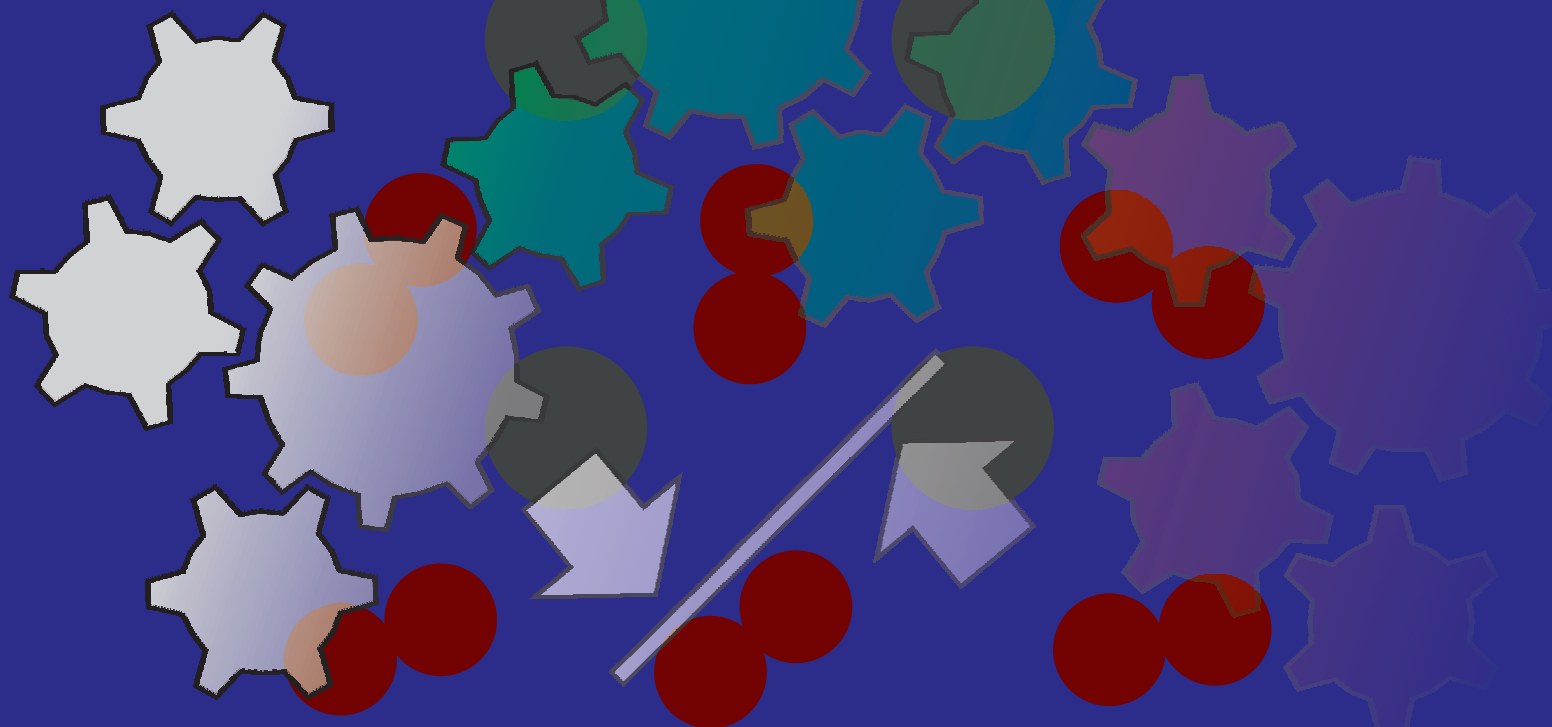
ACTA TECNOLOGÍA

electronic journal
ISSN 2453-675X
Volume 10
Issue 4
2024



International Scientific Journal about Technologies

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(DECEMBER 2024)

Acta Tecnología – International Scientific Journal
Volume: 10 2024 Issue: 4 ISSN 2453-675X

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Acta Tecnología - International Scientific Journal about Technologies
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https://doi.org/10.22306/atec.v10i4.211 *Received: 26 June 2024; Revised: 20 Sep. 2024; Accepted: 09 Nov. 2024*

Design and production of personalized cervical orthosis using CAD/CAM systems

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Keywords: cervical orthosis, personalized orthotics, CAD/CAM, 3D scanning.
Abstract: The aim of this work was to design and manufacture a personalized cervical orthosis using CAD/CAM systems through additive manufacturing technology. Cervical orthoses are practically used to ensure the stability of the cervical spine. The work was motivated by recent research into personalized orthoses made using additive manufacturing technologies. This study describes the methodology of 3D scanning the cervical area, CAD design, and CAM manufacturing of a personalized cervical orthosis. As a basis for modelling the orthosis, a 3D scan of the subject's head, neck, shoulders, and upper chest was obtained using an optical 3D scanner Artec Eva. The scan was processed in CAD software Meshmixer and served as a basis for the modelling of a personalized cervical orthosis, considering the support points. The orthosis was made by additive manufacturing technology Multi Jet Fusion (MJF) on a HP 5200 3D printer from biocompatible polymer PA12. The advantage of manufacturing a cervical orthosis using MJF technology is the individualized design, improved production efficiency, as well as increased quality and comfort in using the orthosis. It meets attributes such as copying the subject's morphology, airiness, lightness, and easy fastening.

1 Introduction

Cervical orthoses, which provide mechanical support and stabilization of the cervical spine, are key tools in the rehabilitation and treatment of various neurological and musculoskeletal diseases [1]. A cervical orthosis provides relief and support for the neck [2], limiting cervical spine movement or immobilizing it, depending on the medical condition [3]. Cervical orthoses are divided into three categories: soft (basic, made of foam rubber covered with a soft lining), semi-rigid (padded mandibular and occipital supports), and cervico-thoracic orthoses (support comparable to column braces with rigid metal linkage between the front and back parts) [2,3].

Traditional methods of manufacturing these aids, often based on manual measurement, plastering and manual finishing, are time-consuming and can be limiting in creating a unique design. Cervical orthoses made using traditional methods are commonly available and crafted from thermoplastics or leathers. The traditional process of custom orthosis manufacturing is manual and relies on the orthotic technician's skills. The disadvantages of these orthoses include delivery time, cost, and the quality of the orthosis [4].

Innovative technologies such as 3D scanning and CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) technologies offer new possibilities in the personalization of orthopaedic aids, thereby improving the comfort and effectiveness of treatment [5].

The development of personalized cervical orthoses using these technologies is a subject of several scientific studies [5-8]. These studies show that the use of adittive manufacturing technology and advanced software tools can reduce manufacturing time and costs, improve fitting and patient comfort, and even contribute to the environmental sustainability of orthopaedic devices. These methods were used in studies especially for subjects with complex clinical needs, where previous designs were insufficient. The predominant technology for production was FDM (Fused Desposition Modelling) technology, and CT tomography as the technology for obtaining measurement data, in addition to 3D scanning [9].

In this work, the Multi Jet Fusion (MJF) technology was used, where the manufacturing method involves uniformly heating the applied powder using a thermal head. Printing heads are used to apply agents that support the 3D printing process. The first agent is applied to the

surface of the model to enhance the absorption of thermal radiation. The second agent is applied to the outer contours of the produced model to facilitate the separation of the unfused powder from the final model [10].

The MJF technology enables production using polyamide - PA12. This material is characterized by high mechanical, thermal, and fatigue strength, as well as resistance to less aggressive chemicals. PA12 is highly hygroscopic, quickly absorbing water from the environment. A significant property of this material is its skin-contact biocompatibility according to ISO 10993-1, and it is also approved for food contact according to EU directive 2002/72/EC (excluding alcoholic products). An essential property that the orthosis should meet also relates to the aesthetics of its production. PA12 offers many possibilities for finishing parts, such as polishing, dyeing, painting, powder coating, or gluing products [10].

The aim of this study was to design and manufacture a personalized cervical orthosis using innovative technologies. Our approach seeks to demonstrate the implementation of CAD/CAM technologies in the production of custom cervical orthoses, showcasing a more efficient and precise alternative to conventional methods.

2 Methodology

The design and manufacturing of an individual cervical orthosis consists of 3 steps:

1. 3D scanning of the cervical area,
2. CAD design and creation of a 3D model of the cervical orthosis,
3. Additive manufacturing of the cervical orthosis.

2.1 Methodology of 3D scanning of the cervical spine

A handheld optical 3D scanner ArtecEva (Artec 3D, Senningerberg, Luxembourg) was used for data obtainment. This scanner uses structured light technology which is used to obtain the shape and texture of area of interest. This technology is suitable for use in the field of prosthetics and orthotics, based on it´s resolution [9]. With the help of a 3D scanner, the topography of the neck can be digitalized [10].

The scanning was done while the subject was sitting, which is more practical for the 3D scanner operator. At the same time, sitting minimizes unwanted micro-movements of the scanned subject, which increases the overall accuracy of the scanning process. In the case of 3D scanning the neck area, it is important that the person being scanned has their hair tied back and has jewellery on the neck or ears. Due to the volume of hair and the impossibility of capturing the surface of the occipital part of the head, the scan was performed in a tight-fitting swimming cap. It is also necessary that the face, neck, shoulders and chest areas are uncovered. The subject being scanned should be instructed not to move and possibly keep their eyes closed due to the intense flashing light during the scanning process. The movement with the 3D scanner should be smooth and slow so that the scanner has time to capture all the details of the surface.

After the scanning process, the resulting 3D scan isedited and processed in the Artec Studio 13 software (Artec 3D, Senningerberg, Luxembourg). The Artec Studio software then automatically fills in the missing parts of the scan that were not captured. The modified file is subsequently exported in STL format and further adjustments were made in Meshmixer (Autodesk Inc., San Francisco, CA, U.S.A.), which is a freely downloadable CAD software suitable for 3D scans editingand has the necessary functions to create a 3D model of a personalized orthosis.

2.2 Design of a personalized cervical orthosis using CAD systems

The editing of the 3D model itself consists in thoroughly smoothing the surface so that the subsequently modeled orthosis is smooth and without defects. Before CAD modelling of the orthosis, it is necessary to identify the areas that need to be fixed. Cervical braces should limit head and neck movements, as well as to mechanically limit flexion, extension, lateral flexion, and rotation of the head and cervical spine [1].

Because the orthosis supports part of the weight of the head, the cervical spine is partially relieved. The basic support points of cervical orthoses include the shoulders, chin, head and jaw. The upper limbs can provide some support, depending on its design, contributing to overall stability. A chin rest or collar helps keep the chin in a neutral position and prevents excessive movement. Supporting the back of the head is important for distributing pressure and increasing stability. These support points, or landmarks, are designed to improve overall posture and alignment.

After smoothing the surface and determining the support points, the actual modelling of the orthosis follows, as shown in Figure 1. This procedure involves several steps. First, a sketch of the orthosis is created on the 3D model, including ventilation holes that improve comfort and reduce the weight of the orthosis; the middle hole is intended for a possible tracheostomy. The pattern is then extruded with the thickness of the brace set to 4 mm. Subsequently, a drawing of the back part of the orthosis is created on the scan. The orthosis is designed in two parts for improved positioning and easier fitting.

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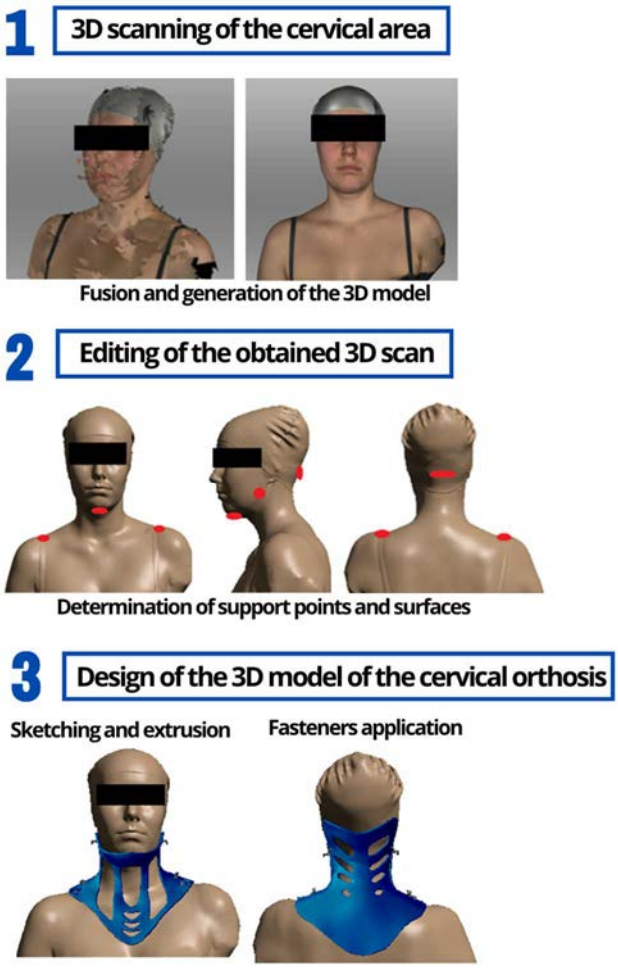

Figure 1 Step-by-step design methodology

Since the orthosis has two parts, the fastening component was created in SOLIDWORKS software (Dassault Systems, Waltham, USA) to allow both parts to be joined. The connection shown in Figure 2 was simple and functional and was designed to be suitable for additive manufacturing. The joint consists of two parts: the gear teeth and the locking tooth.

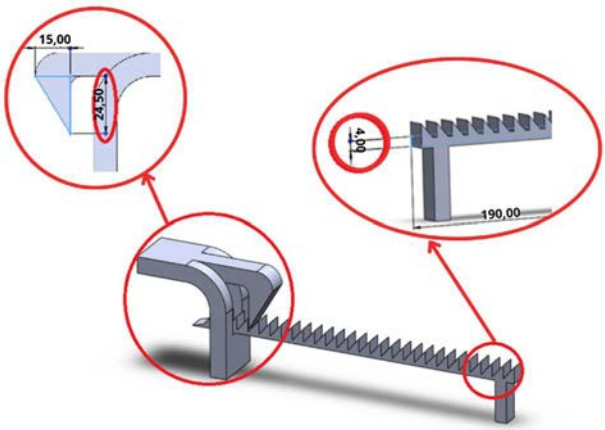

Figure 2 3D model of the fastening component and its dimensions

2.3 *Additive manufacturing of the cervical orthosis*

The proposed orthosis was manufactured using MJF (Multi Jet Fusion) additive manufacturing technology, on a HP MJF 5200 (Hewlett Packard Enterprise, Houston, Texas, USA) 3D printer from the Nylon 12 (PA12) material, which was chosen for its high applicability in medical practice and mechanical properties for the development of such device. The printer manufacturer states that this technology and material allow the creation of parts with fine details, dimensional accuracy of ± 0.2 mm and optimal mechanical properties, which are suitable for prosthetics and medical equipment. The build volume of the printer is 380 x 284 x 380 mm, with a tolerance of ± 0.2% (minimum 0.2 mm), and the print price starts at €0.29 per cm^3. [11] After manufacturing the orthosis (Figure 3) using MJF technology from PA12 material, the surface of the raw product was gray and rough. To achieve a uniform and aesthetically appealing surface, the orthosis was painted black. This finishing process is referred to as HQ Black (Figure 4).

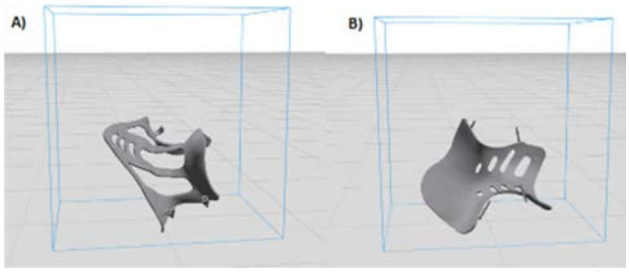

Figure 3 Two-part orthosis position simulation in the space for printing the part on the official website of the HP company [12]

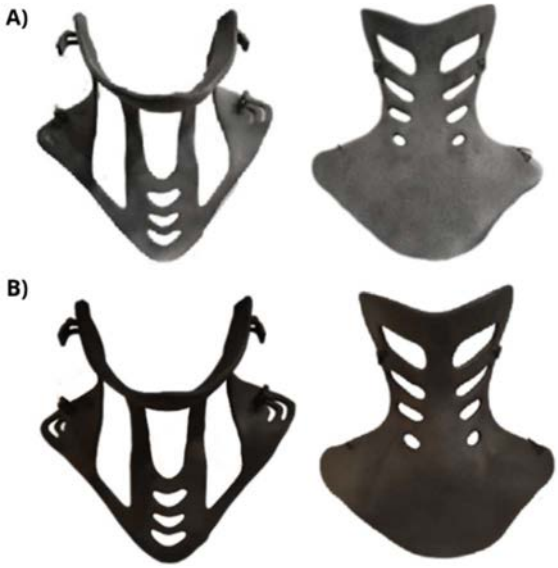

Figure 4 Both parts of the cervical brace before and after finishing

3 Results and discussion

The manufactured two-part cervical brace is designed to stabilize the cervical spine with a chin support and is equipped with a simple and customizable fastening. It is intended for use in post-traumatic conditions, postoperative immobilization, degenerative diseases and discopathy. The orthosis has a tracheostomy opening and maintains a neutral position of the cervical spine, limiting flexion in every direction.

In terms of the time efficiency of designing and manufacturing a personalized orthosis, additive technology appears to be much faster. This two-piece brace was designed and manufactured within approximately 72 hours of scanning the subject. The maximum length of MJF printing of the entire build is 12.5 hours [11], while it is possible to print several prosthetic and orthopedic aids at the same time. On the other hand, the production of a personalized orthosis by the conventional method according to Hale et al. it takes about 6 days [5], which is due to the collection of measurement data and subsequent adjustments. The cervical brace 3D scanning process can take approximately 15 minutes, including subject preparation. The innovative method eliminates the need for manual casting and mold making, saving time while being more environmentally friendly and economical. According to Hale et al., the total price of such a device made by the Fused Filament Fabrication (FFF) method was approximately 386 €, while they stated that this method is inherently slow compared to the Selective Laser Sintering (SLS) method. According to them, this price of the orthosis is comparable to an estimate of 415 € for similar aids made by conventional methods in their hospital [5]. The total price of the proposed two-part cervical orthosis is 273.29 € and it weight 295 g.

To ensure the comfort of the patient, the material "SOHATEX" is recommended as a lining, which is commonly used in the production of prosthetic-orthopedic aids due to its ability to remove moisture well and provide excellent air circulation. With the help of CNC (Computer Numerical Control) cutting technology, it is possible to automatically cut the desired shape of the lining according to the 3D model. CNC machines are commonly used in prosthetic-orthopedic companies in the production of orthopaedic footwear and bandage aids.

The manufactured plastic two-part cervical orthosis, even with the fastening component, is also compatible with an MRI examination, because it has no metal parts. Although this fixation component is designed to be easy to put on and take off, it is not necessary to take it off before this examination.

4 Conclusions

This study successfully demonstrated the application of advanced CAD/CAM systems and additive manufacturing technology in the design and production of a personalized cervical orthosis. Utilizing the Multi Jet Fusion (MJF) manufacturing process with PA12 material, the study highlighted significant improvements in production efficiency, achieving a complete orthosis development within 72 hours—a notable reduction from the conventional six-day timeframe. The resulting orthosis was anatomically precise, lightweight, and customizable, meeting the essential requirements for cervical spine stabilization. Additionally, the integration of these technologies provides a scalable approach to personalized medical care, offering potential ecological and economic benefits.

Future research could explore the use of low-cost 3D scanners for data acquisition, potentially expanding the accessibility of this workflow in hospitals and other clinical settings. By lowering the input costs, these technologies could be more widely implemented, allowing a broader range of healthcare facilities to benefit from personalized orthotic solutions. This could lead to greater practical aplication of advanced manufacturing techniques in medical practice, further enhancing patient care and operational efficiency across diverse healthcare environments.

Acknowledgement

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-22-0340. This research was supported by project KEGA 044TUKE-4/2022 Implementation of progressive technologies in prosthetics and orthotics education and support integration with practice. This research was supported by project VEGA 1/0599/22 Design and biomechanical analysis of personalized instruments for arthroscopic applications.

References

[1] JONES, P., UUSTAL, H.: Spinal Orthoses: Principles, Designs, Indications, and Limitations [Online], Available: https://medicine.missouri.edu/sites/default/files/pm-r/Jones_Article_CH38SpinalOrthoses3rdEd0037_v1.pdf. [17 Jun 2024], 2020.

[2] CHOO, Y.J., BOUDIER-REVÉRET, M., CHANG, M.: 3D printing technology applied to orthosis manufacturing: narrative review, *Annals of palliative medicine*, Vol. 9, No. 6, pp. 4262-4270, 2020. https://doi.org/10.21037/apm-20-1185

[3] AMBU, R., OLIVERI, S.M., CALÌ, M.: Neck orthosis design for 3D printing with user enhanced comfort, *International Journal on Interactive Design and Manufacturing*, Vol. 18, pp. 6055-6068, 2024. https://doi.org/10.1007/s12008-023-01507-1

[4] ALRASHEEDI, N.H., TLIJA, M., ELLOUMI, N., LOUHICHI, B.: A critical review of 3D printed orthoses towards workflow implementation in the clinical practice, *Journal of Engineering Research*, pp. 1-14, 2024. https://doi.org/10.1016/j.jer.2024.01.024

[5] HALE, L., LINLEY, E., KALASKAR, D.M.: A digital workflow for design and fabrication of bespoke orthoses using 3D scanning and 3D printing, a patient-based case study, *Scientific Reports*, Vol. 10, No. 7028, 2020. https://doi.org/10.1038/s41598-020-63937-1

[6] BABU, D., VEEZHINATHAN, M., ADITHYA, S., JAGADEESAN, N.: Design and Development of a 3D Printable Neck Brace- A Finite Element Approach. Online, *Journal Of Clinical And Diagnostic Research*, Vol. 16, No. 9, pp. 10-15, 2022. https://doi.org/10.7860/JCDR/2022/57066.16975

[7] AMBU, R., MOTTA, A., CALÌ, M.: *Design of a Customized Neck Orthosis for FDM Manufacturing with a New Sustainable Bio-composite*, In: Rizzi, C., Andrisano, A.O., Leali, F., Gherardini, F., Pini, F., Vergnano, A. (eds) Design Tools and Methods in Industrial Engineering, ADM 2019, Lecture Notes in Mechanical Engineering, Springer, Cham, pp. 707-718, 2020. https://doi.org/10.1007/978-3-030-31154-4_60

[8] XU, Y., LI, X., CHANG, Y., WANG, Y., CHE, L., SHI, G., NIU, X., WANG, H., LI, X., HE, Y., PEI, B., WEI, G.: Design of Personalized Cervical Fixation Orthosis Based on 3D Printing Technology, *Applied Bionics and Biomechanics*, Vol. 2022, pp. 1-8, 2022. https://doi.org/10.1155/2022/8243128

[9] STEFANOVIC, B., ONDREJOVA, B., BEDNARCIKOVA, L., MICHALIKOVA, M., Methodology of CAD design and CAM production of transtibial prosthetic sockets, *Acta Tecnología*, Vol. 9, No. 3, pp. 103-108, 2023. https://doi.org/10.22306/atec.v9i3.178

[10] TUREK, P., BAZAN, A., ZAKRECKI, A.: Influence of post-processing treatment on the surface roughness of polyamide PA12 samples manufactured using additive methods in the context of the production of orthoses, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 238, No. 11, pp. 1694-1708, 2024. https://doi.org/10.1177/09544054231202423

[11] STEFANOVIC, B., ONDREJOVA, B., BEDNARCIKOVA, L., TOTH, T., ZIVCAK, J.: *Comparison of optical handheld 3D scanners suitable for prosthetic and Orthotic Applications*, Proceedings of 3DBODY.TECH 2022 - 13th International Conference and Exhibition on 3D Body Scanning and Processing Technologies, Lugano, Switzerland, 25-26 October 2022, pp. 1-7, 2022. https://doi.org/10.15221/22.06

[12] HP, www.hp3dprint.eu: Online 3D Printing Quote, [Online], Available: https://hp3dprint.eu/3d/online-3d-printing-quote/ [17 Jun 2024], 2024.

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 115-119 ISSN 2453-675X

https://doi.org/10.22306/atec.v10i4.214 Received: 03 July 2024; Revised: 20 Sep. 2024; Accepted: 10 Nov. 2024

Study of iron-based composite materials using modelling and simulation

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Keywords: Hysteresis, composite materials, soft magnetic materials, modelling.
Abstract: Composite materials are materials composed of two or more components that have different physical and chemical properties. These properties complement each other to create a material with unique properties that cannot be achieved by using the individual components alone. Modelling the effect of preparation processes on the properties of composite materials is an important tool to predict the properties of a material prior to its manufacture. This can help in optimizing the preparation technology and obtaining the desired material properties. In the present work the topicality of the problem of iron-based composite materials and the possibilities of modelling and simulation of selected models are presented.

1 Introduction

Magnetic materials are an important part of our lives. Nowadays, these materials have a wide range of application in our homes, cars as well as biomedical needs. Composite magnetic materials are modern magnetic materials. They have been created by combining existing simple materials and the knowledge of physical metallurgy. The base material - the matrix - has the function of a binder. The second component, which includes fibres or dispersed particles, has a reinforcing effect. By composite material we mean substances which are artificially formed, consist of at least two chemically distinct components and the resulting properties of the composites are different from those of the components. Iron-based composite materials are composite materials which contain iron as the main component. These materials are developed by combining iron with other elements or compounds to achieve the desired properties.

There are several approaches to model the influence of technological processes on the properties of composites. One of them is the use of physical models and simulations that include various physical processes such as heat treatment, mechanical stresses, diffusion and interactions between material phases. These models can be based on mathematical equations, numerical methods or engineering simulation software.

Another approach is experimental modelling where the properties of composite materials are investigated under different process settings. This provides experimental data from which relationships and trends between process parameters and material properties can be identified [1].

2 Magnetic materials

Nowadays, magnetic materials have an important position in the economy. These materials can have different physical and magnetic properties according to the arrangement of the fundamental magnetic moments of the atoms of which they are composed. A distinction is made between diamagnetic, paramagnetic and ferromagnetic materials [2].

Magnetic materials are of great importance in engineering and technical practice. Their use has led to a revolution in materials research, physics, electronics and electrical engineering. These materials and their products are used in the design of magnetic circuits, generators, transformers, electric motors, coils, sensors and as storage media in IT technologies. Some magnetic materials have been known for many years while others have only recently been discovered. With the expected advances in the discovery of new magnetic materials their widespread use in areas where they have not yet been applied can be foreseen. Physicists and engineers use electromagnetism in the production of magnetic materials because everything in our environment starting from fundamental particles to groups of galaxies has different electromagnetic properties. In terms of the size of the coercive field, engineering magnetic materials are divided into two basic groups:

1. Magnetically soft materials for which the coercive field value $HC < 100\ Am^{-1}$,
2. Magnetically hard materials where the coercive field HC is greater than 1000 Am^{-1} [3].

2.1 Magnetic soft materials

The term refers to materials that are easily magnetized and can be magnetized repeatedly, and even if the magnetic field is removed, the magnetism disappears. The characteristic feature of this type of material is its high magnetic permeability, Consequently, they can be easily magnetized in a magnetic field and quickly achieve a high magnetization intensity. This type of materials is widely used in high-frequency technologies such as magnetic cores, magnetic heads and memory magnetic cores. Commonly used soft magnets are iron-silicon alloys, iron-nickel alloys and amorphous metals [3].

Magnetically responsive soft materials consisting of ferromagnetic particles and polymer matrix have recently attracted significant research interests due to their untethered, reversible and fast activation under external magnetic fields. The activation and performance of magnetically responsive soft materials largely depend on the magnetization of ferromagnetic particles and structure.

Depending on the magnetization characteristics, ferromagnetic materials can be categorized into soft magnetic materials and hard magnetic materials.

Soft magnetic materials can be easily demagnetized and remagnetized at a relatively small magnetic field. As a result, magnetically sensitive soft materials in which soft magnetic particles are embedded (e.g. magnetorheological elastomers and ferrogels) are usually subjected to simple elongation or shortening deformations by taking advantage of the magnetic force generated in the magnetic field. This limits to some extent the potential of magnetically sensitive soft materials in applications that require complex transformations [3].

Magnetically soft compact powder materials are progressive materials with a rapidly growing application area. They are ferromagnetic materials containing a non-magnetic component in which magnetically soft powder particles are randomly arranged with each other, forming a heterogeneous structure. Depending on their preparation, they can be determined as the so-called compacts (pressed ferromagnetic powder without the addition of insulation) or soft magnetic composites (SMCs), in which the ferromagnetic powder particles are coated with a thin layer of insulation before being pressed [4,5].

In general, magnetically soft materials are used as transformer cores, but they also find applications in motors, inductors and generators. Soft magnetic composite (SMC) material is actually made up of surface-insulated iron powder particles and has a number of advantages including isotropic magnetic and thermal properties, low eddy current losses, and relatively low overall core losses at medium and higher frequencies, but also with the prospect of low-cost mass production. The SMC material, due to its powdery nature and isotropic magnetic properties, is suitable for the construction of electrical machines of three-dimensional (3D) magnetic fluxes and complex structures for which it is almost impossible or very difficult to use layered steels [6].

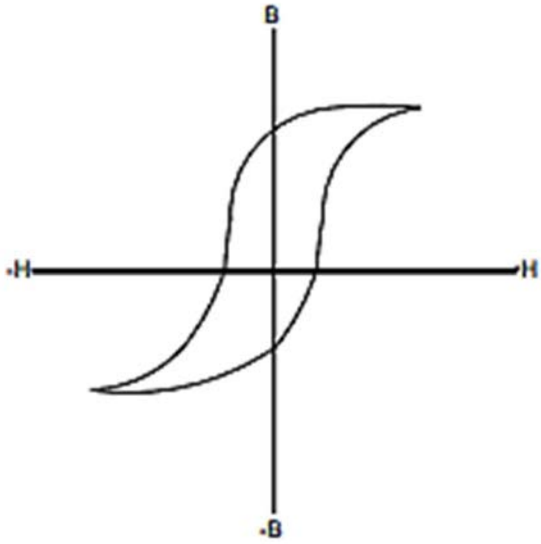

Figure 1 Hysteresis loop of magnetic material

The most important parameters that are determined from the hysteresis loop are the saturation magnetization MS or magnetic induction BS (magnetic flux density), the coercive field HC (the value of the magnetic field strength at which the substance (magnetic) has zero magnetic induction) and the remanent magnetization MR or magnetic induction BR (representing the magnetic induction that remains in the material after the external magnetic field has been switched off). Other important parameters that can be determined from hysteresis loop measurements include the initial permeability μpoc and the maximum permeability μmax (the maximum slope of the B versus H dependence), which can be found in the initial magnetization process. Magnetic induction, referred to as B, is a physical quantity that describes the strength of a magnetic field. It is one of the key parameters in magnetism and plays an important role in the characterization of magnetic fields in various materials. Magnetic induction is correlated with the magnetic field strength (H) and the magnetic permeability of a material. Magnetic induction is used to describe the behavior of magnetic materials as well as to design and analyze electromagnetic devices such as transformers, electric motors, generators, and magnets. In cyclic magnetization of a material, the relationship between B and H is shown in the form of a hysteresis loop, which illustrates the nonlinear and dependent nature of the magnetization of the material, including the energy losses during the cycle. Magnetic induction is a fundamental element in the study of magnetic fields and their interaction with materials, which is important for various applications in industry, technology and science [7-9].

3 Modelling the impact of technological processes

Modelling the influence of technological processes on the properties of composite materials is an important tool in optimising their preparation. In this way, it is possible to predict and analyse how different factors and process parameters affect the properties of materials and their resulting properties. There are several approaches to model the influence of technological processes on the properties of composites. One of them is the use of physical models and simulations that include different physical processes such as heat treatment, mechanical stresses, diffusion and interactions between material phases. These models can be based on mathematical equations, numerical methods or engineering simulation software.

Scientists have been trying to explain and describe ferromagnetic hysteresis for more than 80 years. Over the decades, several approaches have been developed. Micromagnetic methods are used to determine the minimum energy of a system to find the orientation of magnetic moments. These methods are limited to a small range. The other extreme is to fit a measured curve without a physical background. An intermediate solution - a global estimate of the magnetic behaviour based on statistical physics methods modulated by certain microstructural assumptions lies between these two approaches [10,11].

In the second half of the 1980s, another model was proposed by Jiles and Atherton based on Weiss's original ideas on magnetic domains and the effective magnetic field inside a ferromagnetic material, and using a key concept, anhysteretic magnetization, based on a modified Langevin function. Later, Harrison introduced a slightly different concept of ferromagnetic hysteresis with a new dimensionless quantity called the domain coefficient [12,13].

In previous models, the influence of the effective magnetic field is included twice in the energy density equation. This corresponds to the interaction of the magnetic moment with itself. In addition, the flexibility of the domain wall was described by the parameter c, although this parameter was not explicitly defined. These inconsistencies led to the proposal of another differential isotropic model of ferromagnetic hysteresis (DIMFH). In this model, the transition from the paramagnetic Langevin function to the ferromagnetic Langevin function is achieved through the assumption of a magnetic cluster. The fuzzy interaction coefficient α is replaced by a defined interaction coefficient β. The double effective field effect is removed leading to a more stable solution of the model equation, and the coefficient β acquires a different meaning. It turns out that the fixed and flexible interleaving of the attachment sites is indistinguishable for DIMFH (and should be even for previous models) from the interleaving of large curves [12,13].

There are several approaches to ferromagnetic hysteresis loops modelling. Some modelling approaches are based on curve fitting that ignore the fundamental physical properties of the material. On the other hand, other methods take into account all known properties and have a rigorous physical basis but they are too time consuming to be useful for macroscopic applications to real engineering materials. Each value in the modelling of magnetization curves is associated with an infinite number of potential magnetizations depending on the history of the samples [10].

Hysteresis can be caused by three specific phenomena: inter-domain interaction, anisotropy and internal friction. The dominant cause varies from material to material; therefore, it is essential to compare hysteresis in the various models available, which include models such as Stoner - Wolhfarth (S - W), Jiles - Atherton (J - A), Globus and Preisach [12].

Table 1 Comparison of the selected models and their characteristics [15]

Model Characteristics	**Stoner – Wolhfarth**	**Jiles – Atherton**	**Globus**	**Preisachov**
Mechanism	Rotation	Not specified	Wall movement	Not specified
Anisotropy	Uniaxial	Multiaxial	Multiaxial	Not specified
Interaction	Yes	Yes	No	Moving model
Pinning effect	Yes	Yes	Yes	Moving model
Structure	Anisotropic or isotropic	Isotropic	Uniaxial (180 °)	Not specified
Wall energy	No	No	Yes	Yes
Revesibility	Yes	Additional model	Yes	Additional model
Side loops	Yes	-	-	Yes
Demagnetization	-	Yes	-	Yes
Anhysteresis	Yes	Yes	Yes	Yes
Grains	Single domain	Multiple domains	Dual domain	Not specified
Material	Magnetic hard materials	Bulk materials	Soft ferrites	Magnetic thin material

To define the limitations of the use of the available baseline model, the main characteristics and features are summarised in Table 1.

This table shows the importance of the anhysteretic curve, which is defined as the location of global equilibrium states observed in each of the models. It is also clear that a universal model, which is suitable for all kinds of materials, does not yet exist. However, the table allows to highlight similarities and common concepts especially for the J-A, S-W and Globus models, which are physically based models [10].

Based on experimental measurements of coercivity, remanence and saturation magnetization, it is possible to calculate the various model parameters needed to describe hysteresis based on Jiles - Atherton theory, initial anhysteretic susceptibility and maximum deferential susceptibility. The aim is to show the possibilities of determining the hysteresis parameters of experimental hysteresis measurements and then using them to model hysteresis curves. This represents a new development in ferromagnetic hysteresis modelling that allows for the first time to calculate parameters from a set of experimental data. The described method enables to determine the values of these parameters and to an accuracy of a few percent. Comparison of measured and modeled hysteresis loops demonstrates excellent agreement between measured and modeled curves [14].

Accurate modelling of electromagnetic systems is crucial for the development of innovative applications. The micromagnetics approach combines theoretical knowledge with experimental data and plays an important role in this process. For electromagnetic applications, sophisticated modelling techniques need to be developed. Micromagnetic simulation of magnetization dynamics relies on the solution of the nonlinear Landau-Lifshitz-Gilbert (LLG) equation. To simplify the calculations, linearization within the small-angle approximation is commonly used. Interchangeable spring magnets combine hard and soft phase materials to achieve high coercivity, saturation and remanence. They have received considerable attention in the last two decades. The theoretical maximum energy density of the product is given to be around 120 MGOe(mega-gauss-oersted) [14].

The object-oriented micromagnetic framework (OOMMF) was first introduced in 1998. The C++ language is used to write this software. Some commercial software tools allow simulation with finite temperature values. The solution space is divided into rectangular prisms with equal dimensions. In this simulation, A is considered as the exchange constant and M as the magnetization. The total energy in each cell is calculated taking into account the exchange energy, the energy of intrinsic static magnetization, the energy of magnetocrystalline anisotropy as well as the Zeeman energy(or external field energy is the potential energy of a magnetized body in an external magnetic field.). Experimental results show that the remanence is close to the expected values, but the coercivity differs significantly from them. Micromagnetic simulation using 3D OOMMF software allows to reveal the underlying physical phenomena and the influence of the soft phase on the coercivity of nanocomposite magnets.

This study highlights the importance of the microstructure of nanocomposite magnets for understanding their magnetic properties. In addition to high spontaneous magnetization and energy anisotropy, the microstructure plays a key role in the coercivity, remanence and energy density of the product. Micromagnetic simulations allow us to investigate the influence of microstructure on these properties. The theoretical insights from this study can be applied to optimize the properties of nanocomposite magnets. They can be used to select the appropriate soft phase size in the preparation of bulk nanocomposite magnets. Applying numerical methods and computer software, the BH loop of these magnets can be easily calculated, and their performance can be predicted. Micromagnetic simulations also open the way to the development of permanent magnets with low rare-earth content even without omitting them altogether. Simulations will help us to explore the properties of these materials and design optimal compositions for different applications [14].

4 Conclusions

The conclusion shows that despite the popularity of the Jiles-Atherton model of magnetic hysteresis for the treatment of anhysteretic magnetization curves, this model faces challenges in numerical processing that often leads to biased and unreliable results. This can be a hindrance in achieving the objectives effectively using the available software.

On the other hand, modelling the effect of preparation processes on the properties of composite materials has been shown to be a key tool for predicting material properties prior to manufacturing, which helps in optimising the preparation technology. Although this approach offers significant advantages such as accurate prediction of material properties, it is often computationally intensive and does not always provide accurate results.

It is clear that there is currently a lack of simulations that efficiently handle hysteresis loops based on the Jiles-Atherton model, presenting an opportunity for further research and development in this area.

Acknowledgement
This work was funded by Scientific Grant Agency of Ministry of Education of Slovak Republic and Slovak Academy of Science grant numbers VEGA 1/0403/23 and VEGA 1/0016/24.

References

[1] PLUHAR, J., BENEŠ, V.: *Construction and tooling materials*, Praha: ES CVUT, 1980.

[2] DOBRZAŃSKI, L.A., DRAK, M.: Hard magnetic composite materials Nd-Fe-B with additions of iron and X2CrNiMo-17-12-2 steel, *Journal of Alloys and Compounds*, Vol. 449, No. 1-2, pp. 88-92, 2008. https://doi.org/10.1016/j.jallcom.2006.02.092

[3] LU, L., SIM, J., ZHAO, R.R.: Mechanics of hard-magnetic soft materials: A review, *Mechanics of Materials*, Vol. 189, No. February, 104874, 2024. https://doi.org/10.1016/j.mechmat.2023.104874

[4] PÉRIGO, E.A., WEIDENFELLER, B., KOLLÁR, P., FUZER, J.: Past, present and future of soft magnetic composites, *Applied Physics Reviews*, Vol. 5, No. 3, 031301, 2018. https://doi.org/10.1063/1.5027045

[5] Coercive field, [Online], Available: https://beliana.sav.sk/heslo/koercitivne-pole [10 Jun 2024], 2017. (Original in Slovak)

[6] Magnetic materials, [Online], Available: https://www.poziadavka.sk/katalogy/www.poziadavka.sk_4366_56496.pdf [10 Jun 2024], 2007. (Original in Slovak)

[7] Materials with magnetic properties, [Online], Available: https://crushtymks.com/sk/energy-and-power/349-materials-with-magnetic-properties.html [10 Jun 2024], 2019. (Original in Slovak)

[8] ASARI, A., GUO, Y., ZHU, J.: Magnetic properties measurement of soft magnetic composite material (SOMALOY 700) by using 3-D tester, *AIP Conference Proceedings*, Vol. 1875, No. 1, p. 030015, 2017. https://doi.org/10.1063/1.4998386

[9] LIU, CH., LU, J., WANG, Y., LEI, G., ZHU, J., GUO, Y.: Design Issues for claw pole machines with soft magnetic composite cores, *Energies*, Vol. 11, No. 8, 1998, pp. 1-15, 2018. https://doi.org/10.3390/en11081998

[10] LIORZOU, F., PHELPS, B., ATHERTON, D.L.: Macroscopic Models of Magnetization, IEEE Transactions on Magnetics, Vol. 36, No. 2, pp. 418-428, 2000. https://doi.org/10.1109/20.825802

[11] JILES, D.C., ATHERTON, D.L.: Erratum Title of paper: Theory of ferromagnetic hysteresis, *Journal of Magnetism and Magnetic Materials*, Vol. 92, No. 2, p. 289, 1990. https://doi.org/10.1016/0304-8853(90)90646-8

[12] JILES, D.C., THOELKE, J.B., DEVINE, M.K.: Numerical determination of hysteresis parameters the modeling of magnetic properties using the theory of ferromagnetic hysteresis, *IEEE Transactions on Magnetics*, Vol. 28, No. 1, pp. 27-35, 2002. https://doi.org/10.1109/20.119813

[13] CARDELLI, E., DELLA TORRE, E., FABA, A.: Analysis of a unit magnetic particle via the DPC model, *IEEE Transactions on Magnetics*, Vol. 45, No. 11, pp. 5192-5195, 2009. https://doi.org/10.1109/TMAG.2009.2031078

[14] SUNDARA MAHALINGAM, S., MANIKANDAN, B.V., AROCKIARAJ, S.: Review - Micromagnetic Simulation Using OOMMF and Experimental Investigations on Nano Composite Magnets, *Journal of Physics: Conference Series*, Vol. 1172, 012070, pp. 1-11, 2019. https://doi.org/10.1088/1742-6596/1172/1/012070

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 121-129 ISSN 2453-675X

https://doi.org/10.22306/atec.v10i4.224 Received: 07 Sep. 2024; Revised: 13 Nov. 2024; Accepted: 30 Nov. 2024

Enhancing business efficiency through effective inventory management: a systematic literature review

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Keywords: inventory management practices, operational performance, supply chain performance.
Abstract: Efficient inventory management is crucial for various industries' operational performance and financial success. As market demands evolve and technological advancements progress, the complexity and importance of inventory management have increased, making it essential for maintaining a competitive advantage. This study aims to systematically review existing literature to understand the impact of inventory management practices on operational performance across different industries and contexts. Employing the PRISMA framework for systematic literature review, the Scopus database was the primary source for selecting relevant articles. The initial search yielded 791 results, refined through rigorous inclusion and exclusion criteria, ultimately resulting in the thorough analysis of 12 critical articles. This review's findings highlight that advanced inventory management systems, such as deep reinforcement learning and real-time analytics, significantly enhance operational efficiency. These systems facilitate more effective information sharing and enable tailored inventory strategies, which improve supply chain performance. This improvement is particularly evident in sectors such as healthcare and manufacturing, where precise inventory control is critical. Furthermore, financial metrics like days inventory outstanding correlate positively with firm performance, underscoring the strategic importance of inventory management in achieving financial success. The study highlights the importance of advanced inventory management practices in enhancing operational efficiency and financial performance despite high setup costs, technological complexity, and data quality issues. This study synthesizes research on inventory management practices, offering insights for businesses to enhance operational performance and emphasizes the need for continuous innovation for competitiveness.

1 Introduction

Historically, both excessive inventory and inadequate management, as well as insufficient inventory and excessive management, have often been linked to inventory management on a global scale. Extreme behaviour in either direction could lead to severe repercussions. As technology has advanced and allowed organizations to make items more quickly, in larger quantities, and with more designs, inventory problems have multiplied. The problem has been made worse by the public's openness to variations and frequency of design modifications [1]. The strategic advantages of production planning, scheduling, and inventory management have been clear since the mid-1980s. Inventory management enhances business operations by maintaining production, ensuring supply flow, and providing a wide range of goods, thus maximizing organizational performance and productivity [2]. Procurement, utilization, management, and coordination of available supplies are all part of inventory control. Inventory control directs activities to ensure materials are obtained at appropriate times, locations, and quality. Since inventory control is closely related to an organization's production function, its operation will likely impact its profitability directly or indirectly [3].

According to SCM Theory, originally developed by [4], managers should direct supply chain activities holistically to sustain the most efficient flow of goods, services, and information throughout an entire supply chain. SCM Theory postulates that good inventory management will promote better coordination among suppliers, manufacturers, and distributors, thus boosting operational performance. The theory emphasizes that better inventory practices minimize the generation of

inefficiencies, reduce stockouts, and raise the ultimate level of cost efficiency. This study is based on SCM Theory to discuss ways modern inventory management techniques can optimize supply chain processes using real-time analytics and deep reinforcement learning.

Inventories refer to the assortment of completed products, partially completed products, and basic supplies that a corporation maintains to facilitate manufacturing production processes [5]. Consequently, a corporation that mishandles its inventory is prone to have problems with its profitability [6]. [7] inventory management ensures clients have reliable access to the required items or services. It ensures that the procurement, production, and distribution processes are coordinated to meet the marketing and organizational needs for delivering the product to customers. The main purpose of inventory management is to determine the quantity and whereabouts of objects stored [8]. Inventory management is necessary at several places inside a facility or numerous sites in a supply chain to safeguard the smooth and scheduled production process against unexpected disruptions caused by material shortages [9]. Inventory management encompasses various factors such as lead times for replenishment, handling of returns and defective goods, demand forecasting, carrying costs, asset management, physical space availability, inventory valuation, inventory visibility, forecasting future prices, and quality control an optimal inventory level is possible by effectively managing and considering these parameters. This process is ongoing as the company requirements evolve and adjust to the external environment [10]. Inventory control systems, including manual methods like the Two Bin Method, Red Line Method, and computerized systems, help organizations determine the optimal inventory levels using the economic order quantity and keep track of these levels. To avoid underestimating or overestimating profits, a company must properly manage its inventory and accurately assess its value using the appropriate approach [11]. [12] defines inventory management as a corporation's strategic approach to overseeing its stock investments. Organizations employ inventory management as a strategic approach to arrange, store, and replenish inventory to maintain an adequate supply of goods while reducing costs. This involves monitoring stock levels, estimating future demands, and establishing agreements regarding scheduling timing and methods [13-14]. Effective inventory management can substantially impact a company's revenues by identifying cost-saving opportunities in stock storage and ensuring a seamless production flow [15]. According to [16], there is a direct correlation between a company's profitability and its capacity to manage its inventory efficiently [17]. Poor inventory management practices result in heightened waste production for organizations, elevating the cost of storing items and augmenting the likelihood of their loss or destruction [18]. Therefore, successful performance can be attained if businesses create plans to generate the most revenue at the lowest feasible cost. For example, achieving optimal inventory management solutions occasionally impacts the organization's structure, affecting profitability and performance [1,19]. It is noteworthy that inventory management and return on assets (ROA) are directly correlated [3]. To achieve notable enhancements in managing financial resources, companies are generally advised to maintain inventory levels within ideal ranges [5]. Supply chain management is one area where inventory management directly affects business performance. A critical task, supply chain management typically encompasses all processes related to moving products and raw materials from the producer to the end user. Inventory management facilitates the efficient flow of supply chain activities in this scenario by guaranteeing appropriate resource and supply selection, clear production scheduling, effective order processing, seamless inventory management through the facilitation of transfer and storage activities, and, lastly, the provision of valuable customer service [20]. Acquiring and maintaining inventory is high for businesses and accounts for many production expenses. Carrying expenses, like storage and insurance, purchasing costs, like shipping and shop location, and stock-out costs, such as redundancy and lost sales, are all included in inventory costs. A business cannot function exceptionally without effective and appropriate control. Any theft, waste, or overuse of materials results in instant financial loss and lowers a company's performance [21]. According to [22], material control entails the methodical supervision and management of materials' acquisition, holding, and application to preserve a uniform flow. Most manufacturing organizations' performance has been impacted by the issues the manufacturing sector has faced recently, particularly regarding inventory management and material control [23]. Overstocking of materials has resulted in their eventual expiration or out-of-dates. Inventory control can be achieved by introducing various measures to address issues such as understocking, lack of stocking, worker theft of materials, and delays in material delivery to the sites, among other issues. This will help the organization avoid losses from refuelling departments [24]. To prevent inventory loss, the business should establish stringent guidelines for procurement officials and store managers to adhere to when acquiring and keeping materials [25]. An organization must have a robust, efficient, and coordinated inventory management system due to the continuously changing and highly competitive business environment, significantly impacting organizational performance. Key considerations in inventory management for every business revolve around the lead time for replenishment and the order amount.

The failure to address these two issues has substantially raised the overall cost of organizational success. Consequently, uncertainty and planning errors are present in production. These factors have led to reduced machinery usage, wasted labor hours, increased production expenses, unsuccessful firms, and minimal investment profits. The firm faces challenges in handling a sizable workforce and

adjusting to the performance requirements of modern production technology. The literature still lacks a thorough systematic review that summarizes the research on the relationship between inventory management and operational performance, even though the topic has been the subject of many studies. To close this gap, this study will do a thorough literature analysis to investigate how inventory management techniques affect operational performance in various settings and industries. To reach this gap, the following Objectives were identified:

- To systematically review and analyze existing literature on inventory management and its effects on operational performance.
- To assess how inventory management strategies affect key performance characteristics, including cost efficiency, customer service, and productivity.
- To investigate the moderating factors influencing the relationship between inventory management and operational performance, such as organizational size, industry type, and technological advancements.

2 Methodology

This section details how inventory performance publications are obtained. It emphasizes rigorous techniques and article evaluation. The strategy utilizes commonly employed literature review methodologies to discover pertinent publications, such as the Preferred Reporting Items for Systematic Reviews (PRISMA) and Meta-Analyses. The PRISMA framework is essential for conducting systematic reviews as it prioritizes the analysis of randomized trials in review reports. Furthermore, it offers explicit criteria for selecting and excluding studies pertinent to this investigation [26]. The creators of PRISMA have highlighted the value of using PRISMA for systematic reviews that focus predominantly on randomized trials as the primary research source for treatments. However, challenges may arise when evaluating qualitative and mixed-method study designs using the PRISMA framework. PRISMA conducts comprehensive searches across several scientific databases and research sources to identify relevant studies, minimizing the risk of overlooking essential research [27]. The screening strategy employed in PRISMA's selection criteria helps to streamline the workflow by reducing the number of identified research studies [28]. PRISMA, commonly employed in medical research, also applies to operations management because it focuses on systematic reviews.

Furthermore, this method provides clear and detailed criteria for including or excluding certain elements, which are customized to meet the unique goals of the study. In response to the absence of methodological advice in fields other than medicine, researchers have increasingly relied on methodologically focused articles grounded in systematic literature reviews to fill this void. [29] has emphasized that Web of Science (WoS) and Scopus are leading citation databases competing. However, the papers for this evaluation were gathered only from the extensive Scopus database. This systematic search has preferred Scopus for its extensive coverage of scientific literature from many disciplines. Besides the comprehensive indexing in the Scopus database of all peer-reviewed journals and other scholarly publications, we have chosen it because it holds importance, is multidisciplinary, and covers superior research published in peer-reviewed journals, acknowledged conferences, and books [30]. Then again pointed out that Scopus had a much larger scope of materials and more citations than WOS or any other database [31,32]. Being covered by more articles that are directly related to Inventory Management and Organisational Performance, Scopus is very suitable for our study. While WOS and other databases are helpful, Scopus is more comprehensive, with a broader citation metric that would allow a proper and sound literature review. In addition, [33] have highlighted that Scopus is the most comprehensive collection of abstracts and citations across several disciplines, thereby establishing its importance as a beneficial resource for scholars searching for relevant publications. Scopus has recently emerged as a strong challenger threatening WoS's leading position.

2.1 Search strategy and selection process

We thoroughly investigated phrases related to this review by utilizing Scopus search strings. At first, researchers performed a keyword search with a significant focus on "Inventory Management and Organisational Performance." Previous studies were used to identify synonyms, similar terms, and variations, then included as supplementary study keywords to expand the scope. The enlarged keywords were used in the Scopus advanced search tool, which led to the retrieval of 791 articles from the database. [34] state that a literature review's quality depends on the reviewer's thoroughness. To enhance the quality of the findings, this review strictly includes journal articles only [35]. Moreover, only English-language documents were considered for inclusion to streamline the process and avoid complexities arising from translation requirements. For this study, the publication year was not restricted, although many researchers commonly employ it as an exclusion criterion. The search results reveal that the publications span from 2015 to 2023. Therefore, the publication year was not a factor in excluding articles. The inclusion and exclusion criteria for the selected article are summarized in Table 1.

The authors manually assessed 791 articles by reviewing their titles, abstracts, and full texts. Eighty-nine articles were removed due to duplication, and 287 abstracts were excluded during the screening process. Furthermore, 276 articles were rejected after reviewing the entire text, and an additional 127 articles were deemed ineligible after thoroughly evaluating the full text. As a result, 12 documents were identified as suitable for further analysis.

The study is concerned with advanced technologies and methodologies that affect operational performance related

to inventory management. In this respect, 12 articles are selected to provide empirical evidence concerning the link between inventory management practices and their performance related to the integration of deep reinforcement learning, real-time analytics, and AI-based systems, which are increasingly important in addressing contemporary challenges arising in inventory management.

Table 1 Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Articles indexed in Scopus. Scholarly articles published in journals Articles written in English	Articles not indexed in Scopus. Proceedings from conferences, chapters from books, and books Articles written in languages other than English Study based on conceptual analysis

The materials chosen needed to reflect the state of industries, geographical contexts, and inventory management strategies. The 12 selected articles cover key sectors, including health, manufacturing, and retail. They give a wide view of how inventory practices vary across different settings and their eventual effects on operational performance.

This was further justified based on the review's relevance, quality, and focus. The focused selection allows the study to go more in-depth and rigorously analyze the most relevant research in the field; hence, it offers meaningful insights into the role of advanced inventory management techniques in improving operational performance.

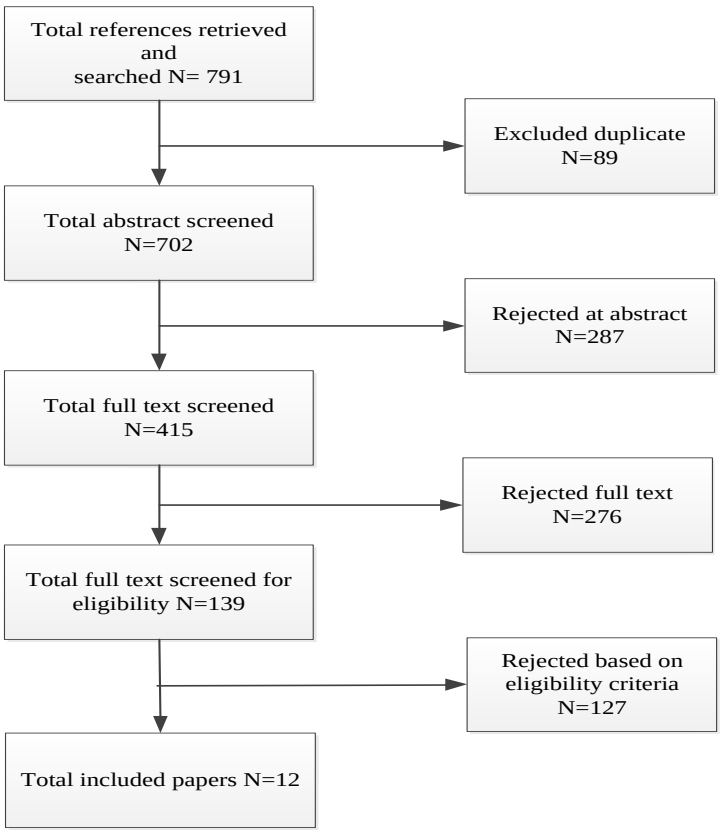

Figure 1 Selection and exclusion process

3 Results and discussion

This part discusses the aim, results, recommendations, and methodologies adopted in prior research on Inventory management and Operational Performance.

Enhancing business efficiency through effective inventory management: a systematic literature review

Mohamed Ali Farah, Ibrahim Hassan Mohamud, Mohamud Ahmed Mohamed, Hassan Ahmed Mohamed Jakuula

Table 1 Content review of the selected articles

Author	Title	Purpose	Methodology	Results
[36]	This study investigates the impact of information sharing and inventory management strategies on companies' performance in supply chain operations.	The article's primary objective is to examine the impact of information-sharing methods and inventory management on company performance.	Questionnaire	The findings indicate enhanced information-sharing procedures and superior inventory management methods increase company performance. Additionally, improved information-sharing enhances inventory management, leading to more robust firm performance.
[18]	An inventory management and warehouse performance model for the South African retail industry.	This study investigates an approach to establishing a connection between inventory management and warehouse performance in the South African retail industry.	Quantitative survey	Three inventory management strategies, namely inventory investment and ABC analysis, have enhanced inventory performance, benefiting the warehouse's overall performance.
[37]	We are utilizing reward shaping to enhance the efficacy of deep reinforcement learning in the context of perishable inventory management.	This research showcases the utilization of potential-based reward shaping to enhance the learning process of Deep Reinforcement Learning (DRL) for inventory control by incorporating domain knowledge from heuristic inventory regulations.	Secondary data	The results show that good replenishment heuristics can improve the performance of DRL.
[15]	This is an investigation into the relationship between knowledge of inventory management procedures and business performance, with a focus on the mediating role of operational performance.	This study aims to examine the relationship between operational performance (OP), business performance (BP), and knowledge of inventory management procedures (KIMP).	Questionnaire	The results indicate that KIMP directly impacts OP, and a company's OP considerably affects total BP. The KIMP does not significantly impact blood pressure. The study results show a substantial and robust mediating influence of organizational practices between knowledge-intensive manufacturing processes and business performance.
[17]	Inventory Management and Performance of Manufacturing Firms	The study aims to assess the performance of steel manufacturing companies by examining how inventory management and distribution turnover affect their ability to compete and operate profitably.	Survey	The study's conclusion states that IMP significantly influences company performance and enhances the knowledge base for inventory management practitioners in the manufacturing business.
[19]	An evaluation of inventory management practices and their influence on the supply chain performance of antiretroviral medicines at public hospitals in Nyamira County.	Identify the inventory management procedures, assess the supply chain performance, and analyze the difficulties impacting the inventory management of ARV drugs in public hospitals.	Questionnaire	The study found that Indian SMEs use standard inventory management methods like scheduled control and demand forecasting. However, issues were observed in safety stock deployment and order lead time management. More workforce and consistent medicine supply are needed to improve inventory control.
[38]	Days inventory outstanding and firm performance: Empirical investigation from manufacturers	This study examines the correlation between Days Inventory Outstanding (DIO) and the performance of energy companies in Saudi Arabia from 2013 to 2019.	Quantitative Methods	The study suggests that regional energy companies plan to improve their inventory management through various strategies, including effective planning, innovative marketing, enhanced pricing, product mix optimization, and focusing on top-selling products.
[39]	Effect of inventory management practices On the performance of commercial state Corporations in Kenya	The study aimed to investigate how inventory management techniques impact the performance of commercial state businesses in Kenya.	Questionnaires	Inventory systems have a beneficial and substantial impact on the functioning of commercial state enterprises. Many firms now utilize the JIT technique to manage their inventory due to its capacity to reduce waste.
[16]	The study examines the role of inventory management knowledge in the link between inventory management practices and performance in micro retailing firms.	This study experimentally investigates inter-organizational market practices (IMPs) in micro retailing firms and the mediating role of knowledge of IMPs in the connection between IMPs and micro-enterprises performance.	Questionnaires	The study reveals that micro-retailing firms use systematic IMPs somewhat, with supplier assessment being the most commonly used IMP.
[40]	Analysing the correlation between inventory management, cost of capital, and business performance in manufacturing firms in Jordan.	This study investigates how the cost of capital influences the relationship between different inventory types and a business's performance.	Quantitative Methods	The findings suggest that different types of inventory management have a lasting influence on corporate performance. Moreover, the cost of capital impacts the correlation between inventory management and achieving organizational objectives.
[14]	Research was conducted to examine the impact of inventory management on the financial performance of the Polish food industry.	The main goal was to study and evaluate alterations in inventory management techniques in the food industry sectors in Poland between 2005 and 2010.	Econometric Analysis	According to the research results, enhancing inventory management effectiveness, as shown by the duration of inventory cycles, can substantially influence financial performance in the Polish food business. Reducing inventory cycles typically leads to increased profitability.

[12]	A study was conducted to investigate the relationship between the efficiency of inventory management and a company's overall success.	The relationship between inventory and business performance is a growing area of research that has received considerable attention in the literature on production and operations management.	Quantitative Methods	The findings demonstrate a direct relationship between the effectiveness of inventory management and the company's overall performance. This finding remains robust when other estimation methods are employed and substitute indicators for firm performance metrics and other variables.

3.1 Years of publication

Notably, the publication timeline depicts a significant rise in articles published annually. In 2023, 134 articles were published, compared to 120 in 2022 and 100 in 2021. This marks a steady increase in publications over the years, with 91 articles in 2020, 74 in 2019, and the lowest publishing rate observed in 2016, with 57 articles. As the data illustrated in Figure 2 indicates, the trend unmistakably demonstrates a consistent uptick in the number of publications produced each year.

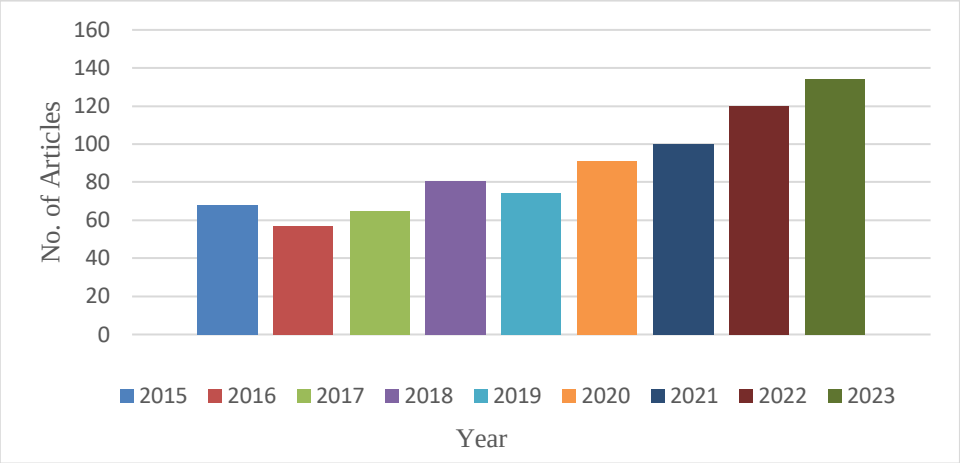

Figure 2 Year of publication

Gebisa's research clarifies how integrated information sharing improves inventory management techniques. Robust information-sharing systems enable businesses to achieve higher performance metrics in their supply chains. This improved information flow results from better decision-making, which is essential in dynamic market situations [36]. The findings suggest that digitization and transparency in inventory processes significantly boost operational efficiency. The research by [37] introduces an innovative perspective by integrating deep reinforcement learning with perishable inventory management. Employing advanced analytics and machine learning optimizes inventory decisions in real-time scenarios, potentially reducing wastage and enhancing responsiveness. This sets a benchmark for future empirical investigations in inventory management systems [15]. Explore the mediational role of knowledge concerning inventory management practices on business performance. A deeper understanding of inventory management influences performance directly and enhances the effects of systematic inventory practices on overall business outcomes. This underscores the importance of training and development in operational strategies for businesses that leverage inventory management as a competitive tool. Studies by [17,19] investigate inventory management within specific contexts—healthcare and manufacturing, respectively. Meticulous inventory management practices significantly uplift Kenya's supply chain performance of antiretroviral medicines. Sophisticated inventory management techniques correlate positively with the performance of manufacturing firms, stressing the sector-specific benefits of tailored inventory strategies [14,38]. Provide insights into the financial aspects linked with inventory management. Effective inventory management, reflected through metrics like days inventory outstanding, directly correlates with improved firm performance and cost management. These findings connect operational practices with financial outcomes, highlighting inventory management as a strategic financial lever. The work of [12,18] extends the discussion to a global and cross-industry perspective, underscoring the universal relevance of efficient inventory management across different geographical and industrial landscapes. The results of this study align with [36] research, which underscores the positive impact of information-sharing systems on supply chain performance.

The current research, however, extends earlier ones through additional analysis of further benefits from integrating real-time analytics and deep reinforcement learning. These findings therefore suggest that in extant literature on inventory management, there should be increased emphasis on how digital technologies can be employed to achieve operational efficiency. The studies advocate for the strategic importance of inventory

management practices in enhancing operational efficiency and adapting to global market demands. The literature suggests advanced inventory management systems significantly enhance operational efficiency and financial performance. Technologies such as deep learning and real-time analytics allow firms to accurately predict and respond to supply chain demands, thus minimizing overstocking and understocking issues. Improved information exchange promotes collaboration throughout the supply chain, improving operations coordination and decreasing lead times.

Moreover, having a comprehensive grasp and effective execution of advanced inventory strategies might serve as a crucial edge in the ever-expanding worldwide markets. Although there are advantages, deploying sophisticated inventory management systems is difficult. Smaller organizations may find the initial cost and complexity of establishing such systems too high, preventing them from doing so. Moreover, the dependence on advanced technologies necessitates substantial expertise and ongoing training of staff, which can be a resource-intensive endeavor. Additionally, digital information systems pose a potential danger of data breaches and security vulnerabilities. Moreover, the efficacy of these systems might be constrained by the caliber of the data supplied, rendering them vulnerable to errors if not meticulously handled. This study expands on SCM Theory by emphasizing the need for real-time data and advanced analytics in modern inventory management. While traditional SCM models suggest coordination among supply chain agents is paramount, our findings showed this coordination and fast response capabilities are further augmented by deep reinforcement learning with real-time analytics, particularly under dynamic conditions. Future SCM frameworks should incorporate such advanced technologies for real-time agility in supply chains.

4 Conclusion

The detailed literature analysis emphasizes how vital inventory management is to improving many types of businesses' operational and financial performance. The increasing trend of research articles from 2016 to 2023 demonstrates the progress and increased focus on this issue. Studies indicate that implementing effective inventory management tactics, such as integrating information, utilizing advanced analytics, and employing deep reinforcement learning, significantly improves supply chain efficiency and overall corporate performance. Increased sharing of information improves the decision-making process and promotes operational efficiency. In addition, new technology allows for immediate optimization of inventory decisions, leading to decreased waste and improved responsiveness. Knowledge of inventory management strategies highlights the necessity for ongoing training and development to improve firm performance. Research on specific industries, such as healthcare and manufacturing, has demonstrated that tailored inventory strategies can significantly enhance supply chain and operational efficiency. Financial evaluations show that days of inventory outstanding improve firm performance and expense management. Inventory management becomes a financial strategy. Modern inventory systems are simple to implement but require continuing training and experience, as well as enormous upfront costs and complexity. Maintaining data accuracy and security is crucial. Modern inventory management solutions give organizations a competitive edge in a global market by ensuring they can meet market needs and enhance efficiency despite challenges.

The findings of this study can be implemented in business by integrating real-time analytics with machine learning approaches in the inventory management system. First, it will be fitting for firms to invest in accessible technologies to monitor data flows on a real-time basis, such as cloud-based inventory systems. These tools could add to predictive insights through which stockouts and overstocking are minimized because demand estimates have been made much more valid. It helps SMEs use scalable software solutions, ensuring that processes and operations are becoming cost-effective and enhancing operational flexibility. Besides, businesses should arrange for staff training to use such an advanced system; employees must be able to read data and make informed, agile decisions. The integration of these practices will improve efficiency and can increase responsiveness in real-time by a firm toward market fluctuations.

Acknowledgments
The authors express their gratitude to the SIMAD University Centre for Research and Development for providing financial support for their research grant, and to all participants in the study.

Contributions by the Author
The research was conducted with equal contributions from all authors, ensuring its integrity and academic standing.

Conflict of interest
The authors have disclosed no conflicts of interest, including financial or personal, that could impact the interpretation or publication of their research findings.

References

[1] MATHIAS, J.M., DATCHE OWUOR, E.: Effects of Inventory Management System on Organizational Performance: Case Study of Grain Bulk Handlers Limited, *International Journal of Sciences: Basic and Applied Research*, Vol. 20, No. 2, pp. 215-232, 2015.
[2] MOHAMED, M.A., SHEIKH MOHAMUD, A., MOHAMUD, I.H., FARAH, M.A.: Examining the Effect of Workplace Relationships on Job Satisfaction among Faculty Members at Private Universities in Mogadishu, *International Journal of Organizational Leadership*, Vol. 13, pp. 377-393, 2024.

[3] RUTAGIRA, Y., AWICHI, R.O.: Statistical Analysis of Inventory Management Systems on Organizational Performance, *East African Journal of Business and Economics*, Vol. 2, No. 1, pp. 20-28, 2020. https://doi.org/10.37284/eajbe.2.1.163

[4] FORRESTER, J.W.: Industrial dynamics: a major breakthrough for decision makers, *Harvard Business Review*, Vol. 36, pp. 37-66, 1958.

[5] ATNAFU, D., BALDA, A.: The impact of inventory management practice on firms' competitiveness and organizational performance: Empirical evidence from micro and small enterprises in Ethiopia, *Cogent Business & Management*, Vol. 5, No. 1, pp. 1-16, 2018. https://doi.org/10.1080/23311975.2018.1503219

[6] MUSAU, E.G., NAMUSONGE, G., MAKOKHA, E.N., NGENO, J.: The Effect of Inventory Management on Organizational Performance Among Textile Manufacturing Firms in Kenya, *International Journal of Academic Research in Business and Social Sciences*, Vol. 7, No. 11, pp. 1032-1046, 2017. https://doi.org/10.6007/ijarbss/v7-i11/3543

[7] JOSEPH, F.I., OMODERO, C.O., OKEZIE, U.C.: Inventory Control Management and Revenue Generating Capabilities of Oil and Gas Drilling Firms in Nigeria, *Annals of Spiru Haret University, Economic Series*, Vol. 19, No. 4, pp. 75-95, 2019. https://doi.org/10.26458/1947

[8] GUPTA, S.: Enhancing Business Operations through Effective Inventory Management, *International Journal for Research Publication and Seminar*, Vol. 1, No. 1, pp. 121-125, 2012.

[9] MOHAMED, M.A., FARAH, M.A., JAMA, L.A., MOHAMUD, I.H., MOHAMUD, I.H., SIYAD, M.A., MALIN, I.M.: A Decade of Reverse Logistics Research (2013-2023): A Comprehensive Bibliometric Analysis of Trends, Influences, and Global Engagement, *Journal of Logistics, Informatics and Service Science*, Vol. 11, No. 7, pp. 37-53, 2024. https://doi.org/10.33168/JLISS.2024.0703

[10] OBALLAH, D., WAIGANJO, E., WACHIURI, E.W.: Effect of Inventory Management Practices on Organizational Performance in Public Health Institutions in Kenya: A Case Study of Kenyatta National Hospital, *International Journal of Education and Research*, Vol. 3, No. 3, pp. 703-714, 2015.

[11] AGÙ, A.O., NNATE, E.C.: Effect of Inventory Management on the Organizational Performance of the Selected Manufacturing Firms Obi-Anike, Happiness Ozioma, *Singaporean Journal of Business economics, and management studies*, Vol. 5, No. 4, pp. 56-69, 2016.

[12] ELSAYED, K.: Exploring the relationship between efficiency of inventory management and firm performance: Empirical research, *International Journal of Services and Operations Management*, Vol. 21, No. 1, pp. 73-86, 2015. https://doi.org/10.1504/IJSOM.2015.068704

[13] OROBIA, L.A., NAKIBUUKA, J., BANANUKA, J., AKISIMIRE, R.: Inventory management, managerial competence and financial performance of small businesses, *Journal of Accounting in Emerging Economies*, Vol. 10, No. 3, pp. 379-398, 2020. https://doi.org/10.1108/JAEE-07-2019-0147

[14] GOALS, Z., BIENIASZ, A.: Empirical analysis of the influence of inventory management on financial performance in the food industry in Poland, *Engineering Economics*, Vol. 27, No. 3, pp. 264-275, 2016. https://doi.org/10.5755/j01.ee.27.3.5933

[15] PANIGRAHI, R.R., MEHER, J.R., SHRIVASTAVA, A.K., PATEL, G., JENA, L.K.: Operational performance entitling the knowledge of inventory management practices on business performance: a mediational study, *Global Knowledge, Memory and Communication*, Vol. 73, No. 6/7, pp. 738-756, 2024. https://doi.org/10.1108/GKMC-07-2022-0177

[16] AHMAD, K., ZABRI, S.M.: The mediating effect of knowledge of inventory management in the relationship between inventory management practices and performance: The case of micro retailing enterprises, *Journal of Business and Retail Management Research*, Vol. 12, No. 2, pp. 83-93, 2018. https://doi.org/10.24052/jbrmr/v12is02/tmeokoimitrbimpaptcomre

[17] SAHOO, A., TANDON, D., JENA, D., MISHRA, P.C., MEHER, J.R., PANIGRAHI, R.R.: Inventory Management and Performance of Manufacturing Firms, *International Journal of Value Chain Management*, Vol. 12, No. 2, pp. 149-170, 2021. https://doi.org/10.1504/ijvcm.2021.10033598

[18] JAMA, M., OKOUMBA, W.V. L., MAFINI, C.: A Model for Inventory Management and Warehouse Performance in The South African Retail Industry, *Logforum*, Vol. 19, No. 4, pp. 555-575, 2023. https://doi.org/10.17270/J.LOG.2023.920

[19] JOHNSON, A., PETER, K., SHITAL, M.: Inventory Management Practices and Supply Chain Performance of Antiretroviral Medicines in Public Hospitals in Nyamira County, Kenya, *Rwanda Journal of Medicine and Health Sciences*, Vol. 4, No. 2, pp. 257-268, 2021. https://doi.org/10.4314/rjmhs.v4i2.5

[20] OUBRAHIM, I., SEFIANI, N., HAPPONEN, A.: Supply Chain Performance Evaluation Models: A Literature Review, *Acta logistica*, Vol. 9, No. 2, pp. 207-222, 2022. https://doi.org/10.22306/al.v9i2.298

[21] LAMZAOUEK, H., DRISSI, H., MIALED, K.: On the relationship between cash flow bullwhip and the company performance: study of the Moroccan detergent products branch, *Acta logistica*, Vol. 10, No. 3, pp. 375-388, 2022. https://doi.org/10.22306/al.v10i3.403

[22] CHAKRABORTY, K., MONDAL, S., MUKHERJEE, K.: Developing a causal model to evaluate the critical issues in reverse supply chain implementation, *Benchmarking*, Vol. 25, No. 7, pp. 1992-2017, 2018. https://doi.org/10.1108/BIJ-12-2016-0181

[23] KAZEMI, N., MODAK, N.M., GOVINDAN, K.: A review of reverse logistics and closed loop supply chain management studies published in IJPR: a bibliometric and content analysis, *International Journal of Production Research*, Vol. 57, No. 15-16, pp. 4937-4960, 2019. https://doi.org/10.1080/00207543.2018.1471244

[24] PRAJOGO, D., CHOWDHURY, M., YEUNG, A.C.L., CHENG, T.C.E.: The relationship between supplier management and firms operational performance: A multi-dimensional perspective, *International Journal of Production Economics*, Vol. 136, No. 1, pp. 123-130, 2012. https://doi.org/10.1016/j.ijpe.2011.09.022

[25] SHOU, Y., LI, Y., PARK, Y., KANG, M.: Supply chain integration and operational performance: The contingency effects of production systems, *Journal of Purchasing and Supply Management*, Vol. 24, No. 4, pp. 352-360, 2018. https://doi.org/10.1016/j.pursup.2017.11.004

[26] MOHER, D., LIBERATI, A., TETZLAFF, J., ALTMAN, D.G., GROUP, P.: Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement, *PLoS Medicine*, Vol. 6, No. 7, pp. 1-6, 2009.

[27] ROSA, A.C.M., BRODAY, E.E.: Comparative analysis between the industrial and service sectors: A literature review of the improvements obtained through the application of lean six sigma, *International Journal for Quality Research*, Vol. 12, No. 1, pp. 227-252, 2018. https://doi.org/10.18421/IJQR12.01-13

[28] PAHLEVAN-SHARIF, S., MURA, P., WIJESINGHE, S.N.R.: A systematic review of systematic reviews in tourism, *Journal of Hospitality and Tourism Management*, Vol. 39, pp. 158-165, 2019. https://doi.org/10.1016/j.jhtm.2019.04.001

[29] ZHU, J., LIU, W.: A tale of two databases: The use of Web of Science and Scopus in academic papers, *Scientometrics*, Vol. 123, pp. 321-335, 2020. https://doi.org/10.1007/s11192-020-03387-8

[30] SELIVERSTOVA, Y.: Workforce diversity management: A systematic literature review, *Strategic Management*, Vol. 26, No. 2, pp. 3-11, 2021. https://doi.org/10.5937/straman2102003s

[31] ANKER, M., HADZIBEGOVIC, S., LENA, A., HAVERKAMP, W.: The difference in referencing in Web of Science, Scopus, and Google Scholar, *ESC Heart Fail*, Vol. 6, No. 6, pp. 1291-1312, 2019. https://doi.org/10.1002/EHF2.12583

[32] SALISBURY, L.: Web of Science and Scopus: A Comparative Review of Content and Searching Capabilities, *The Charleston Advisor*, Vol. 2009, pp. 5-18, 2009.

[33] PATEL, A.K., SINGH, M., SINGH, K., PATEL, A.K., VARMA, A.K., KURI, R.: Visualizing Publication Trends in Webology Journal: A Bibliometric Review based on the Scopus Database (2006-2020), *Library Philosophy and Practice (e-journal)*, Vol. 2021, pp. 1-22, 2021.

[34] KRAUS, S., BREIER, M., DASÍ-RODRÍGUEZ, S.: The art of crafting a systematic literature review in entrepreneurship research, *International Entrepreneurship and Management Journal*, Vol. 16, No. 3, pp. 1023-1042, 2020. https://doi.org/10.1007/s11365-020-00635-4

[35] JAMA, L.A., MOHAMUD, I.H.: The Impact of Procurement Practices on Organizational Performance: A Literature Review, *Journal of Logistics, Informatics and Service Science*, Vol. 11, No. 1, pp. 119-135, 2024. https://doi.org/10.33168/JLISS.2024.0108

[36] GEBISA, D.A.: The Impact of Information Sharing and Inventory Management Practices on Firms' Performance in Supply Chain Practices, *Gadjah Mada International Journal of Business*, Vol. 25, No. 2, pp. 199-225, 2023.

[37] DE MOOR, B.J., GIJSBRECHTS, J., BOUTE, R.N.: Reward shaping to improve the performance of deep reinforcement learning in perishable inventory management, *European Journal of Operational Research*, Vol. 301, No. 2, pp. 535-545, 2022. https://doi.org/10.1016/j.ejor.2021.10.045

[38] ALJAAIDI, K., BAGAIS, O.A.: Days inventory outstanding and firm performance: empirical investigation from manufacturers, *Accounting*, Vol. 6, No. 6, pp. 1111-1116, 2020. https://doi.org/10.5267/j.ac.2020.7.007

[39] MULANDI, C.M., ISMAIL, N.: Effect of Inventory Management Practices on Performance of Commercial State Corporations in Kenya, *International Academic Journal of Procurement and Supply Chain Management*, Vol. 3, No. 1, pp. 180-197, 2019.

[40] ALRJOUB, A.M.S., AHMAD, M.K.: Inventory management, cost of capital and firm performance: evidence from manufacturing firms in Jordan, *Investment Management and Financial Innovations*, Vol. 14, No. 3, pp. 4-14, 2017. http://dx.doi.org/10.21511/imfi.14(3).2017.01

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 131-139 ISSN 2453-675X

https://doi.org/10.22306/atec.v10i4.225 Received: 24 Sep. 2024; Revised: 05 Nov. 2024; Accepted: 29 Nov. 2024

Study on reverse logistics and its significant importance – review

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Keywords: supply chain, reverse logistics, operation management, refurbishment, resale.
Abstract: Reverse logistics (RL) has become increasingly significant in the field of supply chain and operation systems in recent years. One of the key components of operation and supply chain systems for carrying out business activities in a more methodical and effective manner to boost value addition for end users is reverse logistics. Returning final used goods from the customer's end to the manufacturer via a store is known as reverse logistics. The main purpose of reverse logistics is to make the final product flow from customer back to seller or manufacturer in order to reuse the product by recycling this reduces the cost of remanufacturing the product also it adds value to the customers through recycling the product. In this article attempt has been made to conduct extensive survey on logistics and its significant role in supply chain operations. In addition to that literature analysis is done by referring from various top-rated journals around the globe. The survey questions were prepared to collect the inputs from various customers to further reframe the design of Reverse logistics.

1 Introduction

The process of returning goods from buyers back to sellers or manufacturers It's called reverse logistics. After a customer receives an item, reverse logistics is required for activities like recycling or product returns. The process of reverse logistics involves starting with the final consumer and working backwards through the supply chain to the distributor or the distributor to the producer. Recycling, refurbishing, and resale are examples of processes where the product's disposal is left to the end user can also be included in reverse logistics. When items are sent backward through the supply chain to the seller and maybe back to the suppliers, organizations employ reverse logistics. Getting rid of the thing or recovering its worth is the aim. Returns have grown in frequency with the expansion of e-commerce and are valued at about a trillion dollars annually globally (opens in a new tab). Recovering value and ensuring repeat business are the goals of reverse logistics. In contrast to at least 30% of things ordered online, less than 10% of purchases made in-store are returned (opens in a new tab). Savvy businesses employ reverse logistics to reduce return loss and foster client loyalty and repeat business.

In today's corporate climate, reverse logistics is becoming more and more crucial. Businesses are realizing that in order to support corporate objectives and maintain attempts to become more sustainable, they must manage returns, recalls, and other defective products.

1.1 Were reverse logistics can be applied

Businesses of all kinds can benefit from the practice of reverse logistics. This strategy can help businesses that produce and market goods like electronics, apparel, and furniture. This procedure can also be used by distributors, wholesalers, and retailers to handle refunds and exchanges. Additionally, it can be used by Third-Party Logistics (3PL) providers to offer their business-to-business (B2B) clients services.

Companies in the service sector, such as those that provide equipment, cars, and maintenance services, can also employ this kind of logistics strategy. To handle the return of damaged components from the items that customers rent, they might make use of reverse logistics.

1.2 Discrimination between traditional logistics and reverse logistics

The process of moving products from suppliers to factories, production facilities, distributors, retailers, and final consumers is called traditional logistics, sometimes referred to as forward logistics.

The process by which items arrive from customers and go in the opposite direction to any point or stakeholder in the supply chain is known as reverse logistics.

Physical illustration of reverse logistics are shown in Figure 1.

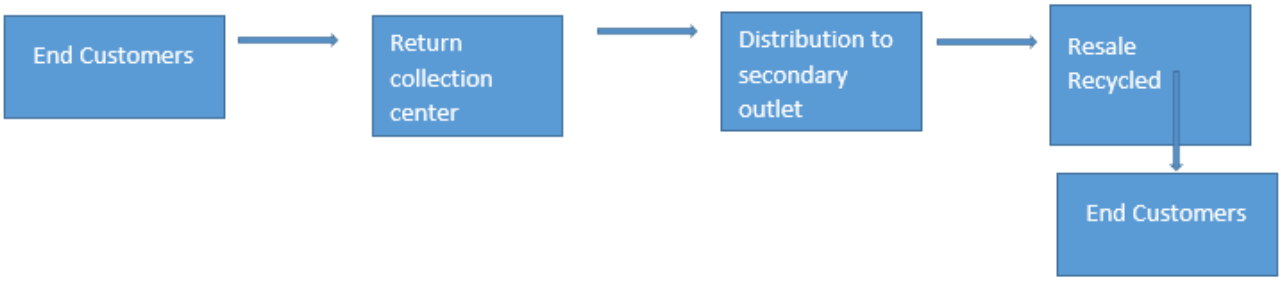

Figure 1 Physical representation of reverse logistics

Over the past ten years, the markets and business models for reverse logistics (RL) and closed loop supply chains (CLSC) have received more attention. This is caused in part by the impact of green regulations, especially in Europe, and the realization of the growing value of the goods and technologies developed in this area at the end of broad direct supply chains. Because of urbanization and the growing population density of metropolitan regions, the question of how to properly dispose of waste, trash, and junk has always existed. Due to the emergence of hazardous products and waste, the effects on the environment, and the increasing need to manage and dispose of human and animal waste in order to preserve public health and safety, the issues grew more urgent during the industrial revolution.

Since reverse logistics is a relatively new idea, scholars and logistics firms have only recently attempted to concentrate on how it affects managerial choices. Additionally, the emphasis on enhancing customer happiness has grown significantly in recent years since it is now seen as a critical component of any business's growth. Reverse logistics can significantly increase customer satisfaction, according to recent studies.

2 Literature review

Senthil S. and Sridharan R. (2014) The purpose of this study is to motivate and provide academics with ideas for future reverse logistics research topics. Because supply chains are designed for onward flow, it might be difficult to include product recovery into the network architecture. The analysis of reverse logistics' difficulties is one of the most significant duties of senior management and could be essential to the future survival of the sector. Reverse logistics practices are reviewed in this research using published literature [1].

Anon S. Y. et al (2024) Reverse logistics (RL) is essential for fulfilling sustainability goals, cutting waste, and improving supply chain management in today's more interconnected world. With the aid of mathematical algorithms, deterministic decision-making models evaluate variables and predetermined criteria, including capacity, cost, and reliability, across different geographic locations. The unpredictable nature of real-world situations, on the other hand, is incorporated into uncertain decision-making models by taking into account the uncertainties and ramifications of decisions and choices based on insufficient knowledge, ambiguity, unreliability, and the possibility of several likely outcomes [2].

Namweseza Z. et al. (2024) Reverse logistics is becoming an essential skill for pharmaceutical companies in the highly competitive market. These companies look to gain a competitive edge by managing returns and recalls effectively, whether it is because of errors, expired stock, quality or environmental issues, non-compliance, or other customer-related concerns. Even however, the significance of RL is not well recognized in many developing nations where the pharmaceutical industry plays a significant role in the economy. Four essential reverse logistics capabilities—logistics information systems, process formalization, flexibility, and top management support—are the focus of this study, which investigates the conflicting effects of these capabilities on pharmaceutical supply chains in developing nations [3].

Banihashemi T. A. et al (2019) As a strategic option, reverse logistics (RL) is receiving a lot of attention from organizations because to its positive effects on sustainable development. In order to evaluate the efficacy of the reinforcement learning process in connection to the social, economic, and environmental aspects of sustainability, this manuscript aims to perform a comprehensive literature review. The findings of this investigation show that most studies have focused on assessing RL's performance while accounting for economic and environmental performance. Due to the positive social results it produces, RL's social side has been underused and requires more study. Furthermore, the impact of each disposal option on the triple-bottom-line sustainability performance has not been assessed in any study [4].

Rubio S. and Jiménez-Parra B. (2014) Reverse logistics (RL) is a research area focused on the management of the recovery of products once they are no longer desired (end-of-use products, EoU) or can no longer be used (end-of-life products) by the consumers, in order to obtain an economic value from the recovered products. This paper aims to introduce the concept of RL and its implications for supply

chain management (SCM). Because of this, RL has grown to be a strategic concern and is now taken into account by businesses when making decisions on the structure and evolution of their supply networks. Finally, a summary of the implications of reinforcement learning (RL) for supply chain management (SCM) will be covered, along with an examination of some of the potential benefits and drawbacks implied by RL [5].

Pokharel S. and Mutha A. (2009) Through a content analysis of the available literature, this paper examines the current state of research and practice in reverse logistics (RL). We have located and reviewed the literature using a variety of web-based search engines, books, and conference proceedings. As per the review, research and practice in reverse logistics (RL) are concentrated on every facet of RL, starting from the gathering of old items, processing them, and ultimately arriving at the processing outputs, which include recycled materials, spare parts, remanufactured products, and disposal of waste materials [6].

Kazemi N. et al. (2019) Green supply chains may benefit from the use of reverse logistics and closed loop supply chain management (RL&CLSCM), two widely acknowledged eco-friendly techniques. A significant amount of literature has evolved as a result of the popularity of these research areas. To date, the area has benefited from the contributions of numerous journals; among the most well-known of these is the International Journal of Production of Research (IJPR). In-depth bibliometric and content analyses of 94 papers published in IJPR between 2000 and July 2017 are presented in this report. Initially, a thorough bibliometric and mapping analysis was conducted on the papers, which assisted in identifying their characteristics. The contents of the sample papers were then carefully assessed. The papers were categorized into two primary groups and their subcategories based on the results of the content analysis, and their attributes were then carefully determined [7].

Dabees A. et al. (2023) Reverse logistics is becoming a necessary competitive requirement for sustainability. The costs and customer service of many supply chains have been negatively impacted by a lack of resources to implement reverse logistics solutions, making it hard to meet return processing standards. Under such circumstances, the primary forces behind successful sustainability operations are client requests for greater service quality. The purpose of this study is to provide the theoretical framework for sustainable reverse logistics service quality, or SRLSQ, that reverse logistics service providers (RLSPs) supply. 56 papers from 2011 to 2022 were found utilizing a systematic approach protocol that examines reputable academic journals using PRISMA criteria based on the research scope. The primary focus of the study is on the SSQ and RLSQ aspects in order to establish a research framework [8].

Turrisi M. et al. (2012) This research aims to analyze how reverse logistics affects inventory variance and order amplification in a single-echelon supply chain (SC) and suggests a new order policy to reduce this amplification. The research is based on a general examination of the literature on reverse logistics's effect on SC performance and on sustainable operations. Modeling and analyzing a closed SC, the authors employ a difference equation math technique. The resulting numerical results are validated by an appropriate experiment design and data gathered from the statistics of the European Union [9].

Agrawal S. et al. (2015) Because of rising environmental concerns, laws, corporate social responsibility, and sustainable competitiveness, reverse logistics (RL) has become a crucial area of focus for all firms in recent years. When we talk about reuse, repair, remanufacturing, recycling, or disposal, we're talking about the series of steps needed to gather used products from customers. An analysis of the literature reveals that the subject of reinforcement learning is still developing and that there is a lack of comprehensive reviews on topics including adoption and implementation, product return predictions, outsourcing, RL networks from the standpoint of secondary markets, and disposition decisions [10].

De Brito M. P. (2005) The procedures involved in moving goods, parts, and materials from owners or users to other users are known as reverse logistics. In this work, over sixty case studies on reverse logistics are reviewed and their contents analyzed. The case studies address topics including inventory management, planning and control, information technology, network structure, and the interactions between the various stakeholders on the networks [11].

Shi C. et al. (2009) The importance of reverse logistics implementation was first discussed in the paper, which also examined its challenges from the perspective of supply chain management. Finally, countermeasures for the implementation of reverse logistics management were suggested [12].

Govindan K. et al. (2015) Reverse logistics and closed-loop supply chain challenges have brought attention from academics and practitioners due to environmental, legal, social, and economic factors. A large number of these works have been published in scientific journals in recent years, demonstrating this focus. For this reason, a thorough literature evaluation of current and cutting-edge works is essential to provide context for the past and to suggest future lines of inquiry. In order to better understand reverse logistics and closed-loop supply chains, this study will evaluate recent publications in scientific journals. The

selected and evaluated papers are a total of 382 published between January 2007 and March 2013 [13].

Alkahtani M. et al. (2021) Today, organizations and scholars all around the world are concentrating on sustainable development. Various ideas have been presented to promote sustainability in supply chains, including closed-loop supply chains and reverse logistics (RLs). Reusable goods (RLs) are the actions required by customers to gather used goods for recycling, remanufacturing, reuse, or disposal. Collection systems is one of the many procedures that go into reinforcement learning. The term "collection" describes how a business comes into possession of particular goods. We examine the research on collection mechanisms for RLs. To gain more knowledge about the topic and identify any patterns, a bibliometric studywascarriedout. First, based on review papers that are currently available, we share the classification schemes that are applied in the field. Furthermore, we assess scholarly works pertaining to many domains that are associated with the technical aspects or the problem formulation. Presentations and classifications of various viewpoints are made. Manuscripts relevant to the reader's interests can be found more easily with this strategy. Emerging themes in assessing the effectiveness of collection systems are recognized throughout the assessment of the literature, along with suggested avenues for further investigation [14].

Straka M. (2019) All company processes connected with logistics are repeated, the so-called logistic propeller. Supply, storage, production, planning and transportation activities are divided into separate parts, which requires systematic planning to ensure effective coordination of material flow, production and distribution of products. Inventory holding costs include costs associated with inventory management, packaging of goods, and costs associated with reverse logistics activities [15].

Mohamed A. G. et al. (2015) Because of the advantages used-product recovery offers on the social, economic, and environmental fronts, its implementation is growing in the industrial and service sectors alike. For any product recovery to be successful, there must be a consistent supply of old goods because reverse supply is obviously necessary. In the distribution channel, reverse logistics refers to the transfer of used goods from the customer to the manufacturer. A number of factors, including legal requirements, rising trash levels, and consumer awareness of eco-friendly products, were identified in the literature analysis as drivers of reverse logistics that compel organizations to apply. The advantages of using reverse logistics, including cost savings, improved customer satisfaction, and the availability of less expensive products, have been explained by numerous writers. The majority of earlier research focuses on showing how reverse logistics can be used in various industries. Few research, meanwhile, have looked at how reverse logistics affects customer satisfaction [16].

Guo S. et al. (2017) Reverse logistics is an extremely relevant and important field as environmental sustainability is becoming more and more widely known. The performance of logistics systems has historically been demonstrated to be improved by the application of supply chain contracts. Supply chain contracts in reverse logistics, however, are the subject of a patchy body of current scholarship. The objective of this work is to examine the latest research on supply chain contracts, specifically focusing on reverse logistics systems, and reviewing the state-of-the-art literature from 2006 to 2016.

We examine how common various supply chain contract types are and list the most successful scholars in the field. We categorize and review the literature in terms of the channel leaderships (i.e., the person who leads) and the supply chain structure (i.e., the chain links that are engaged). Lastly, we address the corresponding research problems, identify the research gaps, and propose five main areas for future research initiatives [17].

Jayant, A. et al. (2012) Sustainability in supply networks is believed to be founded on the rise of environmental and economic concerns, which have a substantial influence on reverse supply chain management. A review of the literature reveals that the field of reverse supply chain management lacks a well-developed framework. While research on this topic is still in its early stages, it has recently been apparent that the reverse logistics components of sustainable supply chain practices contribute to better integrated supply chains, which in turn can enhance economic performance. It is imperative that companies take into account the perspectives of the economy and the environment. The features of RSCM that are presented here can aid future study and practice advancement for researchers and practitioners [18].

Umeda S. (2013) Businesses aim to minimize their negative environmental impact by reusing, remanufacturing, and recycling used products as a form of ecological and environmental responsibility. One of the key components needed to build a supply chain system this sustainable is reverse logistics. The modeling and analysis techniques for supply chain systems with reverse logistics flows are proposed in this work. The two forms of reverse supply chains covered in this research are PULL- and PUSH-type reverse logistics. Analysis examples of particular features will be shown together with the introduction of generic models [19].

Le S.-T. (2023) The importance of reverse logistics systems for improving an organization's overall financial and environmental performance is now widely recognized, especially for poorer countries where these issues are more

pressing. In industrialized nations, the majority of study looked at implementation drivers and impediments. With a focus on developing nations like Vietnam, this study seeks to identify the key variables that favorably affect reverse logistics practices. 287 managers from 5 different industries were included in the study's sample. The results indicated that the following four major factors—economic, competitive, outsourcing, and environmental—had an impact on the deployment of reverse logistics in developing nations.

Contrary to expectations, reverse logistics performance is not much impacted by regulation drivers or reputation drivers. The results aid researchers in comprehending the variables affecting reverse logistics activities in developing countries. The results also show that developing and developed nations have different drivers for the execution of reverse logistics [20].

Rehman S. A. and Khan S. S. (2017) In recent years, the idea of reverse logistics has become increasingly popular. Reverse logistics is undoubtedly growing more significant in the automotive industry's supply chain management. The primary aim of this study is to discuss the significance of reverse logistics within the context of supply chain management, with a particular emphasis on the automotive sector. The purpose of this article is also to highlight the significant obstacles facing reverse logistics in the automotive sector. When products are managed after they are no longer useful to customers, it is known as reverse logistics [21].

Tyagi V. (2021) Scholarly articles on the subject attest to the frequency with which scholars have focused on supply chain and reverse logistics issues impacted by a variety of changeable environmental elements. Upon conducting a comprehensive analysis of the published literature in this field, this review paper was conceived. With this paper, we hope to lay forth a framework that will be useful for conducting more research in this area. Review and analysis were done on 150 publications that were published between 1995 and 2020. The research gaps that can be filled by conducting studies in the near future are thus those that were found after this review. In this publication, it is mentioned that some recent research has been conducted on reverse logistics following the COVID-19 epidemic. These studies provide e-retailers guidance so they can prepare for future encounters with incidents of this nature [22].

Larsen S. B. et al. (2024) Reverse supply chain (RSC) operations have historically been seen by manufacturers as an expensive hassle, but more recent studies have shown that RSC can actually improve a company's financial performance. This study explores the exogenous contingency elements that determine the magnitude of the contribution and highlights the ways in which the RSC might improve the financial performance of the company. The exogenous elements impact the RSC's financial contribution regardless of management policies and design choices since they are uncontrollable by the company's operations and supply chain management. Fifteen different ways for RSC to improve the firm's financial performance have been found by the study. Fifty-six contingency factors have been found in this investigation. Market segmentation, consumer behavior, product design, and the company's distributor network are all connected to these. In addition to the RSC's input, the study provides an interrelationship network between components [23].

Wang M. et al. (2020) A major problem that impedes the advancement of contemporary logistics and supply chain management is the uncertainty inherent in the supply chain, which has grown in complexity. The purpose of the research is to provide a triadic model of reverse logistics uncertainty by conceptualizing it based on supply chain uncertainty literature. Based on a triadic model of supply chain uncertainty and logistics uncertainty, the idea of reverse logistics uncertainty was established. A taxonomy of reverse logistics uncertainty is created through desk research. We address the many forms of reverse logistics uncertainty in the triadic model using case studies in order to more accurately illustrate the uncertainty [24].

Ljubičić K. and Bajor I. (2021) If not continually optimized and frequently left unclear, reverse logistics procedures result in large expenditures associated with logistics. While reverse logistics constraints include things like process length, educated people, and dissatisfied customers, logistics businesses stress the importance of optimization and process uniformization to the greatest extent possible. The logistics market research for the Republic of Croatia has chosen to analyze the reverse logistics process at a supplier's site. The case study focuses on difficulties related to reverse logistics, on-site investigation, and opportunities for process optimization that save time. Analysis and recommendations for optimization have been given for each reverse logistics process over a period of time measurement [25].

Mohamed M. A. et al. (2024) This paper provides a thorough bibliometric analysis of research on reverse logistics (RL) from 2013 to 2023 with the goal of identifying major themes, significant writers, institutional contributions, and international involvement in the subject. Based on information extracted from 1,650 papers in the Scopus database, the Analysis shows how RL is becoming more and more important in supply chain management and sustainability studies. Authorship analysis, temporal analysis, institutional contribution analysis, worldwide participation analysis, journal impact analysis, keyword dynamics analysis, and citation network analysis are only a few of the bibliometric approaches used in the study [26].

Djikanovic, J. and Vujosevic M. (2015) The increase in the quantity of product recovery and recycling activities is mostly driven by regulatory requirements, although user needs also play a role. Consequently, a substantial amount of materials and products have been pulled off the market for a particular cause. This calls for entirely new methods of decision-making that the managers are unfamiliar with. A novel integrated forward and reverse logistics model (IFRL) is presented in this research. Location capacities are assumed to be finite. A problem of mixed-integer linear programming (MILP) aiming at minimizing the overall cost is introduced [27].

Melan, M. B. (2021) The study looks into Chinese university students' practices of returning used paper boxes when they shop online. Additionally, it can look at studies comparing online buying in different nations and implementing the idea of reverse logistics. Nowadays, the most common form of payment is online purchasing, particularly for convenience purposes among working people and students. Online shopping offers the advantages of shorter wait times, lower personal expenses, and a wider selection of less expensive goods. When it comes to packing, the majority of online retailers use specially made paper boxes to package their goods before shipping them to their clients [28].

Mishra O. and Singh S. (2023) In order to recover the value of End of Life (EOL) assets, reverse logistics helps move commodities from the customer to a facility. Product recovery management is able to accomplish this. One way to increase cost competitiveness is by reusing the recovered material as a raw material in manufacture. In addition, reverse logistics (RL) facilitates easy return policies for online shoppers and reduces pollution and costs associated with raw materials and waste. In order to make RRL a viable endeavor and more environmentally conscious, this study emphasizes how important it is. A road map for top management to fulfill their social obligation of caring for End-of-Life products generated by their companies is also provided by the study, since humans are becoming less wasteful and indifferent to their environment. The best application of RL may be to reduce the issues associated with disposing of waste from electronics and plastics, polluting the air, land, and seas, and eliminating rare metals that are valuable to humanity [29].

Antonyová A. et al. (2018) The sustainability of natural resources and our ability to access them directly affect the state and quality of the environment today. Our planet's future is directly impacted by manufacturing activity and related events. The recycling process, which in large businesses frequently develops into a crucial and essential component of the production schedule, is typically difficult in small and medium-sized businesses. A few elements stand out as having a direct bearing on the creation and successful implementation of an efficient reverse logistics system [30].

Xin C. et al. (2022) The crucial influence that safe transportation and efficient handling of hazardous waste have on environmental sustainability and public health has led scholars and practitioners to focus closely on reverse logistics of municipal hazardous waste (RLMHW). A thorough and comprehensive summary of the research activities previously carried out in this specific field is noticeably lacking from the large number of studies that make up the body of existing literature on RLMHW, despite the fact that the study themes covered are numerous and varied. By conducting an extensive and methodical literature assessment of RLMHW over the previous three decades, this paper aims to close the gap and create a foundation for future RLMHW research [31].

Malkus T. and Kozina A. (2023) The concept of the description of negotiations within reverse logistics cooperation is a preliminary approach to the issues under consideration, since they are relatively new, not fully recognized in theory and research, as well as in economic practice. Therefore, it is necessary strive to enrich and broaden his concept, mainly by searching for more precise characteristics of the considered features of the negotiations under consideration. It is also necessary planned to conduct comparative empirical research in order to verify the usefulness of the reverse logistics concept [32].

3 Methodology

In this section an attempt has been made to design survey form for collecting information on reverse logistics in supply chain management. The following are the questionnaire framed in the survey form as listed below:

Q1. How would you be able to rank the performance of Reverse logistics in SCM out of 5.0 scale?

Q2. What is the level of customer satisfaction index towards reverse logistics? Rate it using 5.0 scale?

Q3. How would you be able to rate the strategic value of reverse logistics in SCM?

Q4. Measure the benefit of Reverse logistics in 5.0 scale rating.

Q5. In Reverse logistics maximizing the values of recovered items significantly improves profit margins. Rate it using scale values from 0 to 5.

These are the above set of questionnaires framed and sent to various respondents like students, faculties, industrialists etc.

The total number of responses collected was 11 during the survey analysis.

4 Case study

In this section detailed case study on reverse logistics performance in Supply chain management is presented to

illustrate the survey inputs given by various respondents across the nation. Let us discuss the Responses given by various experts as follows:

Q1. How would you be able to rank the performance of Reverse logistics in Supply Chain Management out of 5.0 scale?

Responses:

a. 81.8 % of the responses given the rating as 4.5 out of 5 scale for Supply chain Management performance in reverse logistics.

b. The remaining 9.1% of the responses were found to be 2.5 and 5.0 out of 5 scale.

Q2. what is the level of customer satisfaction index towards reverse logistics. Rate it using 5.0 scale?

Responses:

a. 60 % of the responses given the rating as 4.5 out of 5.0 scale.

b. The remaining 30 % of the responses were found to be as 2.5 and 10 % of the responses measured to be 5.0 out of 5 scale rating.

Q3. How would you able to rate the strategic value of reverse logistics in SCM?

Responses:

a. 45.5% of the responses fixed their rating as 4.5 for strategic value of reverse logistics in SCM.

b. 45.5% of the responses framed their rating as 5.0 for strategic value of reverse logistics in SCM.

c. 9.1% of the responses fixed their rating as 2.5 for strategic value of reverse logistics in SCM.

Q4. Measure the benefit of Reverse logistics in 5.0 scale rating.

Responses:

a. 50 % of the responses given their rating as 5.0 out of 5 scale for benefits of reverse logistics.

b. 40 % of the responses given their rating as 4.5 out of 5 scales.

c. 10% of the responses given their rating as 2.5

5 Conclusion

In this research work attempt has been made to perform literary work on reverse logistics in SCM performance. Nowadays reverse logistics plays important role in every manufacturing organization to achieve the various objectives. Reverse logistics tries to cut down the wastage costs of final products. Instead, the same products are used again by refilling it without the aid of new one. Case study with various questionnaires prepared by collecting responses from various peoples from education industry, Manufacturing Industry etc. Based on the responses given the results and discussion were analyzed in the case study. The main key input is to maximize the logistics efficiency by minimizing the transpiration cost in holding the items.

References

[1] SENTHIL, S., SRIDHARAN, R.: Reverse Logistics: A Review of Literature, *International Journal of Research in Engineering and Technology*, Vol. 3, No. 11, pp. 140-144, 2014. http://dx.doi.org/10.15623/ijret.2014.0323031

[2] ANON, S.Y., AMIN, S.H., BAKI, F.: Third-Party Reverse Logistics Selection: A Literature Review, *Logistics*, Vol. 8, No. 2, 35, pp. 1-14, 2024. https://doi.org/10.3390/logistics8020035

[3] NAMWESEZA, Z., NDANDIKO, C., OBANDA, P.W., MUGURUSI, G.: Reverse logistics capabilities and supply chain performance in a developing country context, *Supply Chain Forum: An International Journal*, pp. 1-13, 2024, https://doi.org/10.1080/16258312.2024.2384828

[4] BANIHASHEMI, T.A., FEI, J., CHEN, P.S.-L.: Exploring the relationship between reverse logistics and sustainability performance A literature review, *Modern Supply Chain Research and Applications*, Vol. 1, No. 1, pp. 2-27, 2019. https://doi.org/10.1108/MSCRA-03-2019-0009

[5] RUBIO, S., JIMÉNEZ-PARRA, B.: Reverse Logistics: Overview and Challenges for Supply Chain Management, *International Journal of Engineering Business Management*, Vol. 6, No. January, pp. 1-7, 2014. https://doi.org/10.5772/58826

[6] POKHAREL, S., MUTHA, A.: Perspectives in reverse logistics: A review, *Resources, Conservation and Recycling*, Vol. 53, No. 4, pp. 175-182, 2009. https://doi.org/10.1016/j.resconrec.2008.11.006

[7] KAZEMI, N., MODAK, N.M., GOVINDAN, K.: A review of reverse logistics and closed loop supply chain management studies published in IJPR: a bibliometric and content analysis, *International Journal of Production Research*, Vol. 57, No. 15-16, 2019. https://doi.org/10.1080/00207543.2018.1471244

[8] DABEES, A., BARAKAT, M., ELBARKY, S.S., LISEC, A.: A Framework for Adopting a Sustainable Reverse Logistics Service Quality for Reverse Logistics Service Providers: A Systematic Literature Review, *Sustainability*, Vol. 15, No. 3, 1755, pp. 1-16, 2023. https://doi.org/10.3390/su15031755

[9] TURRISI, M., BRUCCOLERI, M., CANNELLA, S.: Impact of reverse logistics on supply chain performance, *International Journal of Physical Distribution & Logistics Management*, Vol. 43, No. 7, pp. 564-585, 2013. https://doi.org/10.1108/IJPDLM-04-2012-0132

[10] AGRAWAL, S., SINGH, R.K., MURTAZA, Q.: A literature review and perspectives in reverse logistics, *Resources, Conservation and Recycling*, Vol. 97, No. April, pp. 76-92, 2015. https://doi.org/10.1016/j.resconrec.2015.02.009

[11] DE BRITO, M.P., DEKKER, R., FLAPPER, S.D.P.: Reverse Logistics: Review of Case studies, In: Fleischmann, B., Klose, A. (eds) Distribution

Logistics. Lecture Notes in Economics and Mathematical Systems, Vol. 544, Springer, Berlin, Heidelberg, pp. 243-281, 2005. https://doi.org/10.1007/978-3-642-17020-1_13

[12] SHI, C., HOU, Z., RUAN, J.: *Study on Reverse logistics based on supply chain management*, 2009 Asia-Pacific Conference on Information Processing, Shenzhen, China, pp. 495-498, 2009. https://doi.org/10.1109/APCIP.2009.127

[13] GOVINDAN, K., SOLEIMANI, H., KANNAN, D.: Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future, *European Journal of Operational Research*, Vol. 240, No. 3, pp. 603-626, 2015. https://doi.org/10.1016/j.ejor.2014.07.012

[14] ALKAHTANI, M., ZIOUT, A., SALAH, B., ALATEFI, M., ABD ELGAWAD, A.E.E., BADWELAN, A., SYARIF, U.: An Insight into Reverse Logistics with a Focus on Collection Systems, *Sustainability*, Vol. 13, No. 2, 548, pp. 1-22, 2021. https://doi.org/10.3390/su13020548

[15] STRAKA, M.: *Distribution and Supply Logistics*, Cambridge Scholars Publishing, Newcastle upon Tyne, United Kingdom, 2019.

[16] MOHAMED, A.G., FATHI, A.A., MAROUF, M.A., HASSAN, M.S., EL BARKY, S.S.: *Impact of Reverse Logistics Applications on Customer Satisfaction*, Proceedings of the 2015 International Conference on Operations Excellence and Service Engineering Orlando, Florida, USA, September 10-11, 2015, IEOM Society, pp. 393-405, 2015.

[17] GUO, S., SHEN, B., CHOI, T.-M., JUNG, S.: A review on supply chain contracts in reverse logistics: Supply chain structures and channel leaderships, *Journal of Cleaner Production*, Vol. 144, pp. 387-402, 2017. https://doi.org/10.1016/j.jclepro.2016.12.112

[18] JAYANT, A., GUPTA, P., GARG, S.K.: Perspectives in Reverse Supply Chain Management(R-SCM): A State of the Art Literature Review, *Jordan Journal of Mechanical and Industrial Engineering*, Vol. 6, No. 1, pp. 87-102, 2012.

[19] UMEDA, S.: *Simulation analysis of supply chain systems with reverse logistics*, Proceedings of the 2013 Winter Simulation Conference: Simulation: Making Decisions in a Complex World (WSC '13), IEEE Press, pp. 3375-3384, 2013.

[20] LE, S.-T.: Investigating the Drivers of the Reverse Logistics Implementation in Reducing Waste in Vietnam, *Environmental Health Insights*, Vol. 17, pp. 1-18, 2023. https://doi.org/10.1177/11786302231211058

[21] REHMAN, S.A., KHAN, S.S.: Reverse Logistics and Challenges: Supply Chain Management of Automobile Industry, *Advances in Applied Sciences*, Vol. 2, No. 5, pp. 80-86, 2017. https://doi.org/10.11648/j.aas.20170205.15

[22] TYAGI, V.: Reverse Logistics In 21 St Centuries In Special Reference To Supply Chain Disruptions During Covid-19, *JK International Journal of Management and Social Science*, Vol. 4, No. 1-2, pp. 1-9, 2021.

[23] LARSEN, S.B., MASI, D., FEIBERT, D.C., JACOBSEN, P.: How the reverse supply chain impacts the firm's financial performance: A manufacturer's perspective, *International Journal of Physical Distribution & Logistics Management*, Vol. 48, No. 3, pp. 284-307, 2018. https://doi.org/10.1108/IJPDLM-01-2017-0031

[24] WANG, M., WANG, B., CHAN, R.: Reverse logistics uncertainty in a courier industry: a triadic model, *Modern Supply Chain Research and Applications*, Vol. 3, No. 1, pp. 56-73, 2021. https://doi.org/10.1108/MSCRA-10-2020-0026

[25] LJUBIČIĆ, K., BAJOR, I.: Supplier's Reverse Logistics Process Management, *International Scientific Journal "Science. Business. Society"*, Vol. 6, No. 2, pp. 58-61, 2021.

[26] MOHAMED, M.A., FARAH, M.A., JAMA, L.A., MOHAMUD, I.H., MOHAMUD, I.H., SIYAD, M.A., MALIN, I.M.: A Decade of Reverse Logistics Research (2013-2023): A Comprehensive Bibliometric Analysis of Trends, Influences, and Global Engagement, *Journal of Logistics, Informatics and Service Science*, Vol. 11, No. 7, pp. 37-53, 2024. https://doi.org/10.33168/JLISS.2024.0703

[27] DJIKANOVIC, J., VUJOSEVIC, M.: A new integrated forward and reverse logistics model: A case study, *International Journal of Computational Intelligence Systems*, Vol. 9, No. 1, pp. 25-35, 2016. https://doi.org/10.1080/18756891.2016.1144151

[28] MELAN, M.B.: Reverse Logistics from Recycling of Used Paper Boxes from Online Shopping in China: A Literature Review, *Turkish Journal of Computer and Mathematics Education*, Vol. 12, No. 3, pp. 1543-1549, 2021. https://doi.org/10.17762/turcomat.v12i3.960

[29] MISHRA, O., SINGH, S.: Investigating Responsiveness of Reverse Logistics for Manufacturing Industries, *Green and Low-Carbon Economy*, Vol. 00, No. 00, pp. 1-9, 2023. https://doi.org/10.47852/bonviewGLCE32021481

[30] ANTONYOVÁ, A., ANTONY, A., SOEWITO, B.: Logistics Management: New trends in the Reverse Logistics, *Journal of Physics: Conference Series*, Vol. 710, pp. 1-10, 2016. https://doi.org/10.1088/1742-6596/710/1/012018

[31] XIN, C., WANG, J., WANG, Z., WU, C.-H., NAWAZ, M., TSAI, S.-B.: Reverse logistics research of municipal hazardous waste: a literature review, *Environment, Development and Sustainability*, Vol. 24, pp. 1495-1531, 2022. https://doi.org/10.1007/s10668-021-01526-6

[32] MALKUS, T., KOZINA, A.: The features of negotiations within reverse logistics cooperation, *Acta logistica*, Vol. 10, No. 1, pp. 111-119, 2023. https://doi.org/10.22306/al.v10i1.364

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 141-150 ISSN 2453-675X

https://doi.org/10.22306/atec.v10i4.228 Received: 06 Oct. 2024; Revised: 05 Nov. 2024; Accepted: 25 Nov. 2024

Forecasting the number of road accidents on a weekday

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Keywords: road accident, forecasting, weekday.
Abstract: Every year, a considerable number of people lose their lives on Polish highwaysAlthough this number remains significant, it has been steadily decreasing over time. Despite a reduction in accidents since the pandemic began, the overall figures are still relatively high. To effectively minimize road accidents, it is essential to identify which days experience the highest frequency of collisions and to predict the number of accidents in the upcoming years. The objective of this article is to forecast the number of accidents occurring on Polish roads for each weekday. To achieve this, monthly accident data from the Polish Police statisticsfor 2007 was analyzed, resulting in predictions for the years 2022-2024. The findings of the study suggest that there will likely be a decrease in accidents on Polish roads compared to pre-pandemic levels; however, the ongoing impact of the pandemic complicates these results. The research employed various time series models using the Statistica program.

1 Introduction

Road accidents are incidents that not only result in injuries or fatalities to road users but also cause damage to property. According to the WHO [1], approximately 1.3 million people die in traffic accidents each year. Many countries worldwide attribute about 3% of their GDP to the consequences of these accidents. The WHO further reports that traffic accidents are the leading cause of death among children and young adults aged 5 to 29. The UN General Assembly aims to halve the number of traffic fatalities and injuries by 2030.

One crucial factor influencing the severity of a traffic accident is its magnitude. To effectively prevent accidents and reduce injuries, fatalities, and property damage, it is essential for relevant authorities to predict the severity of incidents [2,3]. Identifying the key elements that impact accident severity is vital before implementing corrective measures to mitigate and reduce the seriousness of accidents. [4] A multi-layered architecture known as DNN (Deep Neural Network) has been proposed by Yang et al. for predicting different levels of damage, fatalities, and property loss. This model facilitates a comprehensive and precise analysis of the severity of traffic incidents [5].

Accident data is sourced from various channels, primarily collected and analyzed by governmental organizations through relevant agencies. Data collection relies on police reports, insurance databases, and hospital records. Following this, incomplete data regarding traffic accidents is processed more broadly for the transportation sector [6].

Currently, intelligent transportation systems serve as the most significant source of information for analyzing and forecasting traffic accidents. This data can be analyzed in conjunction with the use of GPS devices in vehicles [7]. As noted by Khaliq et al. [8], microwave roadside vehicle detection systems can continuously record vehicle data, such as speed, traffic volume, and vehicle type. Additionally, vehicle license plate recognition systems enable the collection of substantial amounts of data on road traffic over monitored periods [9]. While social media can also serve as a data source for insights on traffic and accidents, its reliability may be limited due to the unpredictability of reports [10].

To accurately represent accident data, it is essential to collaborate with multiple data sources, all of which must be appropriately integrated. The accuracy of analysis results can be enhanced by combining various data sources and integrating heterogeneous data on traffic accidents [11].

A statistical analysis conducted by Vilaca et al. [12] examined the severity of road accidents and their correlation with other road users. The study concluded with recommendations to elevate driving safety standards and implement new transportation safety regulations.

Based on the frequency of traffic accidents and the duration taken to identify their causes, Bak et al. [13] conducted a statistical analysis of traffic safety in a specific region of Poland. This study focused on assessing the safety of individuals who cause accidents through multivariate statistical analysis.

The type of traffic issue reported influences the source of crash data utilized for the study. The accuracy of accident forecasts can be enhanced, and the number of accidents can be reduced when statistical models are combined with additional natural driving data or other information from intelligent transportation systems [14].

Numerous techniques for predicting accident numbers are documented in the literature. Among these, time series

methods are the most widely used for forecasting road accidents [15,16]. However, these methods have several limitations, such as the inability to evaluate the quality of forecasts based on outdated predictions and the frequent autocorrelation of the residual values of the components [17].

Procházka et al. [18] employed a multiple seasonality model for forecasting, while Sunny et al. [19] utilized the Holt-Winters exponential smoothing method. One limitation of these approaches is that they cannot incorporate exogenous variables into the model [20,21].

Other forecasting methods include the vector autoregression model, which requires a substantial number of observations of variables to accurately estimate their parameters [22]. Additionally, Monedero et al. [23] applied autoregression models for fatality analysis, while Al-Madani [24] used curve fit regression models to predict the number of traffic accidents. These models primarily rely on simple linear relationships [25] and autoregression sequences, assuming the series are already stationary [26].

The Random Forest regression method was utilized by Biswas et al. [27] to predict the number of traffic accidents. In this context, smaller groups are favored over larger ones, but this method exhibits instability in approach and peak prediction. The data also includes groups of related features that hold similar importance to the original dataset [28,29].

For the prognostic issue discussed, Chudy-Laskowska and Pisula [30] applied an autoregressive model with a quadratic trend, a one-dimensional periodic trend model, and an exponential smoothing model. Although the moving average model can also be employed for forecasting, it has several drawbacks, including low accuracy of forecasts, data loss over time, failure to account for patterns, and neglect of seasonal impacts [31].

The GARMA technique, used by Procházka and Camej [32], imposes restrictions on the parameter space to ensure the stationarity of the process. Several studies highlight the frequent use of the ARMA model for forecasting stationary processes [19, 32-34] and the ARIMA or SARIMA model for non-stationary processes. While these models offer significant flexibility, this can also be a disadvantage, as effective model identification requires more in-depth research knowledge compared to methods like regression analysis [35]. Additionally, the linearity of the ARIMA model is another limitation [36].

In their 2015 study, Chudy-Laskowska and Pisula [37] employed the ANOVA approach to predict traffic accident numbers. However, this method has the drawback of necessitating additional assumptions, particularly regarding sphericity, the violation of which may lead to incorrect conclusions [38].

Neural network models are also utilized for predicting traffic accident frequency [37,39]. However, Artificial Neural Networks (ANN) come with several drawbacks, including the need for prior knowledge in the field, the final outcome's reliance on the network's initial conditions, a lack of traditional interpretability, and the "black box" nature of ANN, where input data is provided, and results are outputted without insight into the analysis proces [40].

Kumar et al. [41] introduced the Hadoop model as a novel prediction technique. A limitation of this technology is its inability to process small data files [42]. The GARCH model was used by Karlaftis and Vlahogianni [34] for predictions, but its complexity in both form and model poses a challenge [43,44]. On the other hand, the ADF test was employed by McIlroy [45] and colleagues, although this method suffers from low power when dealing with autocorrelation of random components [46].

The authors of the articles [47,48] also explored data-mining approaches for forecasting, which typically face the challenge of handling large datasets with general descriptions [49]. Additionally, a model combination was proposed by Sebe [50], suggesting a blend of various models. Bloomfield [51] also recommended parametric models for predicting the number of traffic accidents in Poland.

2 A study of the seasonality of accidents on the roads

When on Polish highways, a large number of individuals pass away. Despite the value declining year over year, the total is still very substantial. Although there have been fewer accidents on the roads since the pandemic, the number is still relatively high. When the data is examined on a monthly basis, it can be concluded that there are definite variations and a persistent downward tendency. In Poland, there are still a lot more accidents than in the rest of the European Union. On Sundays, there are fewer car accidents than on Fridays, when there are more. Due to this, it is imperative to lower this number and determine the days that will see the greatest number of incidents on the roads (Figure 1).

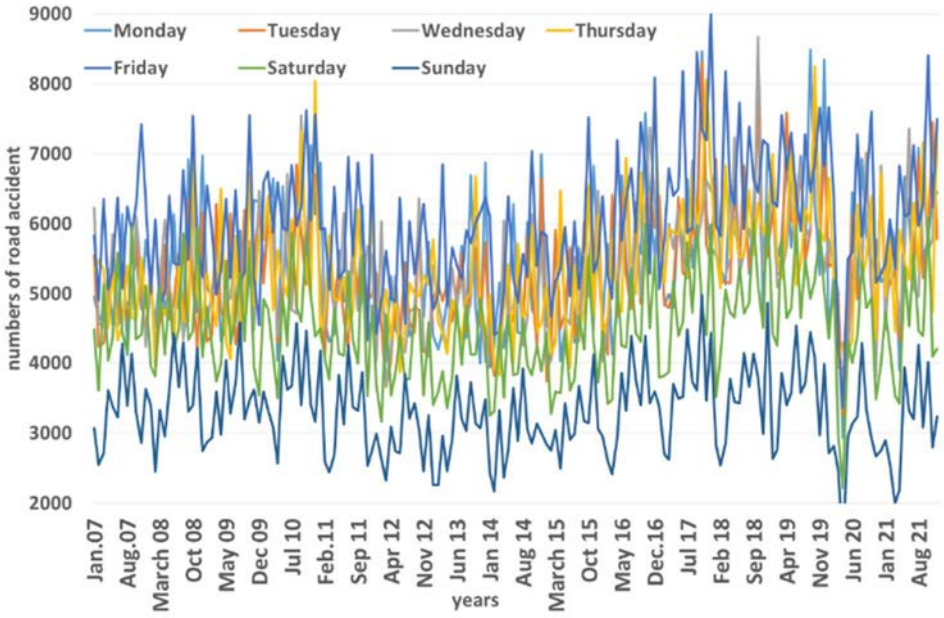

Figure 1 Accidents in Poland between 2007 and 2021

The average number of traffic accidents throughout the studied period was tested after that to determine whether there had been a substantial difference. Poland's non-parametric Kruskall-Wallis test statistic value is 587, with a test probability of p=0.000. In this situation, it is necessary to reject the premise that the average number of traffic accidents during the studied time was equal. This indicates that the average number of incidents in the current situation are consistently declining from year to year (Figure 2). According to the data acquired, Fridays have the highest number of traffic accidents, while Sundays see the lowest number [52].

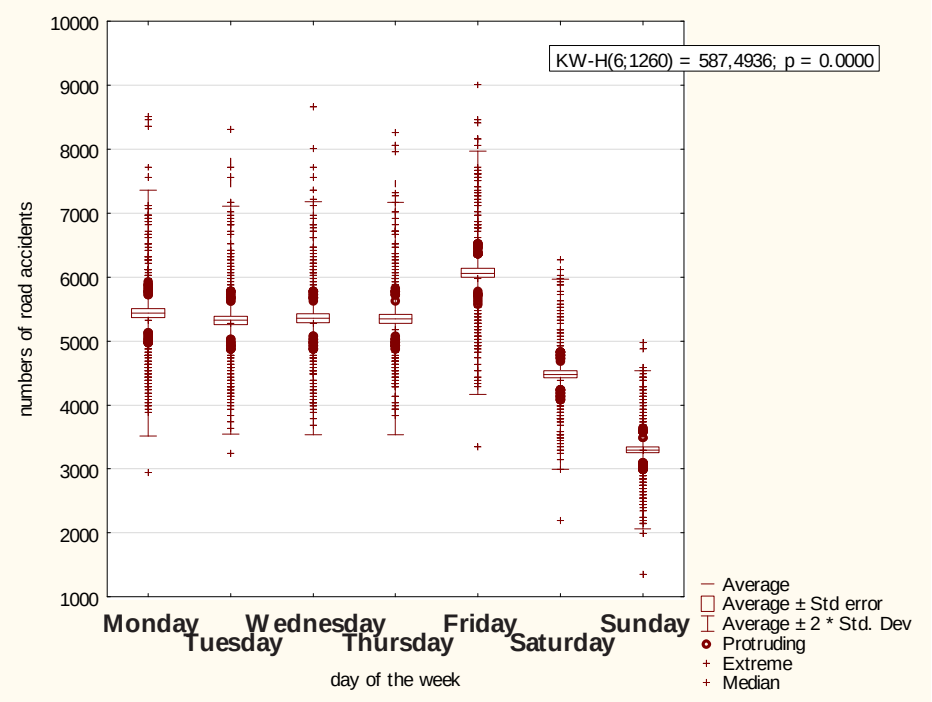

Figure 2 Road accident averages in Poland from 2007 to 2021, broken down by day of the week

The research of the number of accidents on Polish roads leads to the conclusion that they are seasonal in character and on the decline. Therefore, for additional analysis, the expected number of traffic accidents in the investigated period based on the day of the week was determined using a few time series models.

3 Forecasting the number of road accidents

Selected exponential equalization models were used to predict the number of traffic accidents. The fundamental idea behind this approach is that the predicted variable's time series is represented by a weighted moving average, with the weights chosen in accordance with an exponential function. The study's software, Statistica, selected the weights in the most effective way possible.

In this instance, the forecast is based on a weighted average of the series' recent and historical values. The model and its parameters that are selected will determine the forecast's outcome. Selected time series models with a linear trend were used to predict the number of accidents. Specifically, the exponential model and the linear trend model (Holt and Winters technique).

Measures of analytical forecasting perfection were calculated using the errors of forecasts that had expired, which were calculated using equations (1-5):

- ME – mean error

$$ME = \frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_p) \quad (1)$$

- MAE –mean everage error

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Y_i - Y_p| \quad (2)$$

- MPE –mean percentage error

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\frac{Y_i - Y_p}{Y_i} \quad (3)$$

- MAPE - mean absolute percentage error

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|Y_i - Y_p|}{Y_i} \quad (4)$$

- SSE – mean square error

$$SSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_p)^2} \quad (5)$$

where:
n – the projected horizon's length,
Y – observed value of traffic collisions,
Y_p – forecasted value of road accidents.

The mean percentage error was minimized in order to compare the number of accidents that occurred during a pandemic and those that did not.

Forecasting the number of road accidents in Poland

Forecasts for the number of accidents by day of the week were made using information from the Polish Police from 2007 to 2021. Figure 3 - Figure 9 displays the predicted results for each day of the week. The various forecasting techniques utilized in the study are denoted by the letters M1, M2,... and Mn. The following are the forecasting methods applied in the study:

M1 - moving average method 2-points,
M2 - moving average method 3-points,
M3 - moving average method 4-points,
M4 - exponential smoothing no trend seasonal component: none,
M5 - exponential smoothing no trend seasonal component: additive,
M6 - exponential smoothing no trend seasonal component: multiplicative,
M7 - exponential smoothing linear trend seasonal component: none HOLTA,
M8 - exponential smoothing linear trend seasonal component: additive,
M9 - exponential smoothing linear trend seasonal component: multiplicative WINTERSA,
M10 - exponential smoothing exponential seasonal component: none,
M11 - exponential smoothing exponential seasonal component: additive,
M12 - exponential smoothing exponential seasonal component: multiplicative,
M13 - exponential smoothing fading trend seasonal component: none,
M14 - exponential smoothing fading trend seasonal component: additive,
M15 - exponential smoothing fading trend seasonal component: multiplicative).

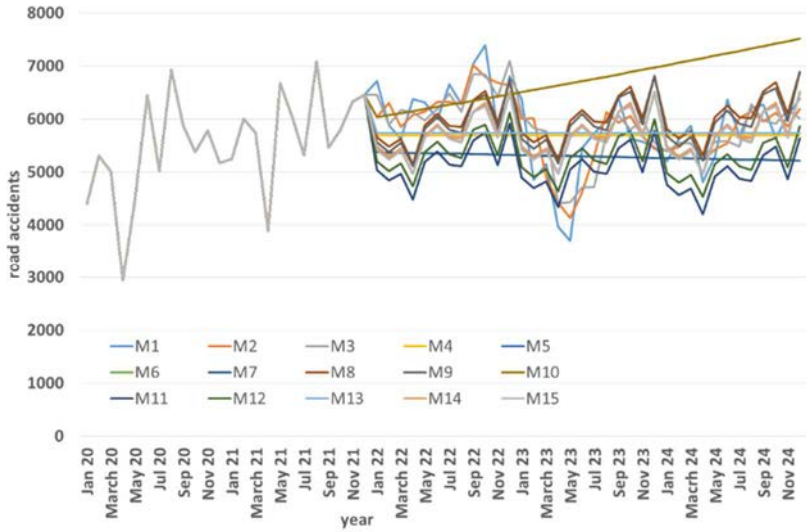

Figure 3 Forecasting the number of traffic accidents on Monday between 2022 and 2024

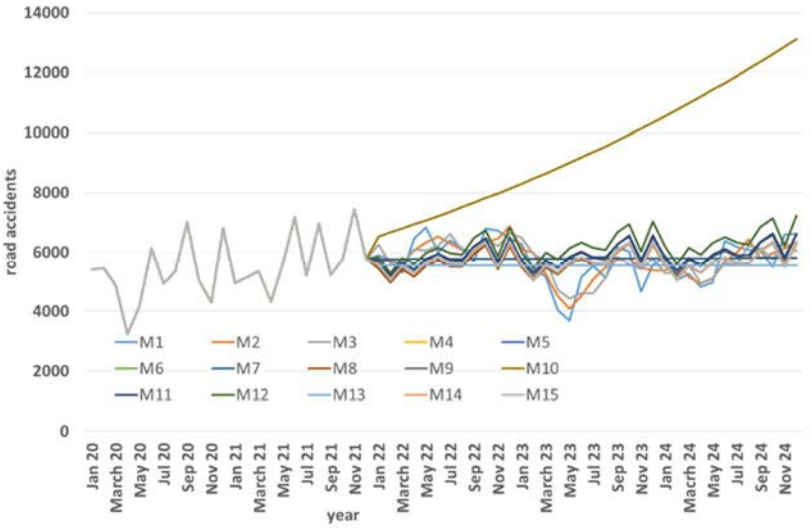

Figure 4 Forecasting the number of traffic accidents on Tuesday from 2022 to 2024

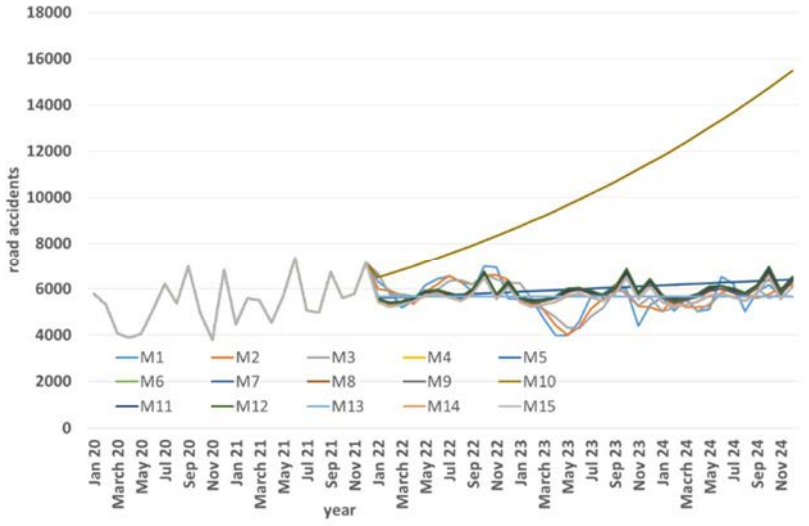

Figure 5 Forecasting the number of road accidents on Wednesday from 2022 to 2024

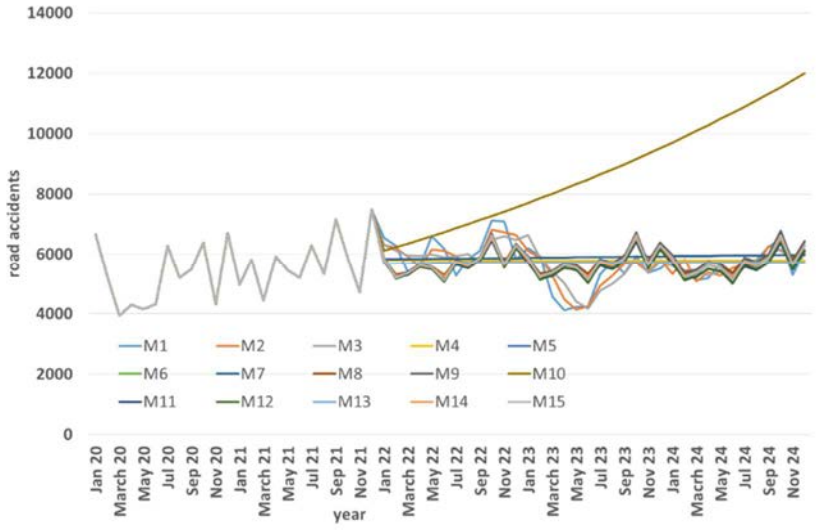

Figure 6 Forecasting the number of traffic accidents on Thursday from 2022 to 2024

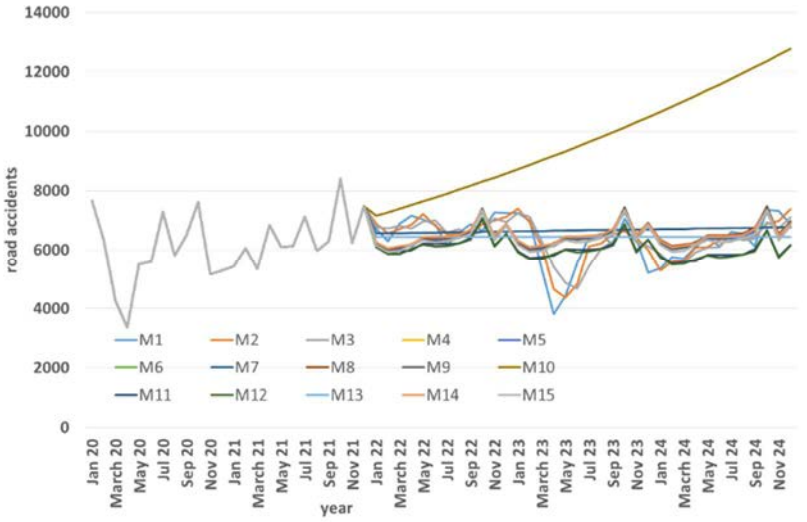

Figure 7 Forecasting the number of road accidents on Friday from 2022 to 2024

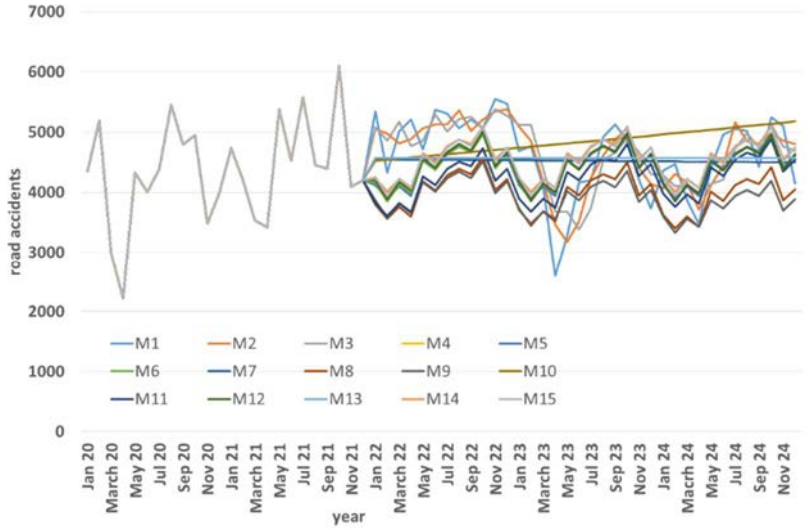

Figure 8 Forecasting the number of traffic accidents on Saturday from 2022 to 2024

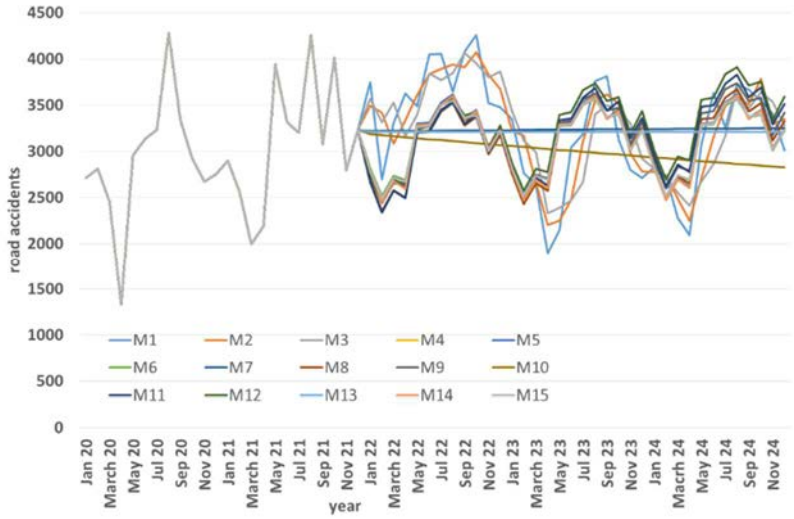

Figure 9 Forecasting the number of traffic accidents on Sunday from 2022 to 2024

Forecasts for the number of accidents by day of the week were made using information from the Polish Police from 2007 to 2021. Figure 3-9 displays the predicted results for each day of the week. The various forecasting techniques utilized in the study are denoted by the letters M1, M2,... and Mn. The following are the forecasting methods applied in the study:

- Monday - M2,
- Tuesday - M3,
- Wednesday - M2,
- Thursday - M3,
- Friday - M2,
- Saturday - M2,
- Sunday - M1.

The moving average approaches provided the minimum MPE error, according to the data received. This served as the foundation for the forecast of the quantity of traffic accidents according to the day of the week depicted in Figure 10, and the resulting forecast errors are displayed in Table 1. The findings indicate that, with a slight drop, we may still anticipate a level of traffic accidents similar to those that existed prior to the epidemic. The pandemic, it should be mentioned, distorted the outcomes. The selection of an efficient forecasting technique is shown by an error value of no more than 5%.

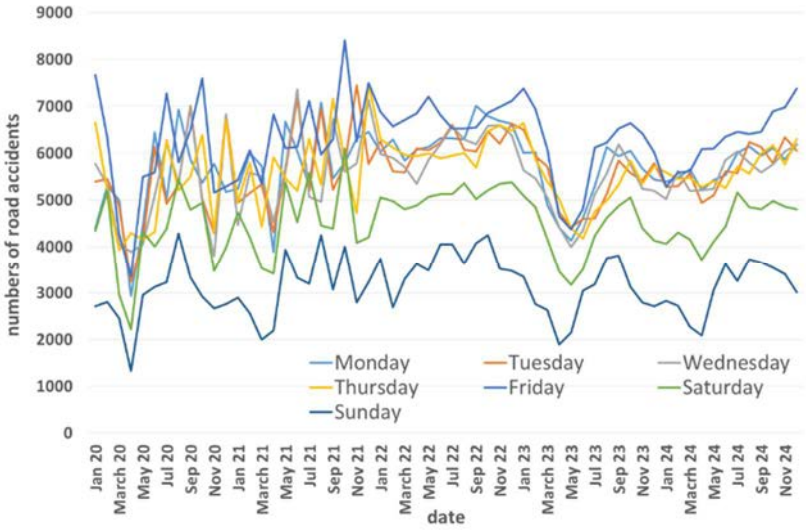

Figure 10 Projected number of traffic accidents by day of the week in 2022-2024

Table 1 Forecast error

Forecast error/day of the week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
ME	141.28	164.40	124.80	172.14	141.07	9.72	58.93
MPE	0.50%	0.23%	0.66%	0.26%	0.24%	2.55%	5.30%
SSE	1099.78	1043.67	1091.87	1126.39	1129.20	816.72	687.25
MAPE	16.04%	15.29%	16.20%	16.06%	14.85%	15.32%	17.96%
MAE	875.66	825.96	871.29	877.93	897.84	664.13	552.28

4 Conclusion

Using the Statistica application, exponential equalization methods were used to predict the number of accidents in Poland. The computer calculated the weights in use to reduce the mean absolute error and mean absolute percentage error.

The findings indicate that, with a slight drop, we may still anticipate a level of traffic accidents similar to those that existed prior to the epidemic. The results were biased by the pandemic, it should be highlighted. The selection of an efficient forecasting technique is demonstrated by the error value of a maximum of 5%.

The article's forecasted traffic accident data can be utilized in the future to develop new policies aimed at reducing accidents in the countries under study. These changes might include, for instance, increasing the fines for moving violations on Polish roads starting in 2022.

The authors intend to include more elements affecting Poland's accident rates in their future research. The amount of traffic, the weather, or the age of the accident's perpetrator are just a few examples extensions.

References

[1] World Health Organization, WHO, The Global status on road safety 2018, [Online], Available: https://www.who.int/publications/i/item/9789241565684 [15 Sep 2024], 2018.

[2] TAMBOURATZIS, T., SOULIOU, D., CHALIKIAS, M., GREGORIADES, A.: Maximising accuracy and efficiency of traffic accident prediction combining information mining with computational intelligence approaches and decision trees, *Journal of Artificial Intelligence and Soft Computing Research*, Vol. 4, No. 1, pp. 31-42, 2014. http://dx.doi.org/10.2478/jaiscr-2014-0023

[3] ZHU, L., LU, L., ZHANG, W., ZHAO, Y., SONG, M.: Analysis of accident severity for curved roadways based on bayesian networks, *Sustainability*, Vol. 11, No. 8, 2223, pp. 1-17, 2019. https://doi.org/10.3390/su11082223

[4] ARTEAGA, C., PAZ, A., PARK, J.: Injury severity on traffic crashes: A text mining with an interpretable machine-learning approach, *Safety Science*, Vol. 132, No. December, 104988, 2020. https://doi.org/10.1016/j.ssci.2020.104988

[5] YANG, Z., ZHANG, W., FENG, J.: Predicting multiple types of traffic accident severity with explanations: A multi-task deep learning framework, *Safety Science*, Vol. 146, No. February, 105522, 2022. https://doi.org/10.1016/j.ssci.2021.105522

[6] GORZELANCZYK, P., PYSZEWSKA, D., KALINA, T., JURKOVIC, M.: Analysis of road traffic safety in the Pila poviat, *Scientific Journal of Silesian University of Technology. Series Transport*, Vol. 107, pp. 33-52, 2020. https://doi.org/10.20858/sjsutst.2020.107.3

[7] CHEN, C.: Analysis and forecast of traffic accident big data, *ITM Web of Conferences*, Vol. 12, 04029, pp. 1-6, 2017. https://doi.org/10.1051/itmconf/20171204029

[8] KHALIQ, K.A., CHUGHTAI, O., SHAHWANI, A., QAYYUM, A., PANNEK, J.: Road accidents detection, data collection and data analysis using V2X communication and edge/cloud computing, *Electronics*, Vol. 8, No. 8, 896, pp. 1-28, 2019. https://doi.org/10.3390/electronics8080896

[9] RAJPUT, H., SOM, T., KAR, S.: An automated vehicle license plate recognition system, *Computer*, Vol. 48, No. 8, pp. 56-61, 2015. https://doi.org/10.1109/MC.2015.244

[10] ZHENG, Z., WANG, C., WANG, P., XIONG, Y., ZHANG, F., LV, Y.: Framework for fusing traffic information from social and physical transportation data, *PLoS ONE*, Vol. 13, No. 8, e0201531, pp. 1-19, 2018. https://doi.org/10.1371/journal.pone.0201531

[11] ABDULLAH, E., EMAM, A.: *Traffic accidents analyzer using big data*, In: 2015 International Conference on Computational Science and Computational Intelligence (CSCI), Las Vegas, NV, USA, pp. 392-397, 2015. https://doi.org/10.1109/CSCI.2015.187

[12] VILAÇA, M., SILVA, N., COELHO, M.C.: Statistical analysis of the occurrence and severity of crashes involving vulnerable road users, *Transportation Research Procedia*, Vol. 27, pp. 1113-1120, 2017. https://doi.org/10.1016/j.trpro.2017.12.113

[13] BĄK, I., CHEBA, K., SZCZECIŃSKA, B.: The statistical analysis of road traffic in cities of Poland, *Transportation Research Procedia*, Vol. 39, pp. 14-23, 2019. https://doi.org/10.1016/j.trpro.2019.06.003

[14] CHAND, A., JAYESH, S., BHASI, A.B.: Road traffic accidents: An overview of data sources, analysis techniques and contributing factors, *materialstoday: Proceedings*, Vol. 47, Part 15, pp. 5135-5141, 2021. https://doi.org/10.1016/j.matpr.2021.05.415

[15] HELGASON, A.: Fractional integration methods and short Time series: evidence from a simulation study, *Political Analysis*, Vol. 24, No. 1, pp. 59-68, 2016. http://www.jstor.org/stable/24573204

[16] LAVRENZ, S., VLAHOGIANNI, E., GKRITZA, K., KE, Y.: Time series modeling in traffic safetyresearch, *Accident Analysis & Prevention*, Vol. 117, No. August, pp. 368-380, 2018. https://doi.org/10.1016/j.aap.2017.11.030

[17] Forecasting based on time series, Prognozowanie na podstawie szeregów czasowych, [Online], Available: http://pis.rezolwenta.eu.org/Materialy/PiS-W-5.pdf [15 Sep 2024], 2022. (Original in Polish)

[18] PROCHÁZKA, J., FLIMMEL, S., ČAMAJ, M., BAŠTA, M.: *Modelling the Number of Road Accidents*, 20th AMSE, Applications of Mathematics and Statistics in Economics, International Scientific Conference: Szklarska Poręba, 30 August - 3 September, 2017, Publishing house of the University of Economics in Wrocław, Wrocław, pp. 355-364, 2017. https://doi.org/10.15611/amse.2017.20.29

[19] SUNNY, C.M., NITHYA, S., SINSHI, K.S., VINODINI, V.M.D., LAKSHMI, A.K.G., ANJANA, S., MANOJKUMAR, T.K.: *Forecasting of Road Accident in Kerala: A Case Study*, 2018 International Conference on Data Science and Engineering (ICDSE), Kochi, India, pp. 1-5, 2018. https://doi.org/10.1109/ICDSE.2018.8527825

[20] DUDEK, G.: *Forecasting Time Series with Multiple Seasonal Cycles Using Neural Networks with Local Learning.* In: Rutkowski, L., Korytkowski, M., Scherer, R., Tadeusiewicz, R., Zadeh, L.A., Zurada, J.M. (eds) Artificial Intelligence and Soft Computing, ICAISC 2013, Lecture Notes in Computer Science, Vol. 7894, Springer, Berlin, Heidelberg, pp. 52-63, 2013. https://doi.org/10.1007/978-3-642-38658-9_5

[21] SZMUKSTA-ZAWADZKA, M., ZAWADZKI, J.: *Forecasting on the basis of Holt-Winters models for complete and incomplete data*, Research papers of the Wrocław University of Economics, Vol. 2009, No. 38, pp. 85-99, 2009.

[22] WÓJCIK, A.: *Autoregressive vector models as a response to the critique of multi-equation structural econometric models*, Publishing house of the University of Economics in Katowice, Vol. 193, 2014.

[23] MONEDEROA, B.D., GIL-ALANAA, L.A., MARTÍNEZAA, M.C.V.: Road accidents in Spain: Are they persistent?, *IATSS Research*, Vol. 45, No. 3, pp. 317-325, 2021. https://doi.org/10.1016/j.iatssr.2021.01.002

[24] AL-MADANI, H.: Global road fatality trends'estimations based on country-wise microlevel data, *Accident Analysis & Prevention*, Vol. 111, No. February, pp. 297-310, 2018. https://doi.org/10.1016/j.aap.2017.11.035

[25] MAMCZUR, M.: Machine learning How does linear regression work? And is it worth using?, [Online], Available: https://miroslawmamczur.pl/jak-dziala-regresja-liniowa-i-czy-warto-ja-stosowac/ [16 Sep 2024], 2020. (Original in Polish)

[26] PIŁATOWSKA, M.: The choice of the order of autoregression depending on the parameters of the generating model, *Econometrics*, Vol. 4, No. 38, 2012.

[27] BISWAS, A.A., MIA, J., MAJUMDER, A.: *Forecasting the Number of Road Accidents and Casualties using Random Forest Regression in the Context of Bangladesh*, 2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT), Kanpur, India, pp. 1-5, 2019.

[28] Random Forest, [Online], Available: https://pl.wikipedia.org/wiki/Las_losowy [16 Sep 2024], 2008. (Original in Polish)

[29] FIJOREK, K., MRÓZ, K., NIEDZIELA, K., FIJOREK, D.: Forecasting electricity prices on the day-ahead market using data mining methods, *Rynek Energii*, Vol. 91, No. 3, 2010.

[30] CHUDY-LASKOWSKA, K., PISULA, T.: Forecast of the number of road accidents in Poland, *Logistics*, Vol. 2014, No. 6, 2014.

[31] KASHPRUK, N.: *Comparative research of statistical models and soft computing for identification of time series and forecasting*, Opole University of Technology, 2010.

[32] PROCHAZKA, J., CAMAJ, M.: *Modelling the number of road accidents of uninsured drivers and their severity*, Proceedings of International Academic Conferences 5408040, International Institute of Social and Economic Sciences, 2017.

[33] DUTTA, B., BARMAN, M.P., PATOWARY, A.N.: Application of Arima model for forecasting road accident deaths in India, *International Journal of Agricultural and Statistical Sciences*, Vol. 16, No. 2, pp. 607-615, 2020.

[34] KARLAFTIS, M., VLAHOGIANNI, E.: Memory properties and fractional integration in trans-portation time-series, *Transportation Research Part C: Emerging Technologies*, Vol. 17, No. 4, pp. 444-453, 2009. https://doi.org/10.1016/j.trc.2009.03.001

[35] ŁOBEJKO, S.: *Time series analysis and forecasting with SAS*, Main business school in Warsaw, Warsaw, 2015.

[36] DUDEK, G.: Exponential smoothing models for short-term power system load forecasting, *Rynek Energii*, Vol. 106, No. 3, pp. 14-19, 2013. (Original in Polish)

[37] CHUDY-LASKOWSKA, K., PISULA, T.: Prognozowanie liczby wypadków drogowych na Podkarpaciu, *Logistics*, Vol. 2015, No. 4, pp. 2782-2796, 2015. (Original in Polish)

[38] Road safety assessment handbook, [Online], Available: https://etsc.eu/network-wide-road-safety-assessment-methodology-published/ [16 Sep 2024], 2024.

[39] WROBEL, M.S.: *Application of neural fuzzy systems in chemistry*, PhD thesis, Katowice, University of Silesia, 2017.
[40] Data mining techniques StatSoft, [Online], Available: https://www.statsoft.pl/textbook/stathome_stat.html?https%3A%2F%2Fwww.statsoft.pl%2Ftextbook%2Fstdatmin.html [17 Sep 2024], 2024. (Original in Poland)
[41] KUMAR, S., VISWANADHAM, V., BHARATHI, B.: Analysis of road accident, *IOP Conference Series: Materials Science and Engineering*, Vol. 590, No. 1, 012029, pp. 1-6, 2019. https://doi.org/10.1088/1757-899X/590/1/012029
[42] Dataflair Team, Top Advantages and Disadvantages of Hadoop 3, [Online], Available: https://data-flair.training/blogs/advantages-and-disadvantages-of-hadoop/ [17 Sep 2024], 2022.
[43] PERCZAK, G., FISZEDER, P.: *GARCH model - using additional information on minimum and maximum prices.* Bank and Credit. Number 2. 2014
[44] FISZEDER, P.: *GARCH class models in empirical financial research*, Scientific Publishers of the Nicolaus Copernicus University, Torun, 2009.
[45] MCILROY, R.C., PLANT, K.A., HOQUE, M.S., WU, J., KOKWARO, G.O., NAM, V.H., STANTON, N.A.: Who is responsible for global road safety? A cross-cultural comparison of factor maps, *Accident Analysis & Prevention*, Vol. 122, No. January, pp. 8-18, 2019. https://doi.org/10.1016/j.aap.2018.09.011
[46] MUCK, J.: Econometrics, Modeling of time series, Stationary, Unit root tests, ARDL models, Co-integration, [Online], Available: http://web.sgh.waw.pl/~jmuck/Ekonometria/EkonometriaPrezentacja5.pdf [17 Sep 2024], 2022.
[47] SHETTY, P., SACHIN, P.C., KASHYAP, V.K., MADI, V.: Analysis of road accidents using data mining techniques, *International Research Journal of Engineering and Technology*, Vol. 2017, No. 4, 2017.
[48] LI, L., SHRESTHA, S., HU, G.: *Analysis of road traffic fatal accidents using data mining techniques*, 2017 IEEE 15th International Conference on Software Engineering Research, Management and Applications (SERA), pp. 363-370, 2017. https://doi.org/10.1109/SERA.2017.7965753
[49] MARCINKOWSKA, J.: *Statistical methods and data mining in assessing the occurrence of syncope in the group of narrow-QRS tachycardia (AVNRT and AVRT)*, Medical University of Karol Marcinkowski in Poznań, Poznań, 2015. (Original in Poland)
[50] SEBEGO, M., NAUMANN, R.B., RUDD, R.A., VOETSCH, K., DELLINGER, A.M., NDLOVU, C.: The impact of alcohol and road traffic policies on crash rates in Botswana, 2004–2011: A time-series analysis, *Accident Analysis & Prevention*, Vol. 70, No. September, pp. 33-39, 2014. https://doi.org/10.1016/j.aap.2014.02.017
[51] BLOOMFIELD, P.: An exponential model in the spectrum of a scalar time series, *Biometrika*, Vol. 60, No. 2, pp. 217-226, 1973.
[52] Statistic Road Accident, [Online], Available: https://statystyka.policja.pl/ [17 Sep 2024], 2024.

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 151-155 ISSN 2453-675X

https://doi.org/10.22306/atec.v10i4.230 Received: 07 Oct. 2024; Revised: 12 Nov. 2024; Accepted: 30 Nov. 2024

Design of an affordable dynamic arm support for motorized wheelchairs

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Keywords: upper limb disabilities, assistive technologies, dynamic arm support, wheelchair, four-bar linkage.
Abstract: Upper limb impairments, resulting from various neurological and neuromuscular conditions, significantly impact daily activities and limit social participation. Assistive technologies, particularly dynamic arm supports, offer promising solutions to enhance independence for individuals facing these challenges. This paper presents the development of an affordable dynamic arm support, designed with a focus on static balancing. The support utilizes a four-bar linkage mechanism to allow smooth vertical movement while maintaining the orientation of the armrest. Furthermore, the integration of rotational and prismatic joints enhances the device's adaptability, enabling horizontal movements. Through comprehensive mathematical modeling and prototype testing, we introduce a cost-effective arm support that effectively counterbalances the arm's weight, ensuring ease of movement and stability across various spatial orientations.

1 Introduction

A variety of neurological and neuromuscular disabilities (e.g. multiple sclerosis, muscular dystrophy, stroke, spinal cord injuries) can lead to upper limb impairments [1-3]. For instance, individuals with such impairments may encounter difficulties in grasping, reaching, and moving objects [4], which can limit their ability to perform daily activities and place an increased burden on their families by requiring significant assistance and restricting social participation. [5]. Assistive technologies (ATs) are used to increase the level of independence of people with upper limb impairments and have been proven to be an effective solution [6], such as eating assistive devices [7,8] arm supports [9], and robotic assistive devices [10]. Dynamic arm supports are a type of AT that provides support to the upper extremity while allowing movement. Hence, they can be useful for a variety of activities of daily living. These ATs are categorized into four groups, namely non-actuated devices, passively actuated devices, actively actuated devices, and devices using the functional electrical stimulation principle [11]. Non-actuated devices can include the following functionalities: tremor suppression, anti-gravity support, and facilitation of flexion and/or extension of the elbow. Passively actuated devices include mechanisms allowing the storage of potential energy within the device. They can provide the following functionalities: manipulation of specific joints, support of anti-gravity movements, and

tremor suppression. These systems primarily allow for the adjustment of the compensation level through a mechanical interface, which is typically operated by a caregiver. Actively actuated devices have the same functionalities as the two precedent categories. The difference lies within the access to external energy such as electrical motors. Users can change the compensation level through an electronic switch and it generally allows them to compensate for the direction of gravity relative to the arm support's base (e.g. if the user is on a slope or the wheelchair is inclined). Finally, devices using functional electrical stimulation stimulate muscles in a task-appropriate fashion, which helps complete an activity; these are mostly used to compensate for upper limb neurological impairments.

Over the years, various dynamic arm supports have been developed [11,12]. Evidence indicates that they enhance users' experience by improving upper limb functionality and overall satisfaction. Furthermore, such supports positively affect users' functional ratings, range of motion, strength, accuracy in broad movements, and patterns of grasp [13,14].

Feedback from participants however revealed several barriers to the daily use of dynamic arm supports. A significant issue was the stationary nature of these supports, such as being attached to a table, which limited their use across multiple activities. Van Der Heide & De Witte (2016) revealed in their study that mounting the support on a wheelchair could interfere with performing daily living activities. Another concern was the bulkiness of the arm supports, suggesting a need for design considerations that prioritize user acceptance and ensure that the device does not obstruct movement through doorways [14].

The objective of the present study was to develop an affordable dynamic arm support that can be seamlessly integrated to a wheelchair while ensuring it remains unobtrusive and functional for the user. The structure of the paper is organized in the following manner: it begins with the methodology section, detailing the static balancing techniques, the design and function of a four-bar mechanism, and the analysis of horizontal movements. It concludes with a summary and implications of the findings.

2 Methods

2.1 Static balancing

The principle of static balancing is adopted in the proposed study. The load to be balanced is represented by the mass '*M*' (Figure 1). The torque this load applies at joint 'J_1' is given by (1):

$$T_1 = M * g * L * sin(\alpha) \quad (1)$$

where α is the angle of the link, '*L*' is the distance between 'J_1' and '*M*', and '*g*' is the gravitational constant.

To statically balance this load, the spring must exert a torque at joint 'J_1' that closely matches 'T_1'.

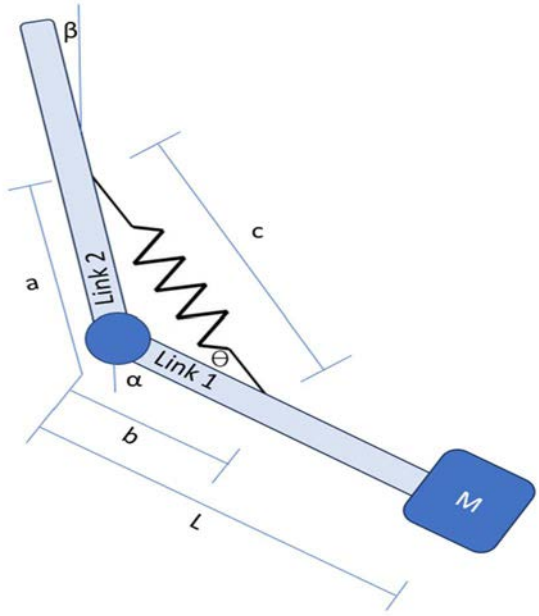


Figure 1 Static balancing parameters

The force exerted by the spring is described by (2):

$$F_k = K * (c - x_0) \quad (2)$$

where *c* is the spring's length and 'x_0' is its free length. The torque applied by the spring at 'J_1' is (3):

$$T_2 = K * (c - x_0) * b * sin(\theta) \quad (3)$$

where '*b*' is the distance between 'J_1' and the spring's attachment, and θ is the angle between Link 2 and the spring (refer to Figure 1).

The sine law is used to relate the angles and side lengths of the triangle formed by the spring and the links in the system. This helps determine the angle between Link 2 and the spring, which is important for calculating the torque applied by the spring at joint J1. This geometric relationship allows for an accurate description of how the spring's force is distributed throughout the system, based on the angles and lengths of the components involved. Hence using the sine law we have (4):

$$\frac{\sin(\theta)}{a} = \frac{\sin(180 - \alpha + \beta)}{c} \quad (4)$$

where beta is the angle of Link 1 with the vertical. This results in the equation (5):

$$\frac{T_2 = K * (c - x_0) * b * a * \sin(180 - \alpha + \beta)}{c} \quad (5)$$

Design of an affordable dynamic arm support for motorized wheelchairs

Alexandre Campeau-Lecours, Charles Larouche, Charles Doyon, Simon Latour, Thierry Laliberte, Jean-Sebastien Roy, Veronique H. Flamand

Figure 2 Four bar mechanism prototype with an arm rest

The parameters, *a*, *b*, *k*, and x_0, are then determined through iteration that best fit so that T_2 is as close to T_1 as possible for different values of *M*. The length '*a*' can be adjusted to fit different masses *M*. Van Dorsser et al. (2007) presented the static balancing principle in detail [15].

2.2 Four-bar mechanism

The basis of the dynamic arm support is a four-bar linkage that allows one to perform vertical movement while the armrest remains horizontal thanks to the four-bar linkage movement. The static balancing for the four-bar mechanism is the same as with the single bar presented above. The four-bar mechanism replaces the wheelchair armrest so that it has a minimal lateral footprint and is not cumbersome. In this prototype, the parameter '*a*' (as shown in Figure 1) can be adjusted using a worm screw to adjust the vertical force compensation level. This principle has also been adopted in earlier models of arm supports.

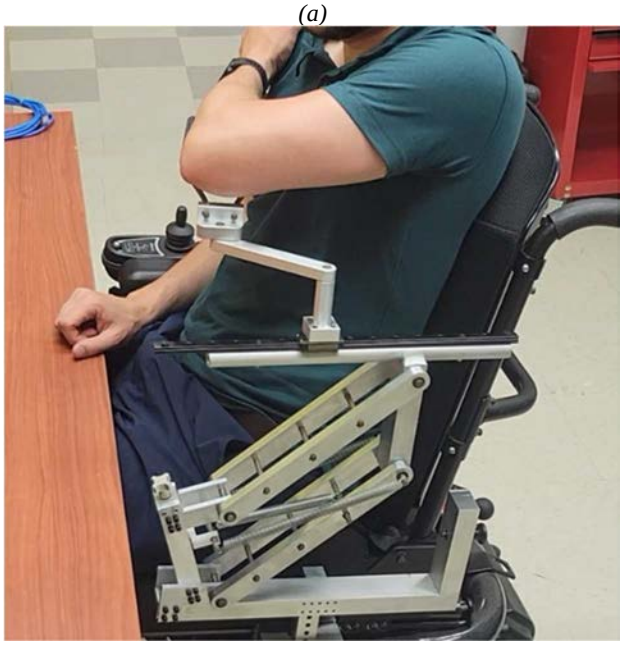
2.3 Horizontal movements

For the horizontal movements, links with rotational joints could be used [16,17]. However, in order to be less cumbersome, especially to allow the wheelchair passing through doors, a prismatic joint combined with two rotary joints is adopted, as shown in Figure 2 and Figure 3.

3 Results

To validate the vertical balancing, the vertical force exerted by the springs is measured for different adjustments of the length '*a*' and in different alpha positions with a Wagner FDX 100 dynamometer. Figure 4 presents the results in terms of vertical force (Figure 4a) and torque (Figure 4b). For the force, in Figure 4a, the ideal curve for a given '*a*' would be a straight line, implying that the force compensation level is the same no matter the angle α. Based on the machining data we gathered during the device manufacturing process, it is estimated that for a production run of 100 devices, the manufacturing cost would be $1,750 USD. This is significantly lower than similar arm support devices, which typically cost between $20,000 and $60,000.

(a)



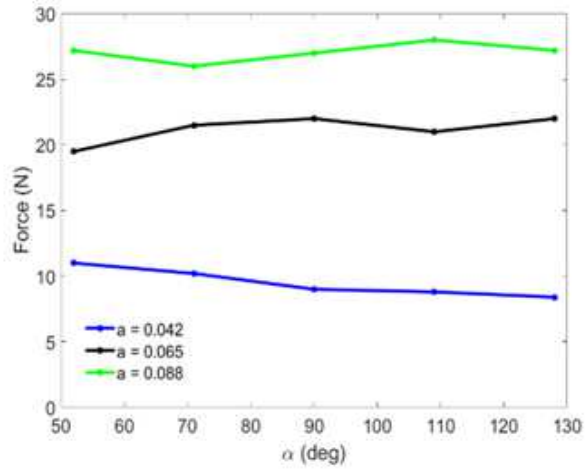
(b)

Figure 3 Prototype with (a) the four-bar mechanism and (b) horizontal movement

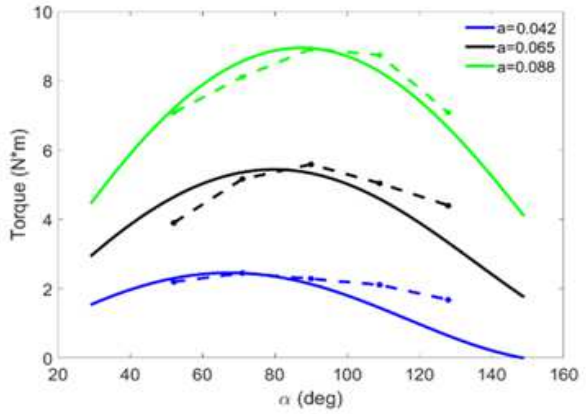
4 Discussion

The quest to improve the quality of life for individuals with upper limb impairments has led to the development of a wide array of assistive technologies. Among these,

dynamic arm supports stand out as a pivotal tool in providing the necessary support while ensuring mobility.



(a)



(b)

Figure 4 (a) Vertical force measured at the arm rest level for three different 'a' parameter for different alpha angles; (b) Transformation of the force measurement into torque at the base joint for different 'a' parameter for different alpha angles. Full lines represent the results from the theoric simulation model and dotted lines represents the measured values on the prototype.

This paper presents the concept of a low-cost dynamic arm support, emphasizing the principle of static balancing, that also has a minimal lateral footprint without being cumbersome by replacing the wheelchair armrest. Through meticulous analysis and application of mathematical models, a mechanism that adeptly counterbalances the arm's weight in any spatial orientation is developed. The foundation of this arm support is a four-bar linkage, which ensures vertical movement while maintaining the arm rest's orientation. Furthermore, the design incorporates both rotational and prismatic joints, optimizing the device for horizontal movements. The significance of this research lies not just in the creation of a functional prototype but in its potential to be a cost-effective solution for many. By understanding and applying the principles of static balancing and leveraging the benefits of four-bar mechanisms, we have taken a step closer to making dynamic arm supports accessible to a broader audience. Future endeavors in this domain should focus on refining the design, ensuring user comfort, and further reducing costs, thereby making it a ubiquitous solution for those in need. Future works will consist of validating the prototype with participants and pursuing iterations.

5 Conclusion

This study presents the development of a cost-effective dynamic arm support designed to assist individuals with upper limb impairments. By employing a four-bar linkage and integrating static balancing principles, the device successfully facilitates vertical and horizontal movements while maintaining minimal lateral footprint. Prototype testing demonstrated effective weight counterbalancing, making the device a promising solution for enhancing mobility and independence. Future research should focus on user validation, further design refinements, and cost reduction to increase accessibility and usability.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author Contributions

ACL: Conceptualization, Mechanical design, Project administration, Methodology, Analysis, Writing- original draft.
CL: Mechanical design, Conceptualization
CD: Mechanical design, Conceptualization
SL: Mechanical design, Conceptualization
TL: Mechanical design, Conceptualization
JSR: Writing – review & editing, Validation Conceptualization
VF: Writing – review & editing, Validation Conceptualization

Funding

This research was supported by funding from Innovation, Science and Economic Development Canada through the Accessible Technology Program.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgment

The researchers would like to express their gratitude to Innovation, Science and Economic Development Canada for the support provided through the Accessible Technology Program. They also acknowledge the contributions of all team members involved in the

mechanical design, methodology, and conceptualization of the research. The researchers appreciate the dedication and collaboration of everyone involved in the project.

References

[1] DAHLGREN, A., KARLSSON, A.K., LUNDGREN-NILSSON, Å., FRIDÉN, J., CLAESSON, L.: Activity performance and upper extremity function in cervical spinal cord injury patients according to the Klein-Bell ADL Scale, *Spinal Cord*, Vol. 45, No. 7, pp. 475-484, 2007. https://doi.org/10.1038/SJ.SC.3101993

[2] DILLINGHAM, T.R., PEZZIN, L.E., MACKENZIE, E.J.: Limb amputation and limb deficiency: epidemiology and recent trends in the United States, *Southern Medical Journal*, Vol. 95, No. 8, pp. 875-883, 2002. https://doi.org/10.1097/00007611-200208000-00018

[3] LANG, E., BLAND, M.D., BAILEY, R.R., SCHAEFER, S.Y., BIRKENMEIER, R.L.: Assessment of upper extremity impairment, function, and activity after stroke: foundations for clinical decision making, *Journal of Hand Therapy*, Vol. 26, No. 2, pp. 104-115, 2013. https://doi.org/10.1016/J.JHT.2012.06.005

[4] SONN, U.: Longitudinal studies of dependence in daily life activities among the elderly: Methodological development, use of assistive devices and relation to impairments and functional limitations, *Scandinavian Journal of Occupational Therapy*, Vol. 2, No. 1, pp. 41-41, 1995. https://doi.org/10.3109/11038129509106798

[5] BIERING-SØRENSEN, T., HANSEN, R.B., BIERING-SØRENSEN, F.: Home aids and personal assistance 10–45 years after spinal cord injury, *Spinal Cord*, Vol. 47, No. 5, pp. 405-412, 2008. https://doi.org/10.1038/sc.2008.132

[6] WILSON, J., MITCHELL, J.M., KEMP, B.J., ADKINS, R.H., MANN, D.W.: Effects of assistive technology on functional decline in people aging with a disability, *Assistive Technology*, Vol. 21, No. 4, pp. 208-217, 2009. https://doi.org/10.1080/10400430903246068

[7] Obi Adaptive Eating Device: Meet Obi: the Adaptive Eating Device - Eat Independently!, [Online], Available: https://meetobi.com/ [05 Oct 2024], 2024.

[8] PATHAK, REDMOND, J., ALLEN, M., CHOU, K.: Clinical Validation of a Handheld Assistive Device for Tremor (S53.005), *Neurology*, Vol. 80, No. 7_supplement, pp. S53.005-S53.005, 2013. https://doi.org/10.1212/wnl.80.7_supplement.s53.005

[9] Focal Meditech: Dynamic arm support, [Online], Available: https://www.focalmeditech.com/products/dynamic-arm-support/ [05 Oct 2024], 2024.

[10] CAMPEAU-LECOURS, A., LAMONTAGNE, H., LATOUR, S., FAUTEUX, P., MAHEU, V., BOUCHER, F., DEGUIRE, CH., CARON L'ECUYER, L.-J.: *Kinova Modular Robot Arms for Service Robotics Applications*, Rapid Automation: Concepts, Methodologies, Tools, and Applications, IGI Global, pp. 693-719, 2019. https://doi.org/10.4018/978-1-5225-8060-7.ch032

[11] VAN DER HEIDE, L.A., VAN NINHUIJS, B., BERGSMA, A., GELDERBLOM, G.J., VAN DER PIJL, D.J., DE WITTE, L.P.: An overview and categorization of dynamic arm supports for people with decreased arm function, *Prosthetics and Orthotics International*, Vol. 38, No. 4, pp. 287-302, 2014. https://doi.org/10.1177/0309364613498538

[12] DUNNING, G., HERDER, J.L.: *A review of assistive devices for arm balancing*, 2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR), Seattle, WA, USA, pp. 1-6, 2013. https://doi.org/10.1109/ICORR.2013.6650485

[13] LEBRASSEUR, LETTRE, J., ROUTHIER, F., BOUFFARD, J., ARCHAMBAULT, P.S., CAMPEAU-LECOURS, A.: Evaluation of the usability of an actively actuated arm support, *Assistive Technology*, Vol. 33, No. 5, pp. 271-277, 2021. https://doi.org/10.1080/10400435.2019.1629124

[14] VAN DER HEIDE, L., DE WITTE, L.: The perceived functional benefit of dynamic arm supports in daily life, *Journal of Rehabilitation Research and Development*, Vol. 53, No. 6, pp. 1139-1150, 2016. https://doi.org/10.1682/jrrd.2015.06.0099

[15] VAN DORSSER, W.D., BARENTS, R., WISSE, B.M., HERDER, J.L.: Gravity-balanced arm support with energy-free adjustment, *Journal of Medical Devices*, Vol. 1, No. 2, pp. 151-158, 2007. https://doi.org/10.1115/1.2736400

[16] HERDER, J.L., VRIJLANDT, N., ANTONIDES, T., CLOOSTERMAN, M., MASTENBROEK, P.L.: Principle and design of a mobile arm support for people with muscular weakness, *Journal of Rehabilitation Research and Development*, Vol. 43, No. 5, pp. 591-604, 2006. https://doi.org/10.1682/jrrd.2006.05.0044

[17] HAGERMAN: Arm Supports, *Assistive Innovations*, [Online], Available: https://www.youtube.com/watch?v=vUYgIf_3tqo [05 Oct 2024], 2019.

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 157-163 ISSN 2453-675X

Technology and effective tax rates: innovative approaches to tax burden
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https://doi.org/10.22306/atec.v10i4.233 *Received: 17 Oct. 2024; Revised: 26 Nov. 2024; Accepted: 11 Dec. 2024*

Technology and effective tax rates: innovative approaches to tax burden

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Keywords: effective average tax rate, effective marginal tax rate, intangible assets, technology.
Abstract: The indicators of the effective tax burden on corporations present effective tax rates, taking into account the impact of all the design features mentioned in the legislation. The paper addresses the issue of effective taxation through the method of calculating EMTR and EATR with a focus on intangible assets in 2004, 2015 and 2023. The analysis determined the tax depreciated shield, which tracked the amount of tax savings on capital investment and the economic rent of the project with taxation, focusing on the magnitude of the financial benefit of the project with an aspect on taxation. The analysis showed that a 3% increase in the statutory rate over the study period, increased the effective average corporate rate on intangible assets by 13.56%. The annual tax saving achieved for 2023 on intangible assets was at 17.17% with a payback period of five years.

1 Introduction

Effective taxation is one of the key factors influencing a country's economic environment and its attractiveness for business and foreign investment. It involves corporate taxation of firms operating in each (domestic) territory and its setting can have far-reaching implications for the business environment, the inflow of foreign investment and the overall competitiveness of the economy. It also affects the management of organisations, particularly regarding resource allocation, investment strategies and the general financial policy of the company. To optimise their tax obligations and maximise revenues, companies often analyse the tax burden in other countries. And it is the effective tax rates that provide foreign investors with sufficient information on the tax burden of that country.

1.1 Literature review

As early as the 1960s, Jorgenson and Hall (1967) [1] pointed to an effective tax rate that includes a number of indicators, not just the statutory tax rate. The effective tax rate is simply the ratio of the tax burden to the tax base. Effective corporate tax rates consider the statutory tax rate, but also aspects of tax systems that determine the total amount of taxes effectively paid. The differences between the statutory and effective tax rates can be large in some cases. It may be the case that countries with a high statutory tax rate reduce the size of the tax base or reduce tax enforceability. The analysis of corporate tax highlights how tax competition works (Blechova, 2008) [2].

Effective average tax rates depend more strongly on the host country's statutory rate than on the effective marginal tax rate. A country with a high statutory tax rate may have a very low or even negative effective marginal tax rate, but the effective average tax rate will quickly increase with profits if the statutory rate is high. Focusing on the effective average tax rate could explain why tax competition between EU countries seems to have taken the form of a reduction in the level of the statutory rate and why countries with a lower statutory rate, rather than a lower cost of capital, are likely to attract most foreign investment, especially from non-EU countries (Giannini and Maggiulli, 2002) [3].

Empirical studies have looked at the effective tax rate from different perspectives. They address the question of the impact of effective tax rates on the economic behaviour of firms, including their allocation, the issue of investment choices and profit reduction strategies, or they address the issue of tax competition between jurisdictions (Barrios et al., 2014) [4]. Dyreng et al. (2017) [5] tracked changes in effective corporate tax over a 25-year period. Statutory tax rates have remained relatively constant over the period, while effective tax rates have varied. This was because some firms were able to reduce their effective tax rates through tax planning strategies and took advantage of a bargain in the tax system. According to Kubatova and Jares (2011) [6], we divide the indicators of the effective corporate tax rate into fictitious and real. The fictitious indicators look ahead, i.e. into the future, and simulate for us the impact of the tax on the selected entities. Real indicators, on the contrary, look into the past and thus determine the amount of tax burden in a period that has already passed based on measured real data.

The effective average tax rate (EATR) is the ratio of the present value of taxes to the present value of profits. This can be calculated for any discrete investment project, including one in which a positive economic return is expected ex ante. The effective marginal tax rate (EMTR) is a special case of the EATR, where the project is simply divided evenly into phases until the last additional unit

represents zero after-tax rent to the investor (Abbas et al., 2013) [7]. EMTRs tell the tax burden for marginal investment projects by comparing the pre-tax and after-tax cost of capital of such projects (Auerbach, 1979; King and Fullerton, 1984) [8,9].

EMTR represents a marginal investment for which we can assume a pre-tax rate of return sufficient for the investor to conduct the project. This rate of return must be at least at the level of the real interest rate. If the result of the calculation is positive, i.e. if the investment is more profitable than marginal, we expect the after-tax profit to be positive in the future. It is important to compare the result with the EATR which includes the effect of the marginal personal effective tax rate (these are dividends or similar payments) (Modigliani, Miller, 1963) [10].

2 Methodology

The aim of this paper is to address the issue of effective taxation through a method of calculating EMTR and EATR focusing on intangible assets in 2004, 2015 and 2023. To calculate effective corporate tax rates, we used the methodology compiled by Devereux and Griffith (2003) [11]. The effective average tax rate (EATR) is defined as the ratio of the present discounted value of taxes over the present discounted value of a project's (investment's) pre-tax profits. The methodology also includes the calculation of the marginal tax rate (EMTR) as a special case where the after-tax economic rent is zero. The original calculation is based on an investment of one capital unit that is realised over one year and is subsequently sold at its residual value $(1-\delta)(1+\pi)$, where δ is the real economic depreciation and π is inflation. An overview of the variables that enter the calculations is given in Table 1. To calculate EMTR, the after-tax economic rent R must be zero (Devereux-Griffith, 2003) [11]. Subsequently, the required level of pre-tax net profit must be solved for. These changes are captured in the following relationship (1):

$$\tilde{p} = \frac{(1-A-\frac{F}{\gamma})(p-\pi+\delta(1+\pi))}{(1+\pi)\left(1-\tau'-(\tau-\tau')\left(\frac{(1-\delta)(1+\pi)}{1+p}\right)^{Y}\right)} - \delta \qquad (1)$$

where A represents the present discounted value of depreciation, F represents the additional cost of raising finance from own or external sources, τ represents the statutory corporate tax rate, τ' is the tax rate in the special scheme. Present discounted value of depreciation – A, also called a tax shield.

For the calculation of the tax shield, the following relationship applies (2):

$$A = \tau\emptyset\left\{\left(\frac{1}{1+\rho}\right) + \left(\frac{1}{1+\rho}\right)^{2} + \cdots + \left(\frac{1}{1+\rho}\right)^{T}\right\} \qquad (2)$$

where ρ is the shareholder's discount rate. Since there is no personal taxation in this model, then the shareholder discount rate is equal to the nominal interest rate *i*, the value of which has been estimated using the Fisher formula (3):

$$i = (1+r)(1+\pi) - 1 = (1+0.05)(1+0.02) - 1 = 0.071 = 7.1\,\% \qquad (3)$$

This implies $\rho = i = 7.1\,\%$. We then calculate the EMTR as the ratio of the difference between the pre-tax rate of return on marginal investment $\tilde{p}$ and the after-tax rate of return-on-investment r to the pre-tax rate of return on marginal investment $\tilde{p}$ (4):

$$EMTR = \frac{\tilde{p}-r}{\tilde{p}} \qquad (4)$$

EMTR includes in its calculation elements such as the tax base, the method of financing the investment, the method of depreciation of fixed assets, but also the level of inflation, etc. (all calculations in the work have been adapted to the Slovak legislation). We call the indicator $\tilde{p}$ the cost of capital term. This indicator needs to be quantified for each investment separately, as investments may take different forms, financing or lead times. If depreciable assets are included in the investment, the depreciation rate, which affects the tax base, must also be included in the equation for calculating the EMTR. For intangible assets, the relationship takes a basic form (5):

$$\tilde{p} = \frac{(1-A)}{(1-\pi)*(1-\tau)}\{\rho + \delta*(1+\pi) - \pi\} - \delta*e \qquad (5)$$

An important part of the effective corporate tax calculation is the financing of the investment. Financing can be from a variety of sources - retained earnings, new deposits or financing through debt. In the calculation, we assume the absence of personal taxes, so the shareholder tax discrimination variability $\gamma = 1$. The gamma γ expresses the ratio of the funds raised from a given investment to the funds raised from an alternative investment. In the following cases, we present an adjustment of the equations for an intangible asset that is financed through debt (6):

$$\tilde{p}^{DE} = -\frac{(\rho - i(1-\tau))}{(1+\pi)(1-\tau)} \qquad (6)$$

For the financing of an investment from a new deposit or through retained earnings, the relationship applies (7):

$$\tilde{p}^{NE} = \frac{\rho(1-\gamma)(1+e)}{\gamma(1+\pi)(1-\tau)} \qquad (7)$$

Taxes and expected return on investment are closely linked. Countries with high effective marginal tax rates are less attractive to investors as their cost of capital is higher. Another category according to Devereux-Griffith (2003) [11] based on which the attractiveness of a location can be

determined is the EATR. The formula for calculating EATR is (8):

$$EATR = \frac{R^* - R}{p/(1+r)} \quad (8)$$

where R^* is the present discounted value of the untaxed economic rent received, R j is the present discounted value of the after-tax economic rent received, p is the pre-tax profit (excluding depreciation) and r is the real interest rate. In this expression we must include the real rate of capital depreciation, i.e. economic depreciation, assuming that the net return to capital is constant, the expression takes the form (9):

$$EATR = \frac{R^* - R}{p/(r+\delta)} \quad (9)$$

First, the present value of the profit on the investment needs to be calculated. We calculate this value by discounting it at the real interest rate (10):

$$R^* = \frac{p-r}{1+r} \quad (10)$$

Since we know the values of p and r because they are given quantities, we can calculate *R*:*

$$R^* = \frac{0.20-0.05}{1+0.05} = 0.1429 \quad (11)$$

The discounted value of the tax-free economic annuity is 14.29%. This economic rent needs to be taxed according to the tax system in the country to get the economic rent on the investment after tax R.

To apply the equations to conditions in Slovakia, we need to modify them. The basic relationship for intangible assets, using which we calculate the EATR has the form (12):

$$R = \frac{\gamma}{1+\rho} * \{[(p+\delta)*(1+\pi)*(1-\tau)] - [\rho + \delta * (1+\pi) - \pi] * (1-A)\} \quad (12)$$

The funding methods were indicated in the calculation of the EMTR. These are financing through retained earnings and new deposits or through debt. To arrive at the final calculation of the EMTR it is necessary to calculate the cost of these methods of financing the investment. The relationship for debt financing takes the form (13):

$$F^{DE} = \frac{\gamma*(1+e)*(\rho - i + i*\tau)}{1+\rho} \quad (13)$$

where $(1+e)$ is the effective property tax rate paid during the direct investment activity. The rent derived from the investment is increased by the ratio of the discounted value of the difference between the shareholder discount rate and the nominal interest rate and the interest tax shield. For financing through a new deposit, the relationship takes the form (14):

$$F^{NE} = -\frac{\rho(1-\gamma)(1+e)}{1+\rho} \quad (14)$$

2.1 Relationship between EATR and EMTR

The EATR is a derivation of actual cash flows and tax burden. The EMTR has applications in assessing incentives to save and invest. The relationship between these two variables can be expressed by the equation (15):

$$EATR = \frac{\tilde{p}}{p} EMTR + \frac{p-\tilde{p}}{p}\tau \quad (15)$$

As we can see, the effective average tax rate is a broader concept than the effective marginal tax rate. The formula shows that the EMTR is part of the average tax rate. This relationship indicates the location and size of the investment. The relationship is used when the alternatives for locating the investment are mutually exclusive. It is important for the investor to know what the tax rate is in each country. We refer to the value that EMTR acquires. EMTR and EATR are referred to as tax wedges, which express the rate of return on a taxed and untaxed investment.

Table 1 Description and name of the variables entering the calculations of the effective tax rate

Desc.	Variable	Desc.	Variable
A	discounted value of depreciation	***e***	property tax rate
π	inflation	***v***	method of valuation of inventories
δ	tax depreciation	***γ***	shareholder tax discrimination
F	**additional fundraising costs**	***R****	the present discounted value of the untaxed economic annuity received
τ	statutory corporate tax rate	***R***	the present discounted after-tax value of the economic rent received
τ´	special regime tax rate	***p***	profit before tax
ρ	shareholder's discount rate	$\tilde{p}$	return on investment before tax
i	nominal interest rate	***r***	real interest rate

Source: own processing.

2.2 Calculation of the effective corporate tax rate in Slovakia

The calculation of the effective corporate tax rate consists of several steps. First, it is necessary to calculate the tax shield for each type of tangible property. The calculation proceeds by quantifying the effective marginal tax rate, the economic rent of the project, the effective average tax rate and expressing the relationship between

the EATR and the EMTR. Internal and external parameters entered the calculations performed according to the ZEW (2022) [12] methodology. The internal parameters consisted of the corporate tax rate, the effective property tax rate.

Table 2 Development of property tax in Slovakia

Year	Nominal tax rate	Effective tax rate
1998 - 1999	0.11 %	0.07 %
2000 - 2003	0.11 %	0.08 %
2004	0.11 %	0.09 %
2005 - 2012	0.44 %	0.36 %
2013 - 2016	0.44 %	0.34 %
2017 - 2023	0.44 %	0.35 %

Source: ZEW (2022) [12].

The calculations are carried out for 2004, 2015 and 2023. 2023 is the year on which we have focused our attention. The years 2004 and 2015 are for comparison of the situation in the past when different tax rates were in force.

3 Results

Internal economic calculation parameters:

The corporate tax rate in effect in 2004 was 19%, in 2015 - 22% and in 2023 - 21%. The year 2015 is also characterized by a change in the depreciation policy in Slovakia. In this year, the number of depreciation groups and the number of years of depreciation within them changed. Therefore, we present the values of the effective tax rate also in this year. The effective property tax rate was in different amounts in these years (Table 2). In our calculations, we assumed the weighted arithmetic average method for inventory withdrawals. The depreciation period was determined according to the classification of the assets into depreciation groups. The amortization period for intangible assets was 5 years, industrial machinery 6 years, agricultural machinery and basic stock and draft animals 4 years, perennial crops 12 years, industrial buildings 40 years and agricultural buildings 20 years.

External economic parameters for the calculations:

The accounting depreciation rate δ is 15.35% for intangible assets, base stock, perennial cropping units, 3.1% for industrial and agricultural buildings, 17.5% for industrial and agricultural machinery and 0% for financial assets and inventories. The real interest rate was set at r = 5%. This value of the real interest rate is fixed in the case of an open economy. We consider that one country cannot influence the real interest rate because it arises in the international capital market. This is the real interest rate in the case of an alternative investment, i.e. the deposit of funds in a bank. Another external economic parameter is the inflation rate π, set at 2% in all countries, and the pre-tax rate of return p, which is 20%. All the external economic parameters for the calculation come from ZEW (2022) [12] based on which the calculation of the effective average and marginal corporate tax rate is carried out.

Tax shield:

The tax shield represents the present discounted value of depreciation, so before the actual calculation, it is necessary to know what depreciation conditions for each type of asset were in force in the year for which the calculation is made. For 2023, the straight-line depreciation is used for intangible assets and the depreciation period for this type of asset is 5 years. The annual depreciation rate is therefore 20% of the total value.

Table 3 Tax shield for intangible assets in Slovakia in selected years

Type of asset	Year	STR	Annual depreciation rate	Tax shield
Intangible assets	2004	19%	20.00%	15.54%
	2015	22%	20.00%	17.99%
	2023	**21%**	**20.00%**	**17.17%**

Source: own processing according to [12].

Table 3 shows the annual depreciation rates for each type of asset, which have not changed over the years, and the tax shield. The value of the tax shield for each type of asset was calculated according to relation (2). Assuming an investment in assets of EUR 1 million in 2023, the tax saving in the form of the tax shield for intangible assets is 17,17 % of the value of the assets, i.e. EUR 171 700. As intangible assets are depreciated over five years, this saving is spread over the five years of depreciation of the asset. Table 3 also shows the years 2004 and 2015 for a better comparison of the evolution of the tax rates and the tax shield. Different statutory tax rates were in effect in selected years. In 2004, the STR was 19% and in 2015 the STR was at 22%. For intangibles, the tax shield was 15.54% in 2004 when the STR of 19% was in effect. The change in STR in 2015 was an increase of 3% points from 2004. The increase in the tax shield was only 2.45%. In 2023, the STR of 21% was in effect. This was a decrease of 1% from 2015. The tax shield fell by 0.82%. When the STR declines, it declines at a greater rate than the tax shield declines. The use of the tax shield is most effective in asset-intensive industries, i.e., where there is a large amount of fixed assets that can be legally depreciated. Conversely, the service industry may have few assets that can be depreciated, and therefore the use of the tax shield is not as significant for these entities.

3.1 Effective marginal tax rate

The EMTR is the difference between the cost of capital spent on a given investment and the after-tax rate of return on an alternative investment. The higher the tax burden in a country, the higher the cost of capital, which affects the growth of the EMTR. The higher the EMTR, the less likely

it is that the investment will be realized, as it is too tax-intensive for the investor. EMTR values are monitored because of the location of the investment. Investors require the EMTR value to be as low as possible. As with all marginal variables, EMTR is the deciding factor when the effective marginal tax rate is zero. This means that the marginal value of capital equals its cost.

We calculate the EMTR as the ratio of the difference between the pre-tax rate of return on marginal investment ($\tilde{p}$) and the after-tax rate of return on investment r to the pre-tax rate of return on marginal investment $\tilde{p}$. First, the pre-tax rate of return on investment needs to be determined. This is calculated from relation (5). We also need to include in the calculation the method of financing the investment, hence relation (6)-(7). The after-tax rate of return is known. It has been determined as an external parameter at 5%. We then need to put the calculated values into relation (4) to calculate the effective marginal tax rate. If we consider financing through retained earnings or a new deposit, the intangible assets at EMTR reached 13.56% in 2023. When financing through debt, the EMTR values reached negative values because the real rate of return on the alternative investment entered the relationship for the calculation at 5%. If it had been set at 3%, neither EMTR value would have been negative. In the case of the investment in intangible assets, this indicator is -27,09 %. For the investor, negative values of the calculated EMTR are advantageous because they represent a saving compared to the alternative investment, i.e. depositing the funds in a monetary institution Table 4.

Table 4 Calculated EMTR values

Assets	*Year*	*Intagible assets*
Retained earnings and new deposit	2004	13.14%
	2015	13.80%
	2023	**13.56%**
Debt	2004	-21.35%
	2015	-30.29%
	2023	**-27.09%**

Source: own calculations according to ZEW (2022) [12].

3.2 Effective average tax rate

To know where to locate their investment, investors use the calculated EATR, which reflects the effective tax burden. This calculation includes not only the statutory tax rate, but also the financing of the investment, the components of the tax base, or the additional taxes and costs required to make the investment. This indicator is the most accurate for determining the tax burden, in view of the number of variables that enter the calculation.

To calculate the effective average tax rate, we first need to implement the calculation of the present discounted value of the untaxed economic rent R^* given in equation (10). Since the calculation involves external economic parameters that are known, the result is a discounted value of the untaxed economic rent of 14.29%. The next step is to calculate the after-tax economic rent given in relation (12) for intangible assets, considering the financing of the investment from external resources (13) or own resources (14). Once the value of the discounted untaxed economic rent and the after-tax economic rent have been calculated, it is necessary to insert these values in relation (9).

Based on the calculations, the highest value of economic annuity has the lowest value of EATR. For intangible assets, the economic rent ranged from 0.0598 for 2023 to 0.0666 in 2004. As for the EATR, it ranged from 40.02% for 2004 to 43.62% in 2023, we must note that this is a method of financing from retained earnings. If we look at financing through debt, the rates will increase by 1.3 p.p. on average in Table 5.

Table 5 Economic rent of the project and EATR

	Assets	*Year*	*Intagible assets*
Economic rent of the project	Retained earnings and new deposit	2004	0.0666
		2015	0.0564
		2023	0.0598
	Debt	2004	0.0792
		2015	0.0710
		2023	0.0737
	Assets	***Year***	***Intagible assets***
EATR	Retained earnings and new deposit	2004	40.02%
		2015	45.38%
		2023	43.62%
	Debt	2004	41.28%
		2015	46.85%
		2023	45.02%

Source: own calculations according to ZEW methodology [12].

EATR values differ for intangible assets, the reason being the difference between accounting and tax depreciation rates. In calculating the EATR of intangible assets, we considered an accounting depreciation rate of 15.35%, while the annual tax depreciation rate for intangible assets was 20% in 2023. We can interpret the 2004 and 2015 results in the same way. Two parameters entered the calculations that were different in each year. The first was the statutory tax rate, which was 19% in 2004, 22% in 2015 and 21% in 2023. According to ZEW (2022) [12], Slovakia's EATR values in 2023 were approximately at the level of the EU28 average. The statutory tax rate, which taxed the income of business entities, was at 21%. The average EATR was 18.7%, 1.1% below the EU average. EATR for intangible assets was 17.1%. The calculated EATR values for the financing method of retained earnings and new deposit were 43.62% in 2023. The financing of the investment through debt reached a higher EATR value of 45.02%.

3.3 Relationship between effective average and marginal tax rates

The relationship between the effective average tax rate and the effective average tax rate reflects where to place the investment and to what extent. By comparing these two

calculated ratios, we can see to what extent the after-tax profit is reduced by tax. These tax wedges tell the rate of return on a taxed and untaxed investment. The calculation is carried out according to relation (15).

The results of the calculated values for the year 2023 (Table 6) talk about the ratio of EATR and EMTR for intangible assets. While for financing through debt, it shows lower rates. The difference between financing through equity and debt is about 7% already for all types of assets. Also, in the case of financing the investment through debt is intangible assets (11.54%).

Table 6 Economic rent of the project and EATR

Assets	***Year***	***Intangible assets***
Retained earnings and new deposit	2004	17.31%
	2015	19.62%
	2023	**18.85%**
Debt	2004	10.69%
	2015	11.97%
	2023	**11.54%**

Source: own calculations according to ZEW (2022) [12].

It is the combination of the effective average rate and the effective marginal rate that is the most appropriate way to make your investment in the most tax-efficient state in terms of taxes and the scale of the investment. The EATR ↔ EMTR relationship considers the cost of capital, accounting and tax letters, the inflation rate, the shareholder discount rate, as well as the statutory tax rate. It is necessary to take this relationship into account from the point of view of the return on investment to make it as optimal as possible. Many countries, including within the European Union, are trying to attract investors with low tax rates. As we have shown through calculations, it is not the statutory tax rates that are important for the efficient location of investment in an efficient scale. It is therefore necessary to look at corporate taxation in a broader context.

4 Conclusion

The statutory and effective corporate tax rate is an important factor for investors when deciding where to place an investment. Businesses try to find a country where they will pay as little as possible in corporate tax. However, the solution is not to find the country with the lowest statutory tax rate, but with the lowest effective tax rate. The analysis of the effective marginal and average corporate tax rate for 2023 in the Slovak Republic for intangible assets showed several facts. In 2015, there were several changes that significantly affected the level of the effective tax rate. The number of depreciation groups changed, as well as the classification of assets in it. The most recent change in the corporate tax rate in Slovakia was made in 2017, when it was changed from 22% to 21%, which has been in effect ever since. Based on this, we can conclude that the Slovak Republic and the intangible assets under review are becoming tax competitive and interesting for foreign investors. However, we cannot forget that the European Union consists of countries with different levels of national tax systems, and it is the inconsistency of these tax policies that creates a competitive environment. However, the European Union has so far been unsuccessful in its attempts to introduce tax harmonization. Countries fear a loss of competitiveness and are therefore not open to such a change. It is questionable whether tax harmonization will ever be pushed through.

Acknowledgement

This research was supported by the Slovak Scientific Grant Agency as part of the research project VEGA No. 1/0638/22 Intellectual capital and productivity of the regions.

References

[1] HALL, R.E., JORGENSON, D.W.: Tax policy and investment behavior, *The American economic* review, Vol. 57, No. 3, pp. 391-414, 1967.

[2] BLECHOVÁ, B.: *Charakteristika přístupů používaných v EU pro hodnocení efektivního daňového zatížení příjmů korporací*, Teoretické a praktické aspekty veřejných financí, XIII. ročník mezinárodní odborné konference, 11.-12.4.2008, Vysoká škola ekonomická v Praze, pp. 3-4, 2008. (Original in Czech)

[3] GIANNINI, S., MAGGIULLI, C.: *The effective tax rates in the EU Commission study on corporate taxation: Methodological aspects, main results and policy implications*, CESifo Working Paper, No. 666, 2002.

[4] BARRIOS, S., NICODÈME, G.J.A., FUENTES, A.J.S.: *Effective Corporate Taxation, Tax Incidence and Tax Reforms: Evidence from OECD Countries*, CESifo Working Paper, No. 5017, 2014.

[5] DYRENG, S.D., HANLON, M., MAYDEW, E.L., THORNOCK, J.R.: Changes in corporate effective tax rates over the past 25 years, *Journal of financial economics*, Vol. 124, No. 3, pp. 441-463, 2017. https://doi.org/10.1016/j.jfineco.2017.04.001

[6] KUBÁTOVÁ, K., JAREŠ, M.:. Identifikace a kvantifikace daňových úlev v ČR v roce 2008, *Politická ekonomie*, Vol. 59, No. 4, pp. 475-489, 2011. (Original in Czech)

[7] ALI ABBAS, S.M., KLEMM, A.: A partial race to the bottom: corporate tax developments in emerging and developing economies, *International Tax and Public Finance*, Vol. 20, pp. 596-617, 2013. https://doi.org/10.1007/s10797-013-9286-8

[8] AUERBACH, A.J.: Wealth maximization and the cost of capital, *The Quarterly Journal of Economics*, Vol. 93, No. 3, pp. 433-446, 1979.

[9] KING, M.A., FULLERTON, D.: *The taxation of income from capital: A comparative study of the United States, the United Kingdom, Sweden and West Germany*, University of Chicago Press, 1984.

[10] MODIGLIANI, F., MILLER, M.H.: Corporate income taxes and the cost of capital: A correction, *The American economic review*, Vol. 53, No. 3, pp. 433-443, 1963.
[11] DEVEREUX, M.P., GRIFFITH, R.: The impact of corporate taxation on the location of capital: A review, *Economic Analysis and Policy*, Vol. 33, No. 2, pp. 275-292, 2003.
[12] ZEW Annual Report, Project for the EU Commission TAXUD/2022/CC/120, Mannheim: ZEW, [Online], Available: https://www.zew.de/en/zew/news/zew-annual-report-2022-published [06 Jan 2024], 2022.

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 165-170 ISSN 2453-675X

Intellectual capital valuation in digital economy: a review of corporate and national perspectives
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https://doi.org/10.22306/atec.v10i4.237 *Received: 18 Oct. 2024; Revised: 16 Nov. 2024; Accepted: 02 Dec. 2024*

Intellectual capital valuation in digital economy: a review of corporate and national perspectives

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Keywords: digital economy, intellectual capital, technological readiness, human capital.
Abstract: Intellectual capital (IC) has emerged as a critical driver of organizational value and competitive advantage in the knowledge-based economy. Unlike tangible assets, IC encompasses intangible assets such as human capital, structural capital, and relational capital, which collectively contribute to the innovative capacity and strategic positioning of firms and economies. Despite its significance, measuring intellectual capital poses substantial challenges due to its intangible nature and the lack of standardized valuation methods. This paper aims to provide a brief overview of the components and methods used in the measurement of intellectual capital at both corporate and national levels.

1 Introduction

In contemporary academic theory and practice, there are various approaches to valuing intangible assets. The methods for measuring and valuing different types of intangible components of intellectual capital (IC) depend on the analyst's definition of the intangible asset, and the specific objectives of the analysis. The definition of proxy indicators representing intangible IC components is primarily determined by the scope of economic research. Consequently, macroeconomic approaches to valuing intangible IC components focus on different goals and use different proxy indicators than microeconomic methods.

Many scholars view intellectual capital (IC) as a combination of intangible assets held by individuals, companies, institutions, communities, and regions, which are the primary source of intellectual potential.

At the corporate level, intellectual capital can be defined as a combination of intangible assets that enable a company to function [1,2]. From a strategic perspective, the concept of IC can provide answers to key questions regarding the sources of future profitability [3]. Moreover, in terms of corporate innovation activities, intellectual capital can be viewd as the primary dynamic force driving innovation and economic performance in the knowledge economy [4].

Additionally, IC is characterized as collective wisdom and energy, posing challenges in both quantification and management. In synthesis, corporate intellectual capital stands as a pivotal and intricate asset shaping organizational operations, strategic trajectories, and innovative capabilities, notwithstanding the complexities inherent in its quantification and management [5].

The definition of intellectual capital at the national level is quite similar to that at the corporate level, however with a focus on different objectives. The macroeconomic significance of intellectual capital stems from the fundamental goal of every government, which is to provide favorable conditions for economic growth and enhance the overall welfare of its population. Therefore, at the macroeconomic level, national intellectual capital is perceived as a crucial factor that determines the wealth of nations, positively impacting productivity and the competitiveness of the country. National intellectual capital encompasses intangible assets embodied in individuals, businesses, institutions, communities, and regions, representing a fundamental source of wealth, prosperity, and the most important wellspring of a country's productivity in the contemporary knowledge economy context [6]. Unlike corporate intellectual capital, which primarily consists of human and structural capital, which further include customer, organizational, innovative, and process capital [7], national intellectual capital is defined in terms of four main pillars: human capital, market capital, process capital, and renewal capital [6,8]. Some authors include financial capital as an additional pillar of national intellectual capital [9], which comprises indicators like GDP, external debt, industrial production by major branches, and inflation.

It is necessary to note that measuring intellectual capital (IC) is challenging due to its intangible nature and the lack of standardized methods for quantification and comparison. The complexity of this phenomenon makes accurate measurement difficult at both the corporate and national levels. Additionally, obtaining precise data on IC can be tough, and integrating these metrics with traditional financial reporting framework poses further issues. However, a brief classification of methods for measuring IC will be discussed further in this paper.

2 Methods for measuring IC

Measurement of intellectual capital is crucial for understanding which intangible assets drive economic growth and innovation. The information obtained reveals strengths and weaknesses in human capital, infrastructure, and institutional frameworks, guiding policy-making and investment decisions. Evaluating intangible capital helps not only enterprises but also regions and nations enhance their competitiveness and adaptability in the global environment. It promotes sustainable development by identifying areas that require improvement, such as education, research and technology, thereby ensuring long-term prosperity and resilience.

In exploring the methods for valuing intangible assets, several authors provide a comprehensive overview of methods for measuring intellectual capital (IC). They identify and briefly describe 42 approaches to determining the value of intangible assets at both national and corporate levels. These methods are often classified into four categories based on common characteristics. The brief description of the four groups of methods is discussed below [10-12]:

Methods for Direct Intellectual Capital Measurement (DICM) involve valuing corporate intellectual capital through methods based on the monetary estimation of individual intangible components of IC. These components can be valued individually or expressed as an aggregated index. By using selected methods to separately assess each IC component, a company can gain a clearer picture of its intellectual wealth [13,14]. Some authors emphasize that the precise and relatively simple methodology of these procedures allows their application at any level within the organization [15].

Market Capitalization Methods (MCM) derive the value of IC from the existing differences between the market value of the company and its book value. Similar to DICM, MCM represents a monetary approach to valuing intangible assets, allowing for the comparison of companies within the same industry. However, specific methodologies within this group cannot provide a detailed picture of the intangible nature of all components of a company's intellectual capital [13]. Despite the range of understandable and easily applicable methods encompassed by the MCM cathegory, its greatest drawback is that changes in the market value of a company's shares are not entirely under management control, especially during mergers, acquisitions, or short-term economic cycles, which can cause fluctuations in interpreting the real value of the company's IC [10]. Additionally, the authors point out that market capitalization methods do not allow for the comparison of companies of different sizes without excluding the factor of the size of the compared companies.

Return on Assets Methods (ROAM) include methods based on return on assets and methods that calculate the profitability of individual intangible assets of a company. The main advantage of using ROAM methods is their simplicity and clarity, as ROAM procedures are based on traditional accounting principles [14]. This approach is also suitable for testing and comparing different companies within the same industry. However, calculating return on assets indicators often involves a discount factor based on the interest rate or the required rate of return. While this takes into account the time value of money, it also means that the values of these indicators will differ at different points in time. It is worth to highlight one disadvantage of the ROAM approach: it cannot identify which element is the key driver in the value creation process due to the lack of a unified definition of IC. Additionally, ROAM methods do not provide information on how to potentially improve results [10,16].

Scoreboard Methods (SCM) allow for the valuation of intangible assets through specific indicators and indexes calculated for various components of intellectual capital (IC). These methods are highly complex and can be finely tuned to align with the development strategy of a particular company. One of the greatest advantages of these methods is their applicability to companies of any size and in any industry, regardless of how the individual components of intellectual capital are defined within the company [10,14]. The methods encompassed by this approach allow for the capture and valuation of knowledge contained within human capital not only at the microeconomic level but also at the macroeconomic level. This enables the assessment of the quality of education and the individual competitiveness of people in both microeconomic and macroeconomic tasks [6]. A significant limitation of SCM methods is that each company creates its own index that takes into account all the specific aspects of its business activities and environment. As a result, it is very challenging to compare competing companies based on models created using the SCM approach [10].

3 National Intellectual Capital Index (NICI)

One significant method within the scoreboard approaches is the National Intellectual Capital Index (NICI), first introduced by Nick Bontis in his 2004 study [6]. The NICI methodology offers a comprehensive framework for measuring and evaluating intellectual capital (IC) at macroeconomic level, recognizing intangible assets as critical drivers of economic performance and competitiveness of a country. Its methodology focuses on four key components: human capital, market capital, process capital, and renewal capital [6,8].

The method begins with selecting relevant indicators, both quantitative and qualitative, to represent each

category of NICI. Data for these indicators is then collected from reliable sources, including national statistics agencies, international organizations, and academic studies. To ensure comparability, the data undergoes normalization using statistical methods such as z-scores or min-max normalization. Next, the normalized indicators are assigned weights based on their perceived importance and then aggregated to form composite indices for each category of intellectual capital. These weighted and aggregated indicators are then combined to calculate the overall NICI. Subsequently, the resulting indices are analyzed to identify patterns, strengths, and weaknesses in the nation's intellectual capital, which includes examining causal relationships between intellectual capital and economic performance [6,8].

3.1 Components of National Intellectual Capital Index

The most important component of National Intellectual Capital Index is national human capital. Just as employees, with their unique qualities, create value for a company, citizens contribute to the economic growth of a country. ***The national human capital*** includes knowledge, expertise, intuition, and the ability to achieve national goals, along with values rooted in the nation's culture and philosophy. It reflects the population's capabilities in education, health, experience, motivation, and entrepreneurship, as well as the presence of a skilled labor force and available scientists and engineers. These factors are essential for creating and maintaining a nation's competitive advantage. As the most crucial link in the value creation process, human capital underpins the development of other intellectual assets like R&D and training [9].

The goal of every country is to advance in the global environment, and national market capital reflects the ability of the economy to keep up with global trends. ***National market capital*** encompasses a nation's assets in its relationship with the international market, reflecting its capabilities and successes in meeting global client needs through competitive and high-quality exports [6]. It includes factors such as customer loyalty, openness to globalization, economic resilience, and satisfaction from strategic customers and trading partners. These elements collectively enhance the nation's attractiveness and competitiveness on the global stage [9].

National process capital, which involves the cooperation and flow of knowledge supported by structural intellectual assets like information systems, databases, and national infrastructure, plays a pivotal role in the EU's digital transformation. This synergy is complemented by human capital, encompassing skills, expertise, and knowledge possessed by individuals, further enhancing the effectiveness of digital transformation[9].

By fostering digital infrastructure and investing in areas such as IT skills and communication networks, the European Union (EU) aims to enhance its digital capabilities and competitiveness. These efforts, combined with improvements in technological readiness, cybersecurity measures, and research institutions, align with the EU's objectives to foster innovation and digital resilience across European countries [17].

Another crucial component of national intellectual capital is ***National renewal capital***, which encompasses a nation's investments aimed at bolstering its competitive advantage in future markets and fostering subsequent growth. These investments span areas such as research and development, patents, trademarks, startup ventures, and innovation capacity, driving the nation's advancement and competitiveness [9]. By driving the development of new technologies, processes, and capabilities necessary for digital transformation, renewal capital plays a pivotal role in enabling nations to adapt to the evolving digital landscape and harness the full potential of digital technologies for economic and social advancement.

Therefore, knowing the value of intellectual capital at the macroeconomic level is crucial for identifying key areas of strength and improvement, driving economic growth and innovation. Moreover, this understanding also empowers policymakers and investors to make well-informed decisions, thereby fostering long-term competitiveness and sustainable development within the global knowledge economy.

3.2 Methodology of National Intellectual Capital Index

The NICI index consists of multiple quantitative and qualitative variables. To integrate both quantitative and qualitative variables and compute cumulative indices for the internal constructs of the NICI, several steps are must be undertaken, as expressed mathematically below [6,8]:

The first step (1) involves transforming variables with negative values:

$$\bar{r_{ij}} = r_{ij} + |min\, r_{ij}| + 1 \qquad (1)$$

where r_{ij} is the value of the variable *i*, alternative *j*;
$min\, r_{ij}$ is the minimum value of the variable *i*, alternative *j*.

This step is crucial, because transforming variables with negative values enhances the reliability, interpretability, and comparability of the NICI calculation process [8].

The second step (2), (3) involves normalizing variables by adjusting them to a common scale, such as between 0 and 1, to eliminate differences in their scales without altering their relationships [8]:

$$r_{ij} = \frac{min\, r_{ij}}{r_{ij}} \quad (2)$$

$$r_{ij} = \frac{r_{ij}}{max\, r_{ij}} \quad (3)$$

where r_{ij} is the value of the variable i, alternative j;
$min\, r_{ij}$ is the minimum value of the variable i, alternative j.
$max\, r_{ij}$ is the maximum value of the variable i, alternative j.

The third step (4) involves calculating cumulative indices using the Simple Additive Weighting (SAW) method, which is executed as follows [8]:

$$S_j = \sum_{i=1}^{m} \overline{w_{ij}}\, r_{ij} \quad (4)$$

where S_j represents the multi-criteria measurement value of alternative jj.
w_{ij} denotes the weight of variable i.
r_{ij} is the normalized value of variable i for alternative j.

The insights gained from the NICI are invaluable for policymakers, as they help identify areas that need investment and development to enhance national competitiveness. Additionally, the NICI serves as a benchmarking tool, allowing nations to compare their performance against other countries and understand their relative strengths and weaknesses. Businesses and government agencies can also use these insights for strategic planning and investment decisions. However, challenges such as data availability, subjectivity in weighting, and the dynamic nature of intellectual capital can impact the accuracy and applicability of the NICI results. Despite these challenges, the NICI provides a structured and systematic way to measure and analyze the intangible assets that drive a nation's competitiveness [8].

4 Popularity of National Intellectual Capital methodology among researchers

Despite the growing interest in assessing national wealth and intellectual capital, the research area focusing on evaluating IC through the use of NICI methodology is not extensive. This fact is indicated by the number of records of articles in one of the word´s leading database – Web of Science (WoS).

Searching the Web of Science database using keywords like "national intellectual capital" and "national intellectual capital index" as of June 12, 2024, we found only 95 publications addressing these topics covering the period from 2007 to 2024. Looking at the popularity of the topic over the years, we can conclude that the highest number of publications came out in 2014 (40 publications), making up 42.11% of the total records.

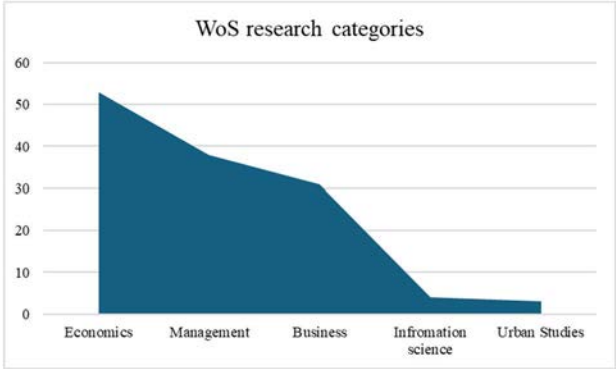

Figure 1 Record count of WoS Categories

The breakdown across various thematic categories reveals that "Economics" leads with the largest share at 55.79%, followed by "Management" at 40.00%, and "Business" at 32.63%. "Information Science" accounts for only 4.21% of publications, while "Urban Studies" makes up just 3.16%. Other categories were comparatively less significant, each contributing less than 2% to the total.

Examining the geographic distribution of individual publications reveals that Finland contributes the highest number with 38 publications, accounting for 40% of the total records. Taiwan follows with 9 publications, representing 9.74% of the records, closely followed by Lithuania and Spain, each with 8 publications. Minor contributors include Vietnam with 5 publications, Romania with 4, and Sweden with 4. Croatia, China, Poland, and the USA each have 3 publications. Other countries have 2 publications or fewer.

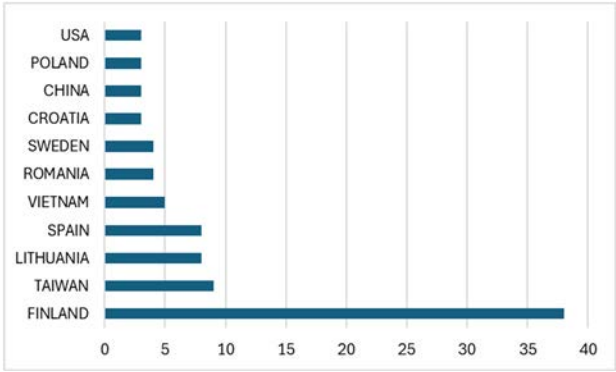

Figure 2 Leading countries in field of NICI research

In the domain of national intellectual capital research, a few authors have emerged as pivotal contributors. Leading figures in this field include Lin C.Y.Y., who has been featured in 43 publications, Edvinsson L. with 41 publications, Beding T. with 35 publications, Chen J. with 32 publications, and Markkula M. also with 32 publications. Notably, the author of the original NICI methodology, Bontis N., has only one publication listed in the Web of Science database.

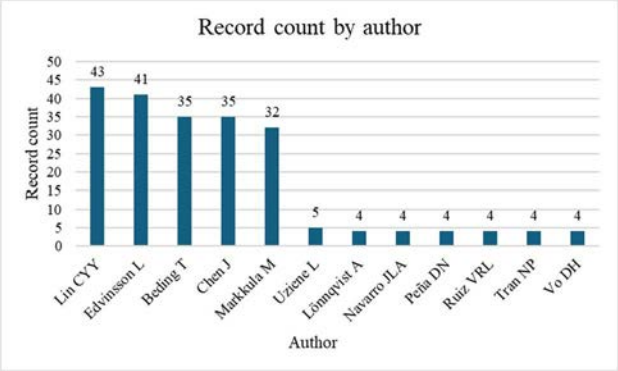

Figure 3 Leading authors in field of NICI research

Interesting findings from some notable publications point out that national culture, described as the intentional efforts of people to manage their surroundings and reduce uncertainty, can significantly influence the intellectual capital of countries [18]. Moreover, national human capital is regarded as the most crucial component of national intellectual capital, driving a country's economic performance and prosperity .[19,20]. Additionally, studies indicate that the Nordic countries may have higher values of national intellectual capital compared to other OECD countries [21]. Overall, the findings highlight key areas for improvement across multiple countries: enhancing university-enterprise cooperation, employee training, intellectual property rights protection, fostering a fair business competition environment, and investing in basic research. Strengthening specific aspects like patents, business R&D, and transparency in government policies is crucial for promoting development and fostering innovation, which in turn stimulates GDP growth [22].

Despite the valuable insights provided by the NICI methodology, its complexity and significant data requirements have limited its popularity among researchers [6]. Additionally, the lack of standardization in defining and measuring components of intellectual capital across different countries or regions complicates cross-country comparisons [13]. Moreover, the inherent intangibility of intellectual capital makes it challenging to measure the individual components of NICI with traditional metrics [16]. Nevertheless, NICI can still offer valuable strategic insights for policymakers and governments capable of implementing it effectively.

5 Conclusion

In today's knowledge-driven global economy, the measurement of intellectual capital is essential for understanding the intangible assets that fuel economic growth and innovation. This paper has briefly discussed the role of intellectual capital at the macroeconomic level and provided a brief description of several methods for its measurement. The main contribution of our paper lies in explaining the key components of national intellectual capital and methods for its measurement.

The discussed methods, including Direct Intellectual Capital Methods (DICM), Market Capitalization Methods (MCM), Return on Assets Methods (ROAM), and Scoreboard Methods (SCM), offer diverse approaches to evaluating the intangible components of intellectual capital. Each method has its strengths and limitations, but together, they provide a comprehensive framework for assessing intellectual capital at different levels.

One particularly valuable method discussed in this paper is the "National Intellectual Capital Index", which focuses on assessing intellectual capital at the macroeconomic level. This approach serves policymakers, enabling economies to adapt to digital advance, and drive economic and social progress. Therefore, it is essential for governments to prioritize enhancing digital infrastructure, investing in IT skills, and fostering innovation to strengthen national digital capabilities and competitiveness.

We specifically examined the popularity of the NICI method among researchers and discovered that its complexity poses a barrier to its extensive adoption among researchers. Based on this paper, we see an opportunity for further research aimed at precisely quantifying the components of NICI and conducting a study offering novel practical insights in this topic.

Acknowledgement

We gratefully acknowledge the funding of this paper by the Slovak Grant Agency of the Ministry of Education of the Slovak Republic, and the Slovak Academy of Sciences (VEGA), project No. 1/0638/22 Intellectual Capital and Productivity of European Regions.

References

[1] BROOKING, A.: *Intellectual capital: Core asset for the third millennium Enterprise*, London, International Thomson Business Press, 1996.

[2] MOORE, L., CRAIG, L.: *Intellectual capital in enterprise success: strategy revisited*, New Jersey, John Wiley & Sons, 2008.

[3] MARR, B.: Impacting future value: how to manage your intellectual capital, [Online], Available: https://www.journalofaccountancy.com/content/dam/jofa/archive/issues/2008/09/mag-intcapital-eng.pdf [01 May 2024], 2008.

[4] AL-ALI, N.: *Comprehensive intellectual capital management: Step-by-step*, New Jersey, John Wiley & Sons, 2003.

[5] STEWART, T.A.: *Intellectual Capital: The new wealth of organization*, New York, Crown Currency, 2010.

[6] BONTIS, N.: National intellectual capital index: a United Nations initiative for the Arab region, *Journal of intellectual capital*, Vol. 5, No. 1, pp. 13-39, 2004. https://doi.org/10.1108/14691930410512905

[7] EDVINSSON, L., MALONE, M.S.: *Intellectual Capital*, New York, Harper Business, 1997.

[8] UŽIENĖ, L.: *National intellectual capital as an indicator of the wealth of nations: the case of the Baltic States*, Procedia-Social and Behavioral Sciences 156, 19th International Scientific Conference; Economics and Management, Riga, Latvia, pp. 376-381, 2014. https://doi.org/10.1016/j.sbspro.2014.11.206

[9] LIN, C.Y.Y., EDVINSSON, L., CHEN, J., BEDING, T.: *National Intellectual Capital and the Financial Crisis in Brazil, Russia, India, China, Korea, and South Africa*, SpringerBriefs in Economics, Springer New York, New York, Springer, 2013. https://doi.org/10.1007/978-1-4614-6089-3_1

[10] SVEIBY, K.-E., LLOYD, T.: Methods for measuring intangible assets, [Online], Available: http://www.sveiby.com/articles/MK-NewPrefacefinal.pdf [01 May 2024], 2010.

[11] LUTHY, D.H.: *Intellectual capital and its measurement*, Conference Proceedings, Asian Pacific Interdisciplinary Research in Accounting Conference (APIRA), Osaka, Japan, pp. 16-17, 1998.

[12] WILLIAMS, S.M.: *Corporate governance diversity and its impact on intellectual capital performance in an emerging economy*, University of Calgary, Faculty of Management, 2001.

[13] GOGAN, L.-M., DRAGHICI, A.: *A model to evaluate the intellectual capital*, Procedia Technology 9, CENTERIS 2013 - Conference on ENTERprise Information Systems, Lisbon, Portugal, pp. 867-875, 2013. https://doi.org/10.1016/j.protcy.2013.12.096

[14] HUANG, S.-Y.: *Intellectual capital measures: Literature review*, Proceedings, PICMET'14 Conference: Portland International Center for Management of Engineering and Technology, Infrastructure and Service Integration, Portland, USA, pp. 1266-1273, 2014.

[15] MOHAMED, I.A.H.: Methods of measuring intellectual capital and the efficiency of investment it: Advantages & disadvantages. Analytical comparative study, *Imperial journal of Interdisciplinary research*, Vol. 3, No. 2, pp. 1083-1092, 2017.

[16] STÅHLE, P., STÅHLE, S., AHO, S.: Value added intellectual coefficient (VAIC): a critical analysis, *Journal of Intellectual Capital*, Vol. 12, No. 4, pp. 531-551, 2011. https://doi.org/10.1108/14691931111181715

[17] European Commission: *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Youth Opportunities Initiative*, [Online], Available: https://youth.europa.eu/sites/default/files/inline-files/Communication%20on%20the%20European%20Year%20of%20Youth%202022.pdf [01 May 2024], 2024.

[18] LEE, I.-C., LIN, C.Y.Y., LIN, T.-Y.: The creation of national intellectual capital from the perspective of Hofstede's national culture, *Journal of Intellectual Capital*, Vol. 18, No. 4, pp. 807-831, 2017. https://doi.org/10.1108/JIC-11-2016-0117

[19] REHMAN, W.U., NADEEM, M., SALTIK, O., DEGIRMEN, S., JALIL, F.: Investing in knowledge assets: a novel approach for measuring national intellectual capital index in emerging economies, *Journal of Intellectual Capital*, Vol. 25, No. 2/3, pp. 535-558, 2024. https://doi.org/10.1108/JIC-07-2023-0155

[20] VO, D.H., TRAN, N.P.: Does national intellectual capital matter for economic growth in the Asia–Pacific economies?, *Journal of Intellectual Capital*, Vol. 25, No. 2/3, pp. 253-274, 2024. https://doi.org/10.1108/JIC-09-2022-0184

[21] LIN, C.Y.Y., EDVINSSON, L.: National intellectual capital: comparison of the Nordic countries, *Journal of Intellectual Capital*, Vol. 9, No. 4, pp. 525-545, 2008. https://doi.org/10.1108/14691930810913140

[22] LIN, C.Y.Y., EDVINSSON, L., CHEN, J., BEDING, T.: *National Intellectual Capital and the Financial Crisis in Bulgaria, Czech Republic, Hungary, Romania, and Poland*, SpringerBriefs in Economics, Springer New York, New York, Springer, 2014. https://doi.org/10.1007/978-1-4614-8018-1

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 171-178 ISSN 2453-675X

https://doi.org/10.22306/atec.v10i4.240 Received: 19 Oct. 2024; Revised: 05 Nov. 2024; Accepted: 18 Nov. 2024

The importance of logistics in the circular economy of agricultural enterprises

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Keywords: logistics, circular economy, agribusiness, sustainability.
Abstract: The article is intended to show the role of logistics in the circular economy. This is because it encompasses the actual flow of products from their source of production to the final consumer, taking into account all the tasks and activities involved, ensuring efficient, sustainable and economic processes. Circular economy aims to maximise product value through eco-design, increased sustainability, improved quality, eco-efficiency and the widespread use of renewable materials. This approach promotes waste reuse, recycling and recovery, as well as treating waste as a valuable resource. The agricultural industry deserves special attention in the context of the circular economy, so improvements have been proposed to change the agricultural enterprise to a greener and more practical one that applies the principles of the circular economy. Thus, biogas production, the transportation of slurry via pipeline system and the creation of an on-site photovoltaic panel farm were suggested. The application of these improvements could make the company independent and use only its resources. Furthermore, by using renewable energy sources, the company could increase its competitiveness in the market, become an independent entity and reduce its operating costs, all while increasing its efficiency.

1 Introduction

In the face of modern environmental challenges, the circular economy (CE) is gaining increasing importance as a model of sustainable development. The concept involves minimising waste and maximising available resources, thus finding its way into various economic sectors, including the agricultural industry. Agricultural companies, due to the nature of their business and their direct impact on the environment, are particularly committed to implementing CE practices. Logistics plays a key role in the implementation of the circular economy, enabling the efficient management of resources, waste, recycling and distribution of products in a sustainable manner. In the context of agricultural enterprises, it contributes to optimising production processes, reducing waste and improving operational efficiency.

The aim of this paper is to assess the role of logistics in supporting the implementation of the CE concept in agricultural enterprises, with particular reference to the solutions proposed to Grolder Sp. z o.o. The following research questions are presented: What logistics solutions can support the implementation of the circular economy in agricultural enterprises? What impact does the practical application of the circular economy concept have on the logistical processes implemented by agricultural enterprises? To find answers for these questions, observations and analysis of various factors were made. The article is based on a literature analysis, case studies and interviews with experts from the agricultural and logistics industry.

2 Logistics and the circular economy

Logistics plays a key role in the CE, as it is essential to the efficient, sustainable and economic operation of the circularity in question. Logistics, in its broadest sense, refers to "the processes of the real flow of products from the sources of acquisition from nature to the marginal links that satisfy the consumer needs of households and the production and investment needs of economic actors" [15]. In the literature, the circular economy is defined as "maximising the added value of products in the value chain by, among other things. introducing eco-design, taking into account the whole life cycle of the product, increasing sustainability, increasing quality, cascading products, eco-efficiency of processes, promoting cooperation in the value chain (economic symbiosis), sharing, widespread use of renewable materials, virtualisation" [9] and as "minimising waste through reuse, recycling and the implementation of full recovery, including above all treating waste - if it arises - as a potential source of secondary raw materials, often not available in the EU due to lack of resources (critical raw materials), widespread use of waste heat or reuse of water" [10]. Logistics supports the basic tenets of CE by effectively managing resources and waste, minimising

waste and costs and maximising the reuse of materials. It also enables the tracking and management of the flow of raw materials, semi-finished and finished products in a way that minimises waste and optimises the use of available resources [8]. In a circular economy, the key is precisely to keep materials in circulation for as long as possible [12]. An important part of logistics is transport, which involves defining routes, their regularity and choosing the right system and the right mode of transport to reduce emissions, including CO_2 and operating costs [2]. Adequate management of the storage and distribution of products and materials is essential to ensure that they are available when they are needed, and that they do not sit unnecessarily in storage, which could lead to them being wasted - the concept of logistics in the broadest sense is also behind these activities. All the tasks in question are accompanied by continuous supervision and control, i.e. information and decision-making processes are present at all times in the execution of the individual goals. The entire process is monitored and checked in real time [16]. Checks are made to ensure that all standards and regulations are being complied with, especially those relating to environmental protection and the safety of people working at a particular stage. Various analyses and reports are collected and used to optimise the processes that are in place all the time and to plan future activities that will make the various stages operate more efficiently and benefit from reduced environmental impact [5].

An important point in the circular economy is waste, which according to its principle should be treated as a valuable resource that can be reintroduced into the production cycle. Here, it is logistics that is behind the organisation of waste collection, sorting and transport of materials for recycling and processing. With the right logistics solutions, any recycling and reuse of materials can be managed efficiently. Logistics processes are responsible for the storage and processing of waste. In addition, they manage temporary waste storage sites and the landfills themselves. Logistics is also related to the issue of organising waste treatment processes, including recycling, composting, incineration and energy recovery. It includes the management of the different types of containers and bins that are used to collect and transport waste, with responsibility for their delivery, replacement and maintenance [3]. Logistics is a key tool to minimise costs throughout the waste management process as well as throughout the supply chain, as it helps to reduce costs by optimising operations, planning efficient routes, minimising waste and monitoring performance. Logistics is an integral element in the pursuit of sustainability, as it is through logistics that efficient waste management takes place. It therefore contributes directly to the sustainable development goals of environmental protection, reduction of greenhouse gas emissions and appropriate waste treatment. If conducted correctly, it also ensures safety and health for people and regulates regulations and procedures. All the aspects of circular economy logistics discussed are important for the efficient and sustainable management of available resources [17]. Cooperation between suppliers, manufacturers, distributors and recyclers allows for more efficient resource management and waste minimisation. In summary, logistics is the foundation on which the circular economy is based. With efficient and sustainable logistics solutions, companies can better manage resources, reduce their environmental impact and support sustainable development.

3 Challenges faced by modern farms

Agriculture includes arable farming and animal husbandry, horticulture, vegetable farming, forestry and inland fisheries, as well as related transport, handling, processing and sales [13]. Farming is a complex activity and highly dependent on nature, weather conditions and other factors beyond human control. Agriculture is seasonal, which means that individual wastes are generated over a short period of time, but intensively, and this can complicate and hinder their management. Farmers need to effectively manage available resources such as artificial and natural fertilisers, agricultural machinery and equipment, as well as water, soil or air, as their poor management can cause groundwater contamination, lead to soil erosion and generate hazardous waste through poor crop planning. The frequent use of pesticides by agricultural workers in the fields should be considered as generating toxic substances, as they are the ones that, which when used, become chemical waste that pose a risk to health and the environment itself. Agriculture depends heavily on energy and fossil fuels for the agricultural machinery that is used every day to work in the fields or with the animals. This generates significant greenhouse gas emissions and waste associated with the maintenance of agricultural machinery and vehicles.

At this point in time, many agribusinesses have begun to engage in caring for the environment and sustainability. In their operations, depending on their specifications, they are taking different steps and actions that benefit the ecosystem. In addition, there is a strong emphasis on the creation and use of renewable energy sources, in view of the enormous air pollution and the running out of fossil fuels or rising fuel and electricity prices. Farms that want to become more environmentally friendly and modern face numerous challenges in adapting to pro-environmental changes and implementing a CE concept. First and foremost, farms need to reduce the consumption of the resources they use, such as water or electricity. To do this, companies are using renewable energy sources - solar panels and wind turbines to power the farms.

Those in the agricultural sector have to produce sustainably, depending on their crop or livestock activities, which means they have to manage the available products properly during production, including reducing the generation of waste and greenhouse gas emissions. For such a specific sector, this involves appropriate crop rotation, i.e. the use of crop rotation, intercropping and

organic farming, which aims to protect the soil and its biodiversity. Another important aspect is the management of manure, which is a hazardous waste. The organic residues that are generated in companies should be diverted according to sustainability, which means composting them and converting them in biogas plants into energy and fertilisers. Companies need to introduce a proper waste separation system, using compost and manure as natural fertilisers. Today, agricultural companies are beginning to use GPS technology for field work and drones to monitor and manage crops in order to optimise resource consumption. Education and environmental awareness provided to entrepreneurs and their employees is also important. Training should be organised on how to conduct and maintain sustainable agriculture and CE practices, and awareness should be raised about the benefits of implementing environmentally friendly practices. The sector is constantly changing, due to a variety of factors.

The impact of economic and political events over the last few decades has changed this sector. Accession to the European Union has had a huge impact on this economic sector, as it has provided it with access to financial resources, which in turn have enabled and accelerated the process of modernisation of farms and allowed it to adapt to new market conditions. As a result of sustainability and environmental protection measures, the conditions and rules of operation are constantly changing. Today, environmental protection is a priority in European Union policy and one of the greatest and most important challenges. Concern for nature, its state and the public good is making regulations more and more stringent in terms of compliance. Agricultural enterprises also have operational requirements to comply with environmental protection [6]. The agricultural sector is therefore covered by a number of documents that specify how waste generated in this sector is to be dealt with, as the majority of waste generated in this sector is hazardous waste, which must be dealt with in a special manner as it has specific handling guidelines. This involves the appropriate optimisation of economic processes and handling methods in order to reduce and change the bad impact of the agricultural sector [14]. Farmers can implement a range of innovations into their businesses that are able to improve production and farm productivity. Adapting to pro-environmental changes not only protects the environment, but also increases competitiveness in the market, resulting in more sustainable and efficient farming.

Implementing a circular economy requires a holistic approach, meaning that all elements are interconnected and influence each other, creating a single system that combines activities at different levels. Agricultural enterprises that successfully adapt to green changes can not only contribute to environmental protection, but also increase their operational efficiency and competitiveness in the market.

4 Logistics in an agricultural enterprise implementing the circular economy concept - examples of solutions and benefits of proposed improvements

Grolder Sp. z o.o. is a company engaged in crop and livestock production. It is an agricultural company that engages in the cultivation of agricultural land and industrial pig rearing. This rearing is a production method in which, according to an established technology, the same production processes are repeated in specific time cycles. The industrial pig farm is a closed-cycle facility, where the rearing period covers all phases of the animal's life. Grolder therefore belongs to the agricultural sector and has 644 ha of farmland, including twelve tractors. Due to the nature of their business, they mostly grow sunflower, rape, barley, triticale and wheat. The company has twelve livestock buildings, or piggery, housing more than 26,000 pigs and comprising piglets and sows. In addition, there are five other buildings necessary for the operation, including administrative and social buildings and various installations needed for the operation of the company.

In order to improve the company's existing operations, it has been proposed to produce biogas, to transport slurry using a pipeline system instead of tractors and to create a photovoltaic panel farm on the site [7]. The waste with the largest mass that is produced on the company's premises is animal manure. The idea of how to use it efficiently was born. The construction of a biogas plant can serve as an alternative energy source, i.e. biogas. According to the definition of agricultural biogas, it is understood to be "a gaseous fuel obtained from agricultural raw materials, agricultural by-products, liquid or solid animal excreta, by-products or residues from the agri-food industry or forest biomass through methane fermentation" [19]. Biogas processing is a process that occurs under anaerobic conditions and involves the decomposition of organic materials such as plant residues, manures or sewage sludge into gas. The main product that arises from this reaction is methane, which can be used in the company as an energy source. The biogas collected is processed and could then be used precisely for the production of electricity and heat, as well as a fuel to power agricultural equipment [1]. Investing in biogas could realistically bring a lot of benefits to the company, as it is a renewable energy source that fits into a CE and offers the opportunity to process a waste product such as slurry, which is largely generated on site, and allows plant waste to be converted into heat and energy, while also creating a substrate that is better for fertilising soils than manure or slurry. From data obtained from the company, 25,911.4 tonnes of slurry were generated in 2022. Assuming, therefore, that one has a slurry volume of around 26,000 tonnes per year, it is necessary to calculate how much biogas can be produced per year. From the available data it is known that about 20 cubic metres of biogas can be obtained from 1 tonne. So:

$$26\,000\ t\ slurry \times 20\frac{m^3}{t} = 520\,000\ m^3\ biogas\ per\ year$$

Another aspect that is known is the average calorific value of biogas, which is approximately 25 MJ/m^3, thus:

$$52\,000\ m^3 \times 25\frac{MJ}{m^3} = 13\,000\,000\ MJ\ per\ year$$

Converting 13 000 000 MJ into kWh results in 3 611 100 kWh. By combining the data obtained from the company and the annual output of the biogas plant, the result is that the company's electricity needs are covered.

Table 1 Summary data for 2022-2023 on the amount of electricity consumed and costs

	2022	2023
Amount of electricity consumed [kWh]	1 017 280	1 119 210
Cost [PLN]	909 920.72	1 228 345.39

To estimate the investment cost (Table 1), costs such as: infrastruktura – zakup lub zmiana przeznaczenia ziemi pod budowę biogazowni, budynków, placów, drogi dojazdowej:

- infrastructure – purchase or change of land use for the biogas plant, buildings, yards, access road;
- technology – the purchase or construction of biogas production facilities, including fermenters, substrate tanks, biogas recovery systems, monitoring and control systems;
- raw materials – the purchase or transport of organic raw materials that will be used for biogas production;
- labour – salaries for the company constructing the biogas plant and salaries for the staff responsible for the operation and maintenance of the biogas plant;
- regulations and legislation – obtaining the necessary permits, certifications, environmental studies and safety audits;
- energy – costs associated with powering the biogas plant, including the consumption of electricity and heat needed to operate the equipment;
- maintenance and repair – costs of regular maintenance of the equipment and possible repairs and upgrades;
- finance – the loan or grant taken out.

The cost of the investment would be estimated at around PLN 10 million, due to the aforementioned costs, details of which for individual cost items are not public. The time after which the investment would pay off was calculated on the basis of available data:

- investment outlay: 10 000 000 PLN;
- annual energy value: PLN 1,228,345.39;
- operating costs per year: PLN 556 328.76.

Calculation of net operating value per annum:

$$1\,228\,345.39\ PLN - 556\,328.76\ PLN = 672\,016.63\ PLN$$

Calculation of the payback period:

$$10\,000\,000\ PLN \div 672\,016.63\ PLN \approx 14.88\ years$$

The time period in which the investment in a biogas plant will pay off, under current assumptions, is approximately 14/15 years.

Due to its operations and needs, the company consumes more and more fuel (Table 2) and has to incur significant costs. The main factors that influence this are the political, economic and business situation in the country. The price of oil has recently increased significantly, by around 65% since 2020.

Table 2 Summary data for 2020-2023 on the amount of fuel consumed and costs

	2020	2021	2022	2023
Number of agricultural hectares [ha]	594	644	644	644
Cost [PLN]	243 797.91	243 952.07	348 617.50	438 170.62
Amount of fuel consumed [l]	60 392	65 607.35	67 246	70 457

As previously mentioned, the company owns agricultural machinery for its own use, which is powered by internal combustion engines and is used for sowing and harvesting crops. The company is constantly investing, but currently also owns older models of tractors that still fulfil their role, but they are less efficient compared to newer and more modern models that are more technologically efficient and in terms of the fuel they consume. The company is a huge farm with 644 hectares in agricultural use, and this contributes to more machine work and results in increased fuel consumption. An unploughed system is used on the fields, which is more efficient compared to the ploughed system, which carries a negative impact in terms of the soil itself, the environment and the harvest result itself. The system used is more sustainable as it reduces soil erosion, which directly contributes to the storage of water in the soil and, importantly, reduces fuel consumption [11]. In order to reduce the amount of fuel used and energy costs and to reduce emissions of CO_2 and other toxic substances, slurry transport through a pipeline system can be used. This system is a technology by which slurry is transferred via pipes from the storage area, in this case the lagoon, to the fields. This method is a more efficient way of applying organic manure than traditional methods using tractors, as it distributes the slurry more precisely [19]. To start with, a company could invest in spreading such a system on 100 ha of fields. Additionally, it would save drivers' time, as

there is also no need to wait for loading or unloading and washing. The system can be managed remotely, which reduces the risk of human error and increases reliability. The driver's working time for spreading slurry takes 16 hours, which saves 32 hours over a year, as twice a year slurry removal takes place, therefore saving four days of employee work. By setting up the system on all fields, the company could increase its efficiency. Most of the fields, about 560 ha, are within the farm, by installing the system in question agricultural machinery would then not be involved in fertilising the fields. The fuel consumption and costs to the enterprise were analysed (Table 3).

Table 3 Summary data for 2022-2023 on fuel consumption volumes and associated costs

	2022	2023
Amount of fuel used [l]	67 246	70 457
Cost [PLN]	348 617.50	438 170.62

It should be noted that the company consumes more than 70 000 litres of fuel. Assuming that the average fuel consumption of the tractor is 10 litres per hour and the average operating time of the tractor on one tank of fuel is 8 hours. This means that the tractor will consume 80 litres of fuel during 8 hours of operation. If an employee works for 16 hours the fuel consumption will be 160 litres. The export takes place twice a year so 320 litres - just for 100 ha.

The cost of the investment is approximately PLN 150 000. Included here are costs such as (details for individual items are not public):

- materials – pipe, fittings, valves, pumps, filters, casing, etc. depending on the type of materials and pipe diameter, costs can vary considerably;
- labour and services – the cost associated with the installation work: employing a company to install the pipeline and the cost of hiring heavy equipment to excavate and lay the pipe;
- engineering and design – the design of the pipeline system by engineers, including the cost of consultancy, field surveys, creation of design documentation, etc.;
- survey and testing – carrying out leakage tests, pressure measurements, checking system performance, etc.;
- regulations and legislation – obtaining necessary permits, notifications, and costs related to environmental and safety compliance and regulations;
- repair and maintenance – regular maintenance, repair and possible upgrading of the pipeline system.

The time after which the investment would pay off was calculated on the basis of available data:

- investment outlay: PLN 150 000,
- annual savings: PLN 30 000 (fuel costs and staff time costs are included here).

Payback period calculation:

$$150\,000\ PLN \div 30\,000\ PLN = 5\ years.$$

The expected return on investment could occur after about five years due to reduced fuel consumption and the salaries of the workers who would have to be paid for their work and maintenance of the equipment. Investing in a slurry spreading system would reduce the costs that currently need to be incurred, in addition to reducing diesel consumption and environmental pollution from toxic substances emitted into the air by agricultural machinery and equipment, while increasing overall energy efficiency [20].

In an effort to continually improve the company's cost-saving and environmental performance, the company is proposing a small change to its electricity consumption and thus reduce costs by setting up a photovoltaic panel farm. This is a long-term investment that will pay off over time through savings in energy costs. Photovoltaic panels, also known as photovoltaic modules, are devices that convert light energy, usually from the sun, into electrical energy [4]. It is a renewable energy technology that is growing in popularity due to its many benefits. The panel consists of photovoltaic cells, usually made of silica. When sunlight falls on the panel, electrons are released, which in turn generates an electric current [18]. Tapping into this renewable energy source could result in the company generating its own electricity and even selling it. The number of panels needed by the company to cover the costs associated with electricity consumption was calculated. Initially, it was necessary to convert the amount of electricity consumed into power:

$$1\,119\,210\ kWh \div 8760\ h \approx 127{,}69\ kW$$

Calculation of the area needed for the panels:

$$127.69\ kW \div 175\ W/m^2 \approx 729.6\ m^2$$

Calculation of the number of photovoltaic panels:

$$729.6\ m^2 \div 1.6\ m^2 \approx 456\ m^2/paneli$$

The investment cost of the farm in question will be approximately PLN 1 500 000 for the company. Included here are such costs as:

- materials – the purchase of photovoltaic panels, which can depend on their type, brand, efficiency, size and quality;
- installation – the assembly of the photovoltaic panels and staff time - connecting, etc;
- infrastructure – costs related to the construction of foundations for the panels, mounting platforms, fencing or an access road;

- regulations and legislation – permits, notifications, and costs associated with environmental and safety compliance;
- maintenance and service – regular maintenance, repair and possible upgrades to the photovoltaic system.

The time after which the investment would pay off was calculated on the basis of available data:

- investment outlay: 1 500 000 PLN,
- annual energy production: 850 590 kWh,
- energy sales price: 0,87 PLN/kWh,
- annual operating costs: PLN 556 328.76.

Calculation of annual revenues from energy production:

$$850\ 590\ kWh \times 0{,}87 \frac{zł}{kWh} = 740\ 013.30\ PLN$$

Calculation of the value of the annual savings resulting from the investment:

$$740\ 013.30\ PLN - 556\ 328.76\ PLN = 183\ 684.54\ PLN$$

Calculation of the payback period:

$$1\ 500\ 000\ PLN \div 183\ 684.54\ PLN \approx 8.17\ years$$

The return on investment is expected to be around eight years. Once this renewable energy source is established, the company will be able to produce its own electricity, which will reduce the dependence on traditional energy sources and thus reduce the electricity costs that the company currently has to pay. Importantly, the use of solar energy is linked to promoting sustainability and improving the energy balance. The use of this energy does not produce harmful substances or generate carbon dioxide emissions, which contributes to the reduction of greenhouse gas emissions and has a positive impact on the environment.

The CE at Grolder Sp. z o.o. would look considerably more efficient once all investments have been made (Figure 1). The plant will carry out these activities in accordance with its sustainability policy. After cultivating the fields and harvesting the crops, the company would feed the pigs with their own grain, then they would produce slurry, which would be poured onto the fields via a pipeline system. The slurry produced, combined with cereal residues or bio-waste, would be fed into a biogas plant, where biofuel or electricity would be generated and further circulated for the company's operations. The resulting substrate from the biogas plant would circulate through the company by means of a pipeline system to the fields instead of slurry, with additional benefits for the soil and the local ecosystem. Such manure would be distributed to the fields so that the crops sown could grow, and this provides an opportunity to feed it to the pigs. By generating energy, the photovoltaic panels could in turn generate electricity to serve the biogas plant or the pipeline system that would be powered by this energy.

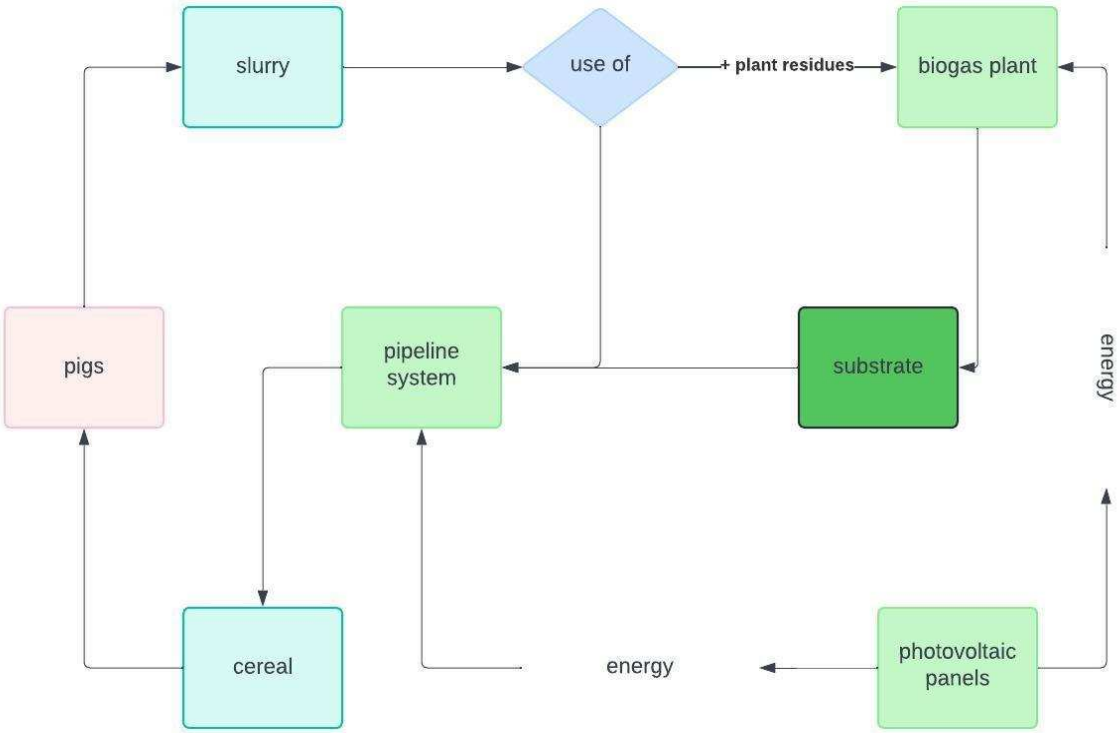

Figure 1 The CE concept on the example of Grolder Ltd.

5 Conclusion

Logistics plays a key role in the implementation of the circular economy concept in agricultural enterprises. The introduction of efficient logistics solutions in line with CE principles brings environmental, economic and social benefits, which is indispensable for sustainable development. Efficient management of logistics processes in agriculture allows for a significant reduction in the emission of harmful substances into the atmosphere.

At Grolder Sp. z o.o., the implementation of the CE could be achieved by investing in a pipeline system, photovoltaic panels and a biogas plant. The use of this pipeline system for transporting slurry or substrate from the biogas plant instead of traditional barrels reduces emissions and fuel consumption. In addition, optimising transport routes with advanced fleet management systems will lead to a reduction in fuel consumption and CO_2 emissions. In this way, logistics supports agricultural operations but also actively contributes to environmental protection. By investing in modern logistics technologies such as a biogas plant or photovoltaic panels, the energy efficiency of agricultural businesses can be significantly improved. The use of renewable energy sources in logistics processes, such as powering agricultural machinery with biomass fuels, offers the opportunity to reduce the company's dependence on fossil fuels, which can not only reduce the carbon footprint, but also lower operating costs, which is crucial for the competitiveness of agricultural businesses.

The application of the CE concept in agricultural enterprises influences the logistical processes there through better management of raw materials, time and costs. Agricultural enterprises that invest in a circular economy gain a competitive advantage in the market. This is because customers increasingly prefer products from sustainable sources. In addition, businesses that demonstrate environmentally sound practices are better perceived. Furthermore, the implementation of such solutions can lead to various environmental certifications, which further increases their attractiveness in the eyes of consumers. Logistics is thus becoming an integral part of the implementation of a circular economy in agricultural enterprises, and its role goes beyond traditional transport and storage functions to become a key tool to support sustainability, technological innovation and, above all, environmental protection. Agricultural enterprises implementing CE strategies are considered green, while at the same time such a company policy is profitable in the long term. Farms are more self-sufficient and waste is reduced, which every enterprise should reduce.

References

[1] BIEŃ, J., BIEŃ, B.: *Biogazownia rolnicza elementem programu gospodarki odpadami i wytwarzania zielonej energii w gminie*, Częstochowa, Wydawnictwo Politechniki Częstochowskiej, 2010. (Original in Polish)

[2] CHOPRA, S., MEINDL, P.: *Supply Chain Management: Strategy, Planning, and Operation*, London, Pearson Education Limited, 2018.

[3] CHANDRAPPA, R., BHUSAN DAS, D.: *Solid Waste Management: Principles and Practice*, Springer, 2012.

[4] DEGUNTHER, R.: *Solar Power Your Home For Dummies*, For Dummies, 2010.

[5] GAJDZIK, B.: Wprowadzenie do systemów logistycznych gospodarki odpadami w przedsiębiorstwach hutniczych, *Logistyka*, Vol. 2009, No. 5, 2009. (Original in Polish)

[6] GÓRAL, J., REMBIUSZ, W.: Produkcja w rolnictwie w kontekście ochrony środowiska, *Roczniki Naukowe Ekonomii Rolnictwa i Rozwoju Obszarów Wiejskich*, Vol. 2017, No. 1, 2017. (Original in Polish)

[7] KACPRZAK, M.: *Waste management logistics on the example of the Grolder Sp. z o. o. company*, Zielona Góra, Engineer's Thesis, 2024.

[8] KALICZYŃSKA, M.: Logistyka – cele i kierunki rozwoju, *Pomiary Automatyka Robotyka*, Vol. 10, 2009. (Original in Polish)

[9] KULCZYCKA, J.: *Gospodarka o obiegu zamkniętym w polityce i badaniach naukowych*, Kraków, IGSMiE PAN, 2019. (Original in Polish)

[10] KULCZYCKA, J., PĘDZIWIATR, E.: *Gospodarka o obiegu zamkniętym – definicje i ich interpretacje*, Kraków, IGSMiE PAN, 2019. (Original in Polish)

[11] JASKULSKI, D., JASKULSKA, I.: *Współczesne sposoby i systemy uprawy roli w teorii i praktyce rolniczej*, Poznań, Centrum Doradztwa Rolniczego w Brwinowie, 2016. (Original in Polish)

[12] JAWORSKI, T., GROCHOWSKA, S.: Circular Economy - the criteria for achieving and the prospect of implementation in Poland, *Archives of Waste Management and Environmental Protection*, Vol. 19, No. 4, 2017.

[13] MUSIAŁKIEWICZ, R., WALCZAK, D.: Rolnik indywidualny (mikro) przedsiębiorca czy rolnik? Analiza ekonomiczno-prawna, *Ekonomiczne Problemy Usług*, Vol. 2014, No. 111, 2014. (Original in Polish)

[14] NOWAK, A., KIJEK, T., KRUKOWSKI, A.: *Polskie rolnictwo wobec wyzwań współczesności*, Uniwersytet Przyrodniczy w Lublinie, Lublin, 2019. (Original in Polish)

[15] SKOWRONEK, C., SARJUSZ-WOLSKI, Z.: *Logistyka w przedsiębiorstwie*, Warszawa, PWE, 2012. (Original in Polish)

[16] STEVENSON, W.: *Operations Management*, McGraw Hill Higher Education, 2006.

[17] TWARÓG, J.: *Koszty logistyki przedsiębiorstw*, Poznań, Instytut Logistyki i Magazynowania, 2003. (Original in Polish)

[18] TYSZKA, J.: *Panele fotowoltaiczne*, Wieś Mazowiecka, Mazowiecki Ośrodek Doradztwa Rolniczego w Warszawie, No. 10, 2015. (Original in Polish)

[19] Ustawa z dnia 10 kwietnia 1997 r. Prawo energetyczne, art. 3, pkt. 20a, Dz. U. 2006, nr 89, poz. 625, z późn. zm. (Original in Polish)
[20] WALCZAK, J., GAJ, R., JADCZYSZYN, T.: *Ograniczenie zanieczyszczenia azotem pochodzenia rolniczego metodą poprawy jakości wód*, Warszawa, Wydawnictwo Fundacja na rzecz Rozwoju Polskiego Rolnictwa (FDPA), 2018. (Original in Polish)

Review process
Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 10 2024 Issue: 4 Pages: 179-183 ISSN 2453-675X

https://doi.org/10.22306/atec.v10i4.245 Received: 29 Oct. 2024; Revised: 17 Nov. 2024; Accepted: 02 Dec. 2024

The biotechnology of using mesenchymal stem cells in regenerative medicine

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Keywords: mesenchymal stem cells, regenerative medicine, biocompatibility, technology.
Abstract: Mesenchymal stem cells (MSCs) have garnered significant attention in regenerative medicine due to their multipotent capabilities and ability to differentiate into various cell types, including osteocytes, chondrocytes, and adipocytes. Sourced from bone marrow, adipose tissue, umbilical cord blood, and other tissues, MSCs possess immunomodulatory properties, making them ideal candidates for tissue repair and therapeutic applications. Their capacity to migrate to sites of injury and secrete bioactive molecules that promote tissue regeneration and inhibit inflammation is crucial in treating a range of conditions. Recent advancements have highlighted MSCs' role in the regeneration of bone, cartilage, cardiac tissue, and neural networks. They are also being explored in the treatment of degenerative diseases such as osteoarthritis, myocardial infarction, and neurodegenerative disorders. Despite the promising therapeutic potential, several challenges remain, such as optimizing cell delivery methods, understanding long-term effects, and addressing regulatory hurdles for clinical applications. This article aims to introduce mesenchymal stem cells and their main uses in regenerative medicine, offering a comprehensive overview of their biological properties, current clinical applications, and the potential challenges that need to be addressed for broader therapeutic use.

1 Introduction

Regenerative medicine aims to restore or replace damaged tissues and organs by harnessing the body's natural repair mechanisms. Mesenchymal stem cells (MSCs), due to their ability to differentiate into multiple cell types, self-renew, and modulate the immune response, are one of the most extensively studied cell types in regenerative medicine (Figure 1) [1]. Originally identified in bone marrow, MSCs can also be isolated from other tissues, including adipose tissue, umbilical cord, dental pulp, and even more recently explored sources like placenta and peripheral blood [2,3]. These alternative sources provide easier access to MSCs, often with a less invasive harvesting procedure and higher proliferative capacity, which broadens their potential for widespread clinical applications [4]. The therapeutic utility of MSCs has been explored in diverse clinical settings, including orthopedic, cardiovascular, neurodegenerative, and inflammatory conditions [5]. MSCs have shown the ability to promote tissue repair through direct differentiation into osteoblasts, chondrocytes, and myocytes in conditions like osteoarthritis, bone fractures, and myocardial infarction [6]. Furthermore, their immunomodulatory properties have made them attractive candidates for treating autoimmune diseases, graft-versus-host disease, and neurodegenerative disorders [7,8]. Their role in modulating inflammation and promoting tissue repair by secreting bioactive molecules, such as cytokines, growth factors, and extracellular vesicles, has expanded their use beyond simple tissue engineering [9].

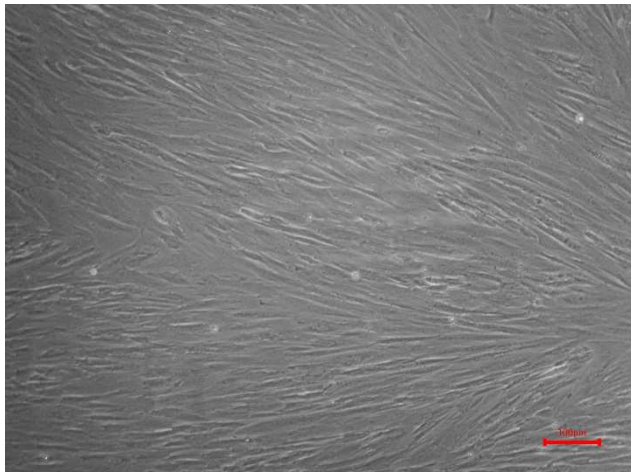

Figure 1 Typical enloged shape of mesenchymal stem cells

2 Definiton of stem cells

MSCs are loosely defined as cells that have the ability to differentiate into many different cell types while retaining the ability to self-replicate and clonogenically grow [2,10]. MSCs are characterized by their adherence to a plastic surface during in vitro culture, differentiation potential and a broadly defined phenotype. The expression of surface features typical for MSCs is as follows: CD105+, CD73+, CD90+ in the population of in vitro cultured cells and at the same time the absence of hematopoietic features CD45-, CD34-, CD14-, CD11b-, CD79-, CD19- and MHC class II molecules. In addition to the above features, MSCs express the following features: CD9+, CD29+, CD44+, CD49+, CD54+, CD61+, CD63+, CD71+, CD97+, CD98+, CD99+, CD106+, CD146+, CD155+, Stro-1+, CD166+, CD166+, CD271+, CD276+

and CD304+ [5]. Adult MSCs have been isolated from many tissues, especially bone marrow, adipose tissue, liver or muscle. In the last decade, MSCs have been isolated from perinatal tissues (Table 1). These tissues are directly related to the development of the embryo and its growth. Given the limitations of the source of stem cells, perinatal tissues represent an important and promising source of MSCs. Postpartum tissues can be used for their isolation, such as placenta, amniotic membranes, amnion or chorion [11-13].

Table 1 Sources of MSCs [5,14,15]

Source	Difficulty to Obtain	Quantity Obtainable (Relative)	Comments on Isolation
Bone Marrow	Moderate	Low to Moderate	Invasive procedure
Adipose Tissue	Low	High	Easier to collect using liposuction
Umbilical Cord	Low	Moderate	Non-invasive collection during childbirth
Dental Pulp	Moderate	Low	Requires tooth extraction
Placenta	Low	High	Non-invasive collection post-delivery
Amniotic Fluid	High	Low to Moderate	Requires amniocentesis; invasive and risky
Peripheral Blood	High	Low	Requires mobilization agents or extensive processing to yield MSCs

3 Mechanisms of mesenchymal stem cells in regenerative medicine

MSCs therapeutic potential is not limited to their ability to differentiate into various cell types; they also play a crucial role in modulating the immune system and promoting healing through the secretion of bioactive molecules. MSCs secrete a range of bioactive molecules through paracrine signaling, which promotes healing, reduces apoptosis, and stimulates angiogenesis. These mechanisms, acting in synergy, underscore the versatility and promise of MSCs in clinical applications [16].

3.1 Differentiation capacity

One of the hallmark properties of MSCs is their ability to differentiate into various cell types, including osteoblasts, chondrocytes, adipocytes, and even neurons under specific conditions. MSCs from different tissue sources exhibit varying differentiation potentials, which may influence their effectiveness in clinical applications [17]. For instance, bone marrow-derived MSCs (BM-MSCs) are known to be particularly adept at differentiating into bone cells, making them valuable for orthopedic applications [10], while adipose-derived MSCs (AD-MSCs) have shown potential in wound healing and skin regeneration [18]. Recent studies have explored how MSC differentiation is influenced by extracellular cues such as growth factors, matrix stiffness, and oxygen tension [19,20]. Understanding these factors is critical for developing effective MSC-based therapies, as they can determine the fate of MSCs in the microenvironment of injured tissues. For example, low oxygen tension (hypoxia) has been shown to enhance the differentiation of MSCs into cartilage and reduce their differentiation into adipocytes, which may benefit cartilage regeneration [21].

3.2 Immunomodulatory and anti-inflammatory effects

In addition to their differentiation abilities, MSCs exert significant immunomodulatory effects, making them useful in treating inflammatory and autoimmune diseases. MSCs can suppress the proliferation of immune cells such as T-cells, B-cells, natural killer cells, and dendritic cells through direct cell-cell contact and the secretion of anti-inflammatory cytokines like interleukin-10 (IL-10) and transforming growth factor-beta (TGF-β) [15,22]. MSCs are also known to influence the polarization of macrophages, shifting them from a pro-inflammatory (M1) to an anti-inflammatory (M2) phenotype, which can promote tissue repair and wound healing [23]. This property has been leveraged in the treatment of graft-versus-host disease (GVHD), where MSCs have been shown to reduce inflammation and promote graft acceptance in allogeneic transplants [7].

4 Applications of mesenchymal stem cells in regenerative medicine

4.1 Orthopedic applications

The use of MSCs in orthopedic applications has shown promise in treating bone defects, cartilage injuries, and osteoarthritis. Several studies have demonstrated that MSCs can enhance bone regeneration when combined with scaffolds or biomaterials, allowing for the formation of new bone tissue in critical-size defects [11-13]. In cartilage repair, MSCs have been shown to differentiate into chondrocytes under appropriate conditions, leading to the restoration of damaged cartilage in osteoarthritic joints. A significant body of research supports the use of MSCs in intra-articular injections for osteoarthritis, where they reduce inflammation and promote cartilage regeneration [6] (Table 2).

Table 2 Examples of orthopedic applications of MSCs [6,24,25]

Disease/Condition	MSC Source	Therapeutic Outcome
Osteoarthritis	Bone marrow	Enhanced cartilage regeneration and reduced inflammation
Non-union fractures	Bone marrow	Accelerated bone healing
Spinal disc degeneration	Adipose tissue	Reduced disc degeneration and improved mobility

4.2 Cardiovascular applications

MSCs have also shown significant potential in treating cardiovascular diseases, particularly myocardial infarction (MI). MSCs can contribute to cardiac repair by differentiating into cardiomyocytes, secreting pro-angiogenic factors that promote neovascularization, and reducing fibrosis in damaged cardiac tissue. Several preclinical and clinical studies have demonstrated that MSCs improve cardiac function and reduce scar size in patients following MI [26]. However, challenges remain in enhancing MSC engraftment and survival in the hostile environment of ischemic cardiac tissue. Strategies such as preconditioning MSCs with hypoxia or using biomaterial scaffolds to deliver MSCs have shown promise in improving their therapeutic efficacy [27].

4.3 Neurological applications

MSC-based therapies are being explored for a range of neurodegenerative and neuroinflammatory conditions, including multiple sclerosis (MS), Parkinson's disease, and spinal cord injury. In the case of MS, MSCs have been shown to reduce inflammation, promote remyelination, and support the survival of neurons in preclinical models [28]. Their ability to cross the blood-brain barrier and their immunomodulatory properties make them attractive candidates for treating central nervous system (CNS) disorders. Recent advances in the use of MSCs for spinal cord injury (SCI) repair highlight their ability to promote axonal regeneration, reduce glial scar formation, and improve functional recovery. While clinical trials are ongoing, the preclinical data support the potential of MSCs to provide significant benefits for patients with SCI [29].

5 Future directions

The field of mesenchymal stem cells in regenerative medicine has made significant strides, but there is still much to be explored in enhancing their therapeutic efficacy and expanding their clinical applications. Ongoing research is focusing on optimizing MSC delivery methods [4], improving their engraftment and survival [8], and overcoming challenges related to heterogeneity and scaling up for clinical use. Advances in biotechnology, such as 3D printing and biocompatibility analysis using stem cells, hold great potential for pushing the boundaries of MSC-based therapies.

5.1 Use of stem cells in biocompatibility analysis

As the field of biomaterials grows, the need for accurate and reliable methods to assess biocompatibility is critical. Traditionally, biocompatibility testing involved the use of animal models or isolated cell lines, but the advent of MSC-based biocompatibility analysis offers a more sophisticated and physiologically relevant approach. MSCs, due to their ability to mimic various tissue types, can be used as a model system to assess how biomaterials interact with living cells [11,30]. Mesenchymal stem cells are ideal candidates for biocompatibility testing because of their sensitivity to environmental cues and their ability to differentiate into various cell types. This makes MSCs highly suitable for assessing the cytotoxicity, cell adhesion, proliferation, and differentiation capabilities of novel biomaterials. For example, a biocompatibility study using MSCs can evaluate whether a material promotes or inhibits MSC adhesion and proliferation, which are crucial factors in determining its suitability for tissue engineering applications [12,13]. Recent studies have used MSCs to test the biocompatibility of various scaffolds, hydrogels, and implants designed for tissue regeneration. The outcomes of these tests not only determine the material's safety but also provide insights into how well the material supports MSC-mediated tissue repair [11,31].

5.2 3D Printing using MSCs

One of the most exciting frontiers in regenerative medicine is the integration of mesenchymal stem cells with 3D printing technologies. This approach, also known as "bioprinting," involves the use of stem cells to create three-dimensional, tissue-like structures that mimic the natural architecture of human tissues. MSCs, due to their ability to differentiate into multiple cell types, are particularly well-suited for this technology, allowing researchers to engineer complex tissues such as bone, cartilage, and even organs [32]. Bioprinting using offers several advantages over traditional tissue engineering approaches. First, it allows for precise control over the spatial arrangement of cells, which is critical for replicating the intricate microenvironment of tissues. Second, bioprinting enables the incorporation of bioactive materials, such as growth factors and scaffolds, which can enhance MSCs differentiation and promote tissue maturation. These advancements have significant implications for regenerative medicine, particularly in developing personalized therapies tailored to individual patients [30]. Recent studies have demonstrated the potential of 3D-printed MSC constructs for cartilage regeneration, where printed scaffolds seeded with MSCs were shown to promote cartilage tissue formation and repair in osteoarthritic models [33-35].

6 Conclusion

The future of mesenchymal stem cell-based therapies lies in advancing both the technologies used to harness their potential and the strategies to overcome the current limitations [30]. Innovations such as 3D bioprinting and the use of MSCs in biocompatibility testing represent critical steps forward in optimizing MSC-based therapies for clinical use. As research continues, the combination of MSCs with emerging technologies will undoubtedly expand the therapeutic applications of stem cells, bringing regenerative medicine closer to fully restoring damaged tissues and organs in a range of medical conditions [5]. These future directions hold the key to unlocking the full regenerative potential of MSCs, making them a cornerstone in the evolution of modern medicine.

References

[1] ORYAN, A., KAMALI, A., MOSHIRI, A., ESLAMINEJAD, M.B.: Role of mesenchymal stem cells in bone regenerative medicine: what is the evidence?, *Cells Tissues Organs*, Vol. 204, No. 2, pp. 59-83, 2017. https://doi.org/10.1159/000469704

[2] ZACHAR, L., BAČENKOVÁ, D., ROSOCHA, J.: Activation, homing, and role of the mesenchymal stem cells in the inflammatory environment, *Journal of Inflammation Research*, Vol. 15, No. 9, pp. 231-240, 2016. https://doi.org/10.2147/JIR.S121994

[3] CAPLAN, A.I.: *Chapter 15 - Mesenchymal Stem Cells in Regenerative Medicine*, Principles of Regenerative Medicine, Elsevier, pp. 219-227, 2019. https://doi.org/10.1016/B978-0-12-809880-6.00015-1

[4] ZHAO, W., LI, K., LI, L., WANG, R., LEI, Y., YANG, H., SUN, L.: Mesenchymal Stem Cell-Derived Exosomes as Drug Delivery Vehicles in Disease Therapy, *International Journal of Molecular Sciences*, Vol. 25, No. 14, 7715, pp. 1-26, 2024. https://doi.org/10.3390/ijms25147715

[5] PATEL, D.M., SHAH, J., SRIVASTAVA, A.S.: Therapeutic potential of mesenchymal stem cells in regenerative medicine, *Stem Cells International*, Vol. 2013, No. 1, 496218, 2013. https://doi.org/10.1155/2013/496218

[6] BAČENKOVÁ, D., TREBUŇOVÁ, M., DEMETEROVÁ, J., ŽIVČÁK, J.: Human chondrocytes, metabolism of articular cartilage, and strategies for application to tissue engineering, *International Journal of Molecular Sciences*, Vol. 24, No. 23, 17096, pp. 1-25, 2023. https://doi.org/10.3390/ijms242317096

[7] KADRI, N., AMU, S., IACOBAEUS, E., BOBERG, E., LE BLANC, K.: Current perspectives on mesenchymal stromal cell therapy for graft versus host disease, *Cellular & Molecular Immunology*, Vol. 20, No. 6, pp. 613-625, 2023.

[8] GARG, A., KHAN, S., LUU, N., NICHOLAS, D.J., DAY, V., KING, A.L., FEAR, J., LALOR, P.F., NEWSOME, P.N.: TGFβ1 priming enhances CXCR3-mediated mesenchymal stromal cell engraftment to the liver and enhances anti-inflammatory efficacy, *Journal of Cellular and Molecular Medicine*, Vol. 27, No. 6, pp. 864-878, 2023. https://doi.org/10.1111/jcmm.17698

[9] BAGNO, L., HATZISTERGOS, K.E., BALKAN, W., HARE, J.M.: Mesenchymal stem cell-based therapy for cardiovascular disease: progress and challenges, *Molecular Therapy*, Vol. 26, No. 7, pp. 1610-1623, 2018.

[10] BAČENKOVÁ, D., TREBUŇOVÁ, M., MOROCHOVIČ, R., DOSEDLA, E., BALOGOVÁ, A., GAŠPAROVÁ, P., ŽIVČÁK, J.: Interaction between mesenchymal stem cells and the immune system in rheumatoid arthritis, *Pharmaceuticals*, Vol. 15, No. 8, p. 941, 2022. https://doi.org/10.3390/ph15080941

[11] BAČENKOVÁ, D., DEMETEROVÁ, J., DOSEDLA, E., GAŠPAROVÁ, P., TREBUŇOVÁ, M.: The use of alginate in the cultivation of mesenchymal cells in biomedical engineering, *Acta Technologia*, Vol. 10, No. 2, pp. 45-49, 2024. https://doi.org/10.22306/atec.v10i2.198

[12] TREBUŇOVÁ, M., PETROUŠKOVÁ, P., BALOGOVÁ, A., IŽARÍKOVÁ, G., HORŇÁK, P., BAČENKOVÁ, D., DEMETEROVÁ, J., ŽIVČÁK, J.: Evaluation of biocompatibility of PLA/PHB/TPS polymer scaffolds with different additives of ATBC and OLA plasticizers, *Journal of Functional Biomaterials*, Vol. 14, No. 8, 412, pp. 1-22, 2023. https://doi.org/10.3390/jfb14080412

[13] TREBUŇOVÁ, M., GROMOŠOVÁ, S., BAČENKOVÁ, D., ROSOCHA, J., ŽIVČÁK, J.: Biocompatibility of the human mesenchymal stem cells with bovine bone tissue at the cellular level in vitro, *Clinican and Technology*, Vol. 48, No. 2, pp. 59-65, 2018.

[14] TROHATOU, O., ROUBELAKIS, M.G.: Mesenchymal stem/stromal cells in regenerative medicine: past, present, and future, *Cellular reprogramming*, Vol. 19, No. 4, pp. 217-224, 2017.

[15] BAČENKOVÁ, D., TREBUŇOVÁ, M., ČIŽKOVÁ, D., HUDÁK, R., DOSEDLA, E., BALOGOVÁ, A., ŽIVČÁK, J.: In vitro model of human trophoblast in early placentation, *Biomedicines*, Vol. 10, No. 4, 904, 2022. https://doi.org/10.3390/biomedicines10040904

[16] AUGELLO, A., DE BARI, C.: The regulation of differentiation in mesenchymal stem cells, *Human Gene Therapy*, Vol. 21, No. 10, pp. 1226-1238, 2010. https://doi.org/10.1089/hum.2010.173

[17] BEREBICHEZ-FRIDMAN, R., MONTERO-OLVERA, P.R.: Sources and clinical applications of mesenchymal stem cells: state-of-the-art review, *Sultan Qaboos University Medical Journal*, Vol. 18, No. 3, p. e264, 2018.

[18] MAZINI, L., ROCHETTE, L., AMINE, M., MALKA, G.: Regenerative capacity of adipose derived stem cells (ADSCs), comparison with mesenchymal stem cells (MSCs), *International Journal of Molecular Sciences*, Vol. 20, No. 10, p. 2523, 2019.

[19] ZHANG, X., ZHANG, S., WANG, T.: How the mechanical microenvironment of stem cell growth affects their differentiation: A review, *Stem cell research & therapy*, Vol. 13, No. 1, p. 415, 2022.

[20] KUSUMA, G.D., CARTHEW, J., LIM, R., FRITH, J.E.: Effect of the microenvironment on mesenchymal stem cell paracrine signaling: opportunities to engineer the therapeutic effect, *Stem cells and development*, Vol. 26, No. 9, pp. 617-631, 2017.

[21] LAMMI, M.J., QU, C.: Regulation of oxygen tension as a strategy to control chondrocytic phenotype for cartilage tissue engineering and regeneration, *Bioengineering*, Vol. 11, No. 3, p. 211, 2024.

[22] GAŠPAROVÁ, P., BALLOVÁ, Z., BAČENKOVÁ, D., TREBUŇOVÁ, M., DOSEDLA, E.: Trophoblast stem cells, trophoblast invasion, and organoids – advancements in gynecology, *Czech gynecology = Journal of the Czech gynecology and obstetrics society*, Vol. 89, No. 2, pp. 151-155, 2024. https://doi.org/10.48095/cccg2024151

[23] YANG, G., FAN, X., LIU, Y., JIE, P., MAZHAR, M., LIU, Y., DECHSUPA, N., WANG, L.: Immunomodulatory mechanisms and therapeutic potential of mesenchymal stem cells, *Stem Cell Reviews and Reports*, Vol. 19, No. 5, pp. 1214-1231, 2023.

[24] HARRELL, C.R., MARKOVIC, B.S., FELLABAUM, C., ARSENIJEVIC, A., VOLAREVIC, V.: Mesenchymal stem cell-based therapy of osteoarthritis: Current knowledge and future perspectives', *Biomedicine & pharmacotherapy*, Vol. 109, pp. 2318-2326, 2019.

[25] GRANERO-MOLTO, F., WEIS, J.A., LONGOBARDI, L., SPAGNOLI, A.: Role of mesenchymal stem cells in regenerative medicine: application to bone and cartilage repair, *Expert opinion on biological therapy*, Vol. 8, No. 3, pp. 255-268, 2008.

[26] ALA, M.: The beneficial effects of mesenchymal stem cells and their exosomes on myocardial infarction and critical considerations for enhancing their efficacy, *Ageing Research Reviews*, Vol. 89, 101980, 2023.

[27] YUCE, K.: The Application of Mesenchymal Stem Cells in Different Cardiovascular Disorders: ways of Administration, and the Effectors, *Stem Cell Reviews and Reports*, Vol. 20, No. 7, pp. 1671-1691, 2024.

[28] GHASEMI, M., ROSHANDEL, E., MOHAMMADIAN, M., FARHADIHOSSEINABADI, B., AKBARZADEHLALEH, P., SHAMSASENJAN, K.: Mesenchymal stromal cell-derived secretome-based therapy for neurodegenerative diseases: overview of clinical trials, *Stem cell research & therapy*, Vol. 14, No. 1, p. 122, 2023.

[29] MONTOTO-MEIJIDE, R., MEIJIDE-FAÍLDE, R., DÍAZ-PRADO, S.M., MONTOTO-MARQUÉS, A.: Mesenchymal stem cell therapy in traumatic spinal cord injury: a systematic review, *International Journal of Molecular Sciences*, Vol. 24, No. 14, p. 11719, 2023.

[30] BALOGOVÁ, A.F., TREBUŇOVÁ, M., RAJŤUKOVÁ, V., HUDÁK, R.: Fresh method: 3D bioprinting as a new approach for tissue and organ regeneration, *Acta Tecnologia*, Vol. 7, No. 3, pp. 79-82, 2021. https://doi.org/10.22306/atec.v7i3.112

[31] TREBUŇOVÁ, M., DEMETEROVÁ, J., BAČENKOVÁ, D., RAJŤUKOVÁ, V., ŽIVČÁK, J.: Surface biocompatibility of porous titanium structures with stem cells, *Lékař a technika Clinician and Technology*, Vol. 53, No. 1, pp. 15-18, 2023. https://doi.org/10.14311/CTJ.2023.1.03

[32] BARI, E., DI GRAVINA, G.M., SCOCOZZA, F., PERTEGHELLA, S., FRONGIA, B., TENGATTINI, S., SEGALE, L., TORRE, M.L., CONTI, M.: Silk Fibroin Bioink for 3D Printing in tissue regeneration: controlled release of MSC extracellular vesicles, *Pharmaceutics*, Vol. 15, No. 2, 383, pp. 1-19, 2023. https://doi.org/10.3390/pharmaceutics15020383

[33] SUN, T., FENG, Z., HE, W., LI, C., HAN, s., LI, Z., GUO, R.: Novel 3D-printing bilayer GelMA-based hydrogel containing BP, β-TCP and exosomes for cartilage–bone integrated repair, *Biofabrication*, Vol. 16, No. 1, p. 015008, 2023.

[34] MESSAOUDI, O., HENRIONNET, C., BOURGE, K., LOEUILLE, D., GILLET, P., PINZANO, A.: Stem cells and extrusion 3D printing for hyaline cartilage engineering, *Cells*, Vol. 10, No. 1, 2, pp. 1-24, 2020. https://dx.doi.org/10.3390/cells10010002

[35] COSTANTINI, M., IDASZEK, J., SZÖKE, K., JAROSZEWICZ, J., DENTINI, M., BARBETTA, A., BRINCHMANN, J.E., ŚWIĘSZKOWSKI, W.: 3D bioprinting of BM-MSCs-loaded ECM biomimetic hydrogels for in vitro neocartilage formation, *Biofabrication*, Vol. 8, No. 3, p. 035002, 2016.

Review process
Single-blind peer review process.

JOURNAL STATEMENT

Journal name:	**Acta Tecnología**
Abbreviated key title:	Acta Tecnol
Journal title initials:	AT
Journal doi:	10.22306/atec
ISSN:	2453-675X
Start year:	2015
The first publishing:	October 2015
Issue publishing:	Quarterly
Publishing form:	On-line electronic publishing
Availability of articles:	Open Access Journal
Journal license:	CC BY-NC
Publication ethics:	COPE, ELSEVIER Publishing Ethics
Plagiarism check:	Worldwide originality control system
Peer review process:	Single-blind review at least two reviewers
Language:	English
Journal e-mail:	**info@actatecnologia.eu**

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Acta Tecnologia journal supports the San Francisco Declaration on Research Assessment (DORA). The primary directives include open access, reuse of outputs, diversity among authors and reviewers, peer review, description of provided services and related publishing charges.

Publisher:	**4S go, s.r.o.**
Address:	Semsa 24, 044 21 Semsa, Slovak Republic, EU
Phone:	+421 948 366 110
Publisher e-mail:	**info@4sgo.eu**

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