. (2024): An introduction to Industry 5.0: history, foundations, and futures. In: *Industry 4.0 to Industry 5.0.* DOI:10.1007/978-981-99-9730-5_1

[13] European Comission (January 2022): *Industry 5.0.* [On line]. Available: https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en#what-is-industry-50

[14] Arcot, S. (2023): Industry 5.0 and Society 5.0. In: *Industrial Revolution and Metaverse: Industry 5.0*. DOI:10.54368/qpbc.2023.1.1

[15] Madzík, P., Falat, L., Jum'a, L., Vrábliková, M., Zimon, D., (2024): Human-centricity in Industry 5.0 – revealing of hidden research topics by unsupervised topic modeling using Latent Dirichlet Allocation. *European Journal of Innovation Management*. DOI: 10.1108/EJIM-09-2023-0753

[16] Slavić, D., Marjanović, U., Medić, N., Simeunović, N., Rakić, S. (2024): The Evaluation of Industry 5.0 Concepts: Social Network Analysis Approach. *Applied Sciences*, **14** (3), 1291. https://doi.org/10.3390/app14031291

[17] Mladineo, M., Ćubić, M., Gjeldum, N., Žižić, M. C. (2021): *Human-centric approach of the Lean management as an enabler of Industry 5.0*, in SMEs.

[18] Isaías, G., Calderón, A. J., Gaspar, F. J. F., Calderón, D. (2024): *Advanced Industry 4.0/5.0: Intelligence and Automation.*

[19] Meena, M., Sharafuddin, M. A., Wangtueai, S. (2024): Measuring the Industry 5.0 – Readiness level of SMEs using Industry 1.0–5.0 practices: The case of the Seafood Processing Industry. *Sustainability* **16** (5), 2205. https://doi.org/10.3390/su16052205

[20] Wang, X., Xue, Y., Zhang, J., Hong, Y., Guo, S., Zeng, X. (2024): A sustainable supply chain design for personalized customization in Industry 5.0 era. *IEEE Transactions on Industrial Informatics* Vol. **20,** no 6, pp. 8786–8797. doi: 10.1109/TII.2024.3367038

[21] Soori, M., Jough, F. K. G., Dastres, R., Arezoo, B. (2024): *Internet of things and data analytics for predictive maintenance in Industry 4.0*. A review. DOI:10.13140/RG.2.2.30521.79207

[22] Cézanne, C., Lorenz, E., Sagliett, L. (2020): Review of industrial economics. *Industry 4.0: Current Issues and Future Challenges*, pp. 11–35.

[23] European Comission, Directorate-General for Research and Innovation: Breque, M., De Nul, L., Petridis, A. (2021): *Industry 5.0 – Towards a sustainable, human-centric and resilient European industry.* Publications Office of the European Union. https://data.europa.eu/doi/10.2777/308407

[24] Verma, M., Pradesh, U. (2024): Transition from Industry 4.0 to Industry 5.0: A comprehensive Overview. *Reseach Gate* **8** (2), pp. 91–102. https://www.researchgate.net/publication/378814527

[25] Joel, A., Lima, T. M., Gaspar, P. D. (2023): Is Industry 5.0 a Human-Centred Approach? A Systematic review, *Processes* **11** (1), pp. 193.

[26] Kabasakal, İ., Keskin, F. D., Ventura, K., Soyuer, H. (2017): From mass customization to product personalization in automotive industry: potentials of industry 4.0. *Pressacademia* **4** (3), pp. 244–250. DOI:10.17261/Pressacademia.2017.486

[27] Saniuk, S., Grabowska, S., Fahlevi, M. (2023): Personalization of products and sustainable production and consumption in the context of Industry 5.0, In: Carolina Feliciana Machado & João Paulo Davim (eds.), *Industry 5.0*, pp. 55–70, Springer. DOI: 10.1007/978-3-031-26232-6_3

[28] Ghobakhloo, M., Iranmanesh, M., Fathi, M., Rejeb, A., Foroughi, B., Nikbin, D. (2024): Beyond Industry 4.0: a systematic review of Industry 5.0 technologies and implications for social, environmental and economic sustainability. *Asia-Pacific Journal of Business Administration,* Vol. ahead-of-print, No. ahead-of-print. https://doi.org/10.1108/APJBA-08-2023-0384

[29] Argilovski, A., Vasileska, E., Jovanoski, B. (2023): Enhancing manufacturing efficiency – A lean Industry 4.0 approach to retrofitting, *Mechanical Engineering – Scientific Journal* **41** (2), pp. 123–129.

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INSTRUCTIONS FOR AUTHORS

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The journal also publishes (continuously or occasionally) the bibliographies of the members of the Faculty, book reviews, reports on meetings, informations of future meetings, important events and data, and various rubrics which contribute to the development of the corresponding scientific field.

Original scientific papers should contain hitherto unpublished results of completed original scientific research. The number of pages (including tables and figures) should not exceed 15 (28 000 characters).

Short communications should also contain completed but briefly presented results of original scientific research. The number of pages should not exceed 5 (10 000 characters) including tables and figures.

Reviews are submitted at the invitation of the Editorial Board. They should be surveys of the investigations and knowledge of several authors in a given research area. The competency of the authors should be assured by their own published results.

Professional papers report on useful practical results that are not original but help the results of the original scientific research to be adopted into scientific and production use. The number of pages (including tables and figures) should not exceed 10 (18 000 characters).

Acceptance for publication in the Journal obliges the authors not to publish the same results elsewhere.

SUBMISSION

The article and annexes should be written on A4 paper with margins of 2.5 cm on each side with a standard font Times New Roman 11 points and should be named with the surname of the first author and then if more and numbered. It is strongly recommended that on MS Word 2003 or MS Word 2007 and on PDF files of the manuscript be sent by e-mail:

mesj@mf.edu.mk.

A letter must accompany all submissions, clearly indicating the following: title, author(s), corresponding author's name, addres and e-mail addres(es), suggested category of the manuscript and a suggestion of five referees (their names, e-mail and affiliation).

Articles received by the Editorial Board are sent to two referees (one in the case of professional papers). The suggestions of the referees and Editorial Board are sent to the author(s) for further action. The corrected text should be returned to the Editorial Board as soon as possible but in not more than 30 days.

PREPARATION OF MANUSCRIPT

The papers should be written in the shortest possible way and without unnecessary repetition.

The original scientific papers, short communications and reviews should be written in English, while the professional papers may also be submitted in Macedonian.

Only SI (Système Internationale d'Unites) quantities and units are to be used.

Double subscripts and superscripts should be avoided whenever possible. Thus it is better to write $\nu_3(PO_4)$ than $\nu_{3_{PO_4}}$ or exp(–E/RT) than $e^{-E/RT}$. Strokes (/) should not be used instead of parentheses.

When a large number of compounds have been analyzed, the results should be given in tabular form.

Manuscript should containt: title, author(s) full-name(s), surname(s), address(es) and e-mail of the corresponding author, short abstract, key words, introduction, experimental or theoretical background, results and discussion, acknowledgment (if desired) and references.

The **title** should correspond to the contents of the manuscript. It should be brief and informative and include the majority of the key words.

Each paper should contain an **abstract** that should not exceed 150 words, and **3–5 key words**. The abstract should include the purpose of the research, the most important results and conclusions.

The **title**, **abstract** and **key words** should be translated in Macedonian language. The ones written by foreign authors will be translated by the Editorial Board.

In the **introduction** only the most important previous results related to the problem in hand should be briefly reviewed and the aim and importance of the research should be stated.

The **experimental** section should be written as a separate section and should contain a description of the **materials used and methods** employed – in form which makes the results reproducible, but without detailed description of already known methods.

Manuscripts that are related to **theoretical studies**, instead of experimental material, should contain a sub-heading and the **theoretical background** where the necessary details for verifying the results obtained should be stated.

The **results and discussion** should be given in the same section. The discussion should contain an analysis of the results and the conclusions that can be drawn.

Figures (photographs, diagrams and sketches) and **mathematical formulae** should be inserted in the correct place in the manuscript, being horizontally reduced to 8 or 16 cm. The size of the symbols for the physical quantities and units as well as the size of the numbers and letters used in the reduced figures should be comparable with the size of the letters in the main text of the paper. Diagrams and structural formulae should be drawn in such a way (e.g. black Indian ink on white or tracing paper) as to permit high quality reproduction. The use of photographs should be avoided. The tables and the figures should be numbered in Arabic numerals (e.g., Table 1, Figure 1). Tables and figures should be self-contained, i.e. should have captions making them legible without resort to the main text. The presentation of the same results in the form of tables and figures (diagrams) is not permitted. The use of equation editor (MS Word, Microsoft Equation, Math Type 6.0 Equation) for typesetting the equations is recommended. Strokes (/) should not be used instead of parentheses.

Figures and tables must be centred in the column. Large figures and tables may span across both columns (Figure 1).

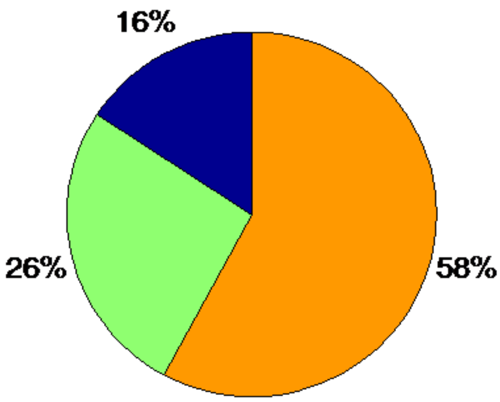

Fig. 1. Example of a graph and a single-line caption (colour)

Graphics may be full colour. Please use only colours which contrast well both on screen and on a black-and-white hardcopy because the Journal is published in black-and-white, as shown in Figure 2. The colour version is only for the electronic version of the Journal.

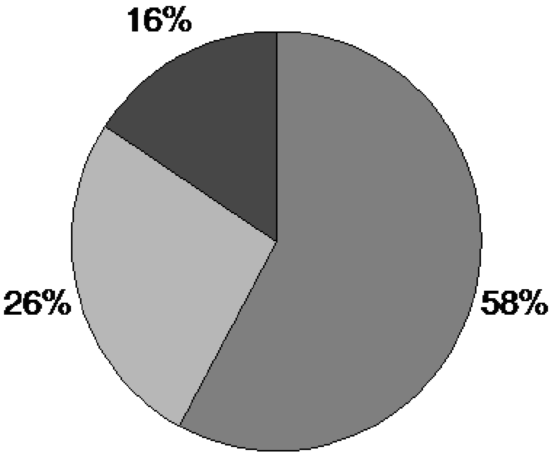

Fig. 2. Example of a graph and a single-line caption (bleck and vhite)

Please check all figures in your paper both on screen and on a black-and-white hardcopy. When you check your paper on a black-and-white hardcopy, please ensure that:

– the colours used in each figure contrast well (Figure 3),

– the image used in each figure is clear,

– all text labels in each figure are legible.

Please check all figures in your paper both on screen and on a black-and-white hardcopy. When you check your paper on a black-and-white hardcopy, please ensure that the image used in each figure is clear and all text labels in each figure are legible.

Fig. 3. Example of an image as it will appear at the electronic version of the Journal and a multi-line caption

Footnotes are also not permitted.

The **reference** should be given in a separate section in the order in which they appear in the text. The surname of one or two authors may be given in the text, whereas in the case of more than two authors they should be quoted as, for example:

Examples of reference items of different categories shown in the References section include:

- example of a book in [1]
- example of a book in a series in [2]
- example of a journal article in [3]
- example of a conference paper in [4]
- example of a patent in [5]
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- example of a web page in [7]
- example of a databook as a manual in [8]
- example of a datasheet in [9]
- example of a master/Ph.D. thesis in [10]
- example of a technical report in [11]
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All reference items must be in 9 pt font. Please use Regular and Italic styles to distinguish different fields as shown in the References section. Number the reference items consecutively in square brackets (e.g. [1]).

When referring to a reference item, please simply use the reference number, as in [2]. Do not use “Ref. [3]” or “Reference [3]” except at the beginning of a sentence, e.g. “Reference [3] shows …”. Multiple references are each numbered with separate brackets (e.g. [2], [3], [4–6]).

The **category** of the paper is proposed by the author(s), but the Editorial Board reserves for itself the right, on the basis of the referees' opinion, to make the final choice.

Proofs are sent to the author(s) to correct printers' errors. Except for this, alterations to the text are not permitted. The proofs should be returned to the Editorial Board in 2 days.

The author(s) will receive, free of charge, 1 reprints of every paper published in the Journal.

REFERENCES

[1] Surname, N(ame).; Surname, N(ame). (Year): *Name of the Book*, Publisher.

[2] Surname, N(ame).; Surname, N(ame). (Year): *Name of the Book*, Name of the Series. Publisher, **vol.** XXX.

[3] Surname, N(ame).; Surname N(ame). (Year): Title of the article, *Name of the Journal*, **vol. XX,** No. XX, pp. XXX–XXX.

[4] Surname, N(ame).; Surname N(ame). (Year): Title of the article, *Proceedings of the Name of the Conference*, vol. **XX,** pp. XXX–XXX.

[5] Surname, N(ame).; Surname, N(ame).: *Name of the Patent*, Institution that issued the patent and Number of the patent (Date dd. mm. yyyy).

[6] N.N. (Year): *The XXX web site*, web address.

[7] Surname, N. (Year): *XXX homepage on XXX*, web address.

[8] N.N. (Year): *Title of the Manual*, Name of the Organization.

[9] N.N.: *XXX data sheet*, Name of the Organization.

[10] Surname, N. (Year): *Title of the Thesis*, Master/Ph.D. thesis (in Language), Institution.

[11] Surname, N(ame).: Surname, N(ame). (Year): *Title of the Report*, Organization that issued the report, number of the report.

[12] Institution that issued the standard (Year): *Name of the Standard* & Number of the standard.