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An Augmented Reality Application for an Immersive Laboratory Experience: The Zittau Flow Tray

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Abstract

Integrating augmented reality (AR) into engineering education can enhance the learning experience for complex concepts. This study presents an AR application's engineering process and prototype for the Zittau Flow Tray using (ZFT) Microsoft HoloLens 2 and Unity 3D. The application provides information on sump recirculation operations after a loss-of-coolant-accident in pressurized water reactors. Key features include interactive 3D models, flow simulations, and dynamic information overlays. Initial testing validated the application's core functionalities, though challenges such as user positioning accuracy and real-time data integration remain. Future enhancements will focus on refining these aspects and broadening the application's usability across various AR platforms.

Keywords

Industry 5.0; Human-computer interaction; Engineering education; Nuclear safety; Loss-of-coolant accident; Pressurized water reactor.

Introduction

Nuclear energy was still involved in power generation in Germany until 2023. Plant and reactor safety had to be guaranteed for the remaining service life of the nuclear reactors. This was one of the research focuses of the department "Nuclear Technology/Soft Computing" of the Institute of Process Technology, Process Automation and Measurement Technology (IPM), a research institute of the Zittau/Görlitz University of Applied Sciences (HSZG). For more than 20 years, this department has been working on nuclear safety research projects, focusing on the controllability of loss-of-coolant accidents (LOCA). The according experimental and methodological work has been carried out in close cooperation with the Helmholtz-Zentrum Dresden-Rossendorf and the Gesellschaft für Anlagen- und

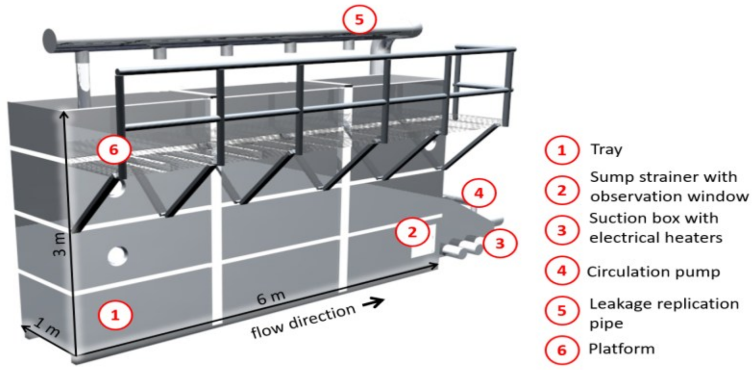
Reaktorsicherheit gGmbH on the following main topics. In the event of a LOCA in the reactor, insulation can be removed from surrounding pipelines when a feedwater line breaks. Investigations included the behavior of these insulation particles in the stationary and flowing coolant, the build-up of filter cakes on retention devices in the containment sump, and the accumulation behavior in the reactor core (Krepper et al., 2008). In a LOCA in PWR, zinc can be released in ionic form due to the corrosion of galvanized internals in the borated coolant (Harm et al., 2023). These zinc ions have the potential to reach the reactor core and transform into solid corrosion products (zinc borates) in hot channels (Kryk et al., 2014; Renger et al., 2018). At the HSZG, zinc corrosion was simulated under near-accident conditions (Kästner et al., 2020; Harm et al., 2022; Kästner et al., 2023). Accidents of this kind can result in complex thermohydraulic and physicochemical effects from the containment to the reactor core. The design of the test rigs used to analyze these processes in detail is correspondingly complex: components of the nuclear facility, such as the reactor sump and geometries of the reactor core, are represented on a semi-technical or even original scale (Renger et al., 2018). Two interconnectable test rigs have played a unique role in the investigations of recent years: the ZFT (Fig. 1) and the core simulator THETIS or Twofold HEaTIng rod configuration for core Simulation. Both systems are fully operational to carry out nuclear safety research. The performance of the system and many measured values can be seen through a dashboard on a local computer, which shows the metrics at runtime as well as some digital actuators (human-machine interface). This work focuses on the first system, the ZFT, which allows the simulation of a sump recirculation operation after a LOCA in a PWR. It is designed to investigate the thermohydraulic effects resulting from corrosion and precipitation processes in the structures of a PWR (Renger et al., 2018) and has the following features:

Source: Own

Fig. 1: *Photo of the ZFT representing the containment sump of a PWR*

- It is a **downscaled German PWR sump model**, modularly designed and constructed as a flow circuit for liquid media like coolant, with a large tray as storage (Fig. 2). The system circulates coolant by transporting it from the tray via a suction box into a horizontal pipe above the tray, from where it returns to the tray through outlets in free fall. Important measured variables, in addition to the tray fill level, are recorded along the flow path, e.g., the coolant's temperature, conduc-tivity, and volumetric flow.
- The stainless-steel **tray** represents the containment sump, downscaled to geometric dimensions of 6 m × 1 m × 3 m (L × W × H). Up to 15.6 m^3 of coolant can be stored in the tray. Particle suspensions can be added here to create a solid-liquid multiphase flow.
- **Sump strainer** (optional): Mounted in front of the suction box's inlet, the strainer (metal grid) ensures quantitative statements regarding the retention of released particles via the retention device in the PWR containment sump. An observation window allows for determining the thickness of the filter cake created from retained particles.

- **Suction box**: The circulating coolant inventory can be heated to a maximum of 80 °C. Three electric heating elements are installed for this purpose.
- **Circulation pump**: This pump is located at the outlet of the suction box and circulates the coolant inside the ZFT test rig. The flow rates in the components and upstream of the sump strainer are set by coarse adjustment of the pump flaps and fine adjustment of the pump's frequency converter.
- **Leakage replication pipe**: A horizontal pipe is installed above the open tray to replicate the leakage jet. This pipe has five downward outlets at different intervals representing different leaking positions (free fall section). Volume flows and spray patterns can be varied. Zinc-coated sources can be placed inside this section to provoke corrosion effects.



Source: Own

Fig. 2: *The main components of the ZFT*

During a lab tour, it can be challenging to communicate the project content and objectives to interested students and scientists. A complicating factor is that many parts of the test facility are not directly visible. Therefore, the references to the parts of the nuclear facility, which are modeled here on a semi-technical scale, are therefore difficult to identify. Here, AR can be a welcome tool for conveying this information clearly and interactively within a short time or remotely, i.e., off-site. AR, as a means of interactive, immersive visualization possibility, poses a promising opportunity to convey hidden and/or complex engineering concepts engagingly. It enhances the real world with holographic digital objects and information in real-time and allows users to interact with these objects (Porter & Heppelmann, 2017). AR and Virtual Reality (VR) are promising tools for training, maintenance, quality and safety management in nuclear power plants in general (Popov et al., 2021; Yim & Seong, 2010). However, there is no one-size-fits-all solution due to the variety of possible AR technologies, applications, and constant advancements. Therefore, each individual task still requires individual solutions. Also, to the authors' knowledge, research on AR in nuclear power plants has not yet included attempts to visualize hidden flows, such as using X-ray vision. However, such efforts are helpful to educate and make transparent the fundamental mechanisms in nuclear power plants to raise awareness and promote safety considerations. Therefore, it was proposed that AR technology be used to further enhance the experience of both tutors and students, with the possibility of extending its use to external people (from schools and energy research communities). The goal was to develop an interactive and immersive AR experience in the Thermal-Hydraulics Facilities for all stakeholders using the Microsoft HoloLens 2 head-mounted display (HMD).

The remainder of the paper is structured as follows. Section 1 reviews the theoretical backgrounds and presents a state-of-the-art overview of current industrial applications of AR, as well as its benefits and challenges. Section 2 describes the methods to design and implement the AR application. In the central part, we report the results concerning the various parts of the application. These include the basics, such as the 3D model scan, positioning and anchoring approach, runtime architecture, and user interface (Subsection 3.1); mandatory features of augmentation, such as info boxes, interaction with the ZFT model, and visualization of a simulated water flow (Subsection 3.2); and an ad hoc evaluation by ZFT domain experts (Subsection 3.3). Finally, we discuss the application of the prototype in practice, its limitations (Section 4), and venues for future research before we conclude.

1 Literature Review on Augmented Reality in Industry and Education

AR or Mixed Reality (MR) refers to augmenting of users' line of sight with digital information by using HMD, handheld devices like smartphones and tablets, or projectors on surfaces. These devices link the physical and digital worlds through immersive and interactive experiences for users. AR enhances the real world by overlaying digital objects in real-time and allowing users to interact with them (Milgram et al., 1995). Key tools for the development of AR and MR include computer vision (to understand and interpret the environment), spatial mapping (3D representation of the physical world), sensors and tracking technologies (Global Positioning System or GPS, localization, and mapping), and respective display technologies. Companies like Microsoft, Magic Leap, Apple, and others have developed state-of-the-art AR and MR devices, such as HoloLens and Apple Vision. These devices provide navigation, education, industry, healthcare, and training simulation applications. Development tools like Unity, ARCore, and Arkit allow programmers to design immersive applications for these devices. According to Porter and Heppelmann (2017), the benefits of AR in organizations are, first, the capability to visualize information in 3D and to allow an X-ray vision of otherwise hidden mechanisms in real-world objects. Second, instructing and guiding others location-independently by domain experts will greatly support knowledge transfers. Moreover, the different interaction possibilities based on gestures, eye gaze, and voice enhance the practicality of AR devices. In industry, AR, in general, is used for assembly, maintenance, logistics, and quality management, investigating benefits on time, error rate, or task load (Egger & Masood, 2020; Fang et al., 2025). With VR, AR has experienced increased attention as a means of visualization in operations management and as a way to support human workers (Lindner et al., 2025). However, ready-to-use AR solutions for operations are uncommon because each application requires software engineering due to individual information technology systems, the specific characteristics of equipment and processes, etc. Mühlan et al. (2021) proposed a framework for industrial AR implementation to assist with such implementation projects. For engineering education in specific, AR can leverage student engagement, make abstract concepts tangible, or improve students' spatial abilities (Tuli et al., 2022; Vásquez-Carbonell, 2022; Winkler et al., 2022). In education and training, the implementation of AR and VR takes advantage of the ability to immerse users in augmented or virtual worlds. This allows users to gain implicit knowledge through experience and interaction (Lindner et al., 2025). This paper attempts to leverage the benefits of AR by applying its principles to the ZFT. This AR engineering project is especially challenging due to several constraints, including limited time (approximately 15 weeks part-time), resources, and the fact that AR software engineers do not develop it but rather industrial engineers and domain experts for their purposes.

2 Methodology

The project was developed in four main phases to create an immersive AR prototype for the ZFT (Fig. 3). These phases were defined using common software engineering and project management principles and processes, including requirements definition, design, implementation, and testing (O'Regan, 2022). First, the familiarization with Unity and

Microsoft's Mixed Reality Toolkit (MRTK) packages to develop the AR application for the HoloLens 2 took place. Second, regular visits to the Thermal-Hydraulic Facilities were necessary to compile and assess all the necessary information on the ZFT, make a 3D scan of it, and define the AR application requirements. Third, the AR application was developed, including its logical flow, menus and actions, object positioning system, additional features, and a flow simulation, before it was finally evaluated. Sections 2 and 3 report the approaches and results regarding steps 2 to 4 in more detail.

Source: Own

Fig. 3: *Methodological approach*

2.1 Engineering Requirements for the Zittau Flow Tray Application

Three mandatory requirements of the to-be-developed application for the ZFT were identified, and two further optional features were defined.

Static but movable elements like texts and/or media should enable the augmentation of the ZFT. Furthermore, the display and interaction with the 3D model of the ZFT should be possible. The visualization of a flow simulation should be available within the 3D model. Real-time data integration and augmentation of the ZFT statuses through cloud services should be achieved, and the visualization of accurate system dynamics simulation based on real-time data resources should be possible (optional, extra-functional features).

To implement these requirements, the following resources were needed: a Microsoft HoloLens 2, a 3D Model of the ZFT, descriptions of each primary part of the ZFT, and a development environment, including the development engine (Unity) and its software dependencies, which are described more in detail in the next subsections.

2.2 Implementation on the Microsoft HoloLens 2

The HoloLens 2 is an MR headset developed by Microsoft, the successor to the original HoloLens. It is designed to blend digital content with the real world, creating interactive MR experiences. This device is a self-contained computer with a see-through holographic display equipped with various sensors, advanced optics, and a custom-built holographic processing unit. HoloLens 2 offers a more immersive and comfortable user experience than its predecessor. It has a more balanced center of gravity, a larger field of view, and hand and eye-tracking capabilities, allowing more natural hologram interactions.[1]

2.2.1 Microsoft's Mixed Reality Development Toolkit

The MRTK is a comprehensive, open-source development framework designed for building MR experiences on the Microsoft HoloLens and Windows MR headsets. It provides tools, components, and features that simplify the development process, making it accessible for developers of varying skill levels. The MRTK includes various functionalities such as spatial awareness, input simulation, hand tracking, and gesture recognition, which are integral to creating immersive and interactive mixed-reality applications. Additionally, it offers customizable templates and pre-built UI controls, enhancing the efficiency and user-friendliness of the design process. Developed primarily in C# and deployable in the Unity 3D

[1] https://www.microsoft.com/en-gb/hololens/

engine, the MRTK is celebrated for its ability to streamline complex aspects of MR development, allowing developers to focus on innovation and user experience. The version used for this project is MRTK 3, its most recent version.[2]

2.2.2 Unity 3D Engine

There are several reasons for choosing Unity 3D as the development engine for this application. The HoloLens 2 is designed to interact primarily with the C# programming language, which is also used within Unity 3D. The MRTK set is programmed in C#, ensuring an optimized and integrated workflow within the engine. Since the goal is to develop a MR application, and MRTK is specifically designed and optimized for integration with Unity 3D, the decision was made to use Unity 3D as the development environment and C# as the programming language.[3]

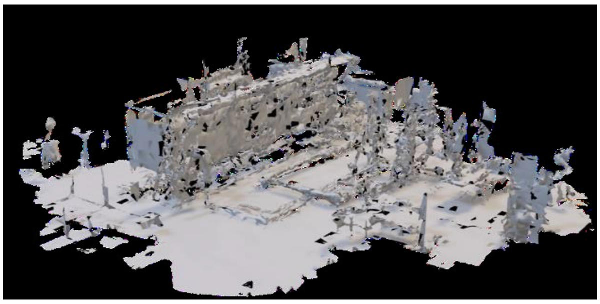
3 Results

In January 2024, the first functional prototype was tested and demonstrated at the ZFT. It includes all the pre-specified three mandatory requirements (Subsection 2.1): augmentation of the ZFT with texts, display, interaction with the 3D model, and simulation of a flow within the 3D model. In the following, the features of the prototype are described in detail.

3.1 Fundamentals

3.1.1 3D Model Scan

For the system's 3D scan, the sensors integrated within the HoloLens 2 were chosen due to their high precision and the ease of data extraction through the tool's interface. The scan took approximately ten minutes. A real-time scan could be viewed through the HoloLens's web interface. Once the scan was finished, the model was downloaded and saved locally (Fig. 4).



Source: Own

Fig. 4: *3D Scan model of the complete ZFT*

The scan encountered some minor issues detecting fine details in certain areas of the system because the machine's material reflects light (Fig. 1), affecting the quality of the 3D scan.

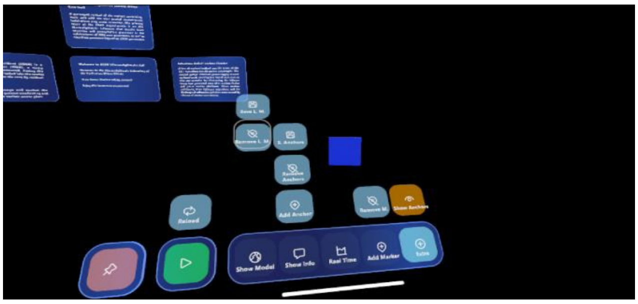
3.1.2 Positioning and Anchoring

The initial positioning of the AR application and the anchors of digital objects are locked to the user's position at startup. This gives laboratory staff and users more flexibility to arrange, scale, and adapt digital objects, such as info boxes and markers, before and during events like lab tours and training sessions for different audiences with varying levels of prior knowledge. Ideally, the anchoring system of the digital augmentations with the real world would be based

[2] https://learn.microsoft.com/en-gb/windows/mixed-reality/mrtk-unity/mrtk3-overview/

[3] https://unity.com/

on AzureSpatialAnchors, a cloud system from Microsoft Azure services that provides object anchoring for AI development purposes. However, due to the lack of documentation and the price of such services, it was decided to develop a local anchoring system. To set up an anchor, it must be created within the environment and made visible for its manipulation. This is done by interacting with the Add Anchors and Show Anchors interactable buttons under the "Extra" menu (Fig. 5).



Source: Own

Fig. 5: *Anchoring system*

As the anchors are positioned, one must be careful of the rotation as the anchoring system is rotation sensitive. Once the anchor game objects are correctly positioned, the Save Anchors method should be called, which can be done when interacting with the S. Anchors button (Subsection 3.2.2). Such a function takes the anchor's game objects' world positions and saves them to a local file. When the world is reloaded, the anchors should be automatically loaded (invisible mesh) and ready to be worked with.

3.1.3 Runtime Architecture

The logical runtime architecture consists of three central states (which inherently define the system's state): "idle" (no subprocesses running), "running" (system operational), and "error" (system halt, error found). The system state is updated based on a simple decision tree paradigm. When the program starts, no main subprocesses are running, meaning that the system state is "idle" and the user is just given one option to start the program. Starting the program changes the system state to "running". If an error is encountered during either state, the system state will be updated to "error", and a log line will be thrown to the console. Tab. 1 shows the system states as variable values.

Tab. 1: *System state definitions*

Variable	State	Value
_state	Error	-1
_state	Idle	0
_state	Running	1

Source: Own

3.1.4 User Interface

When the system state is defined as "Idle", the environment is loaded with static info boxes that introduce the system and are prompted by one interactable button with the play icon (Fig. 6).

At this point, the user can walk around and interact with the info boxes. Once the play button is pressed, then the main menu will become active, with a series of actions to choose from to either set some world settings or interact with the world objects (Fig. 7; Tab. 2). The system state is updated to "Running".

Source: Own

Fig. 6: *System state "Idle"*

Source: Own

Fig. 7: *Main menu with initial information boxes at startup*

Tab. 2: *The main menu action list*

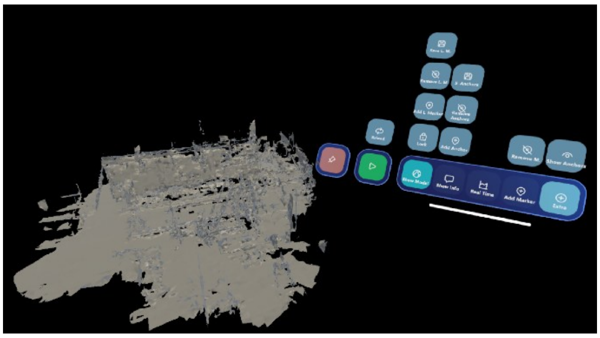
Name	Action
Pin	Fixes menu position.
Play	Toggles between "idle" and "running" state.
Show Model	Shows an interactable 3D model of the system.
Show Info	Shows system-specific info boxes at anchor positions.
Real-Time	Shows real-time data and simulation (only mock-up).
Add Marker	Creates an interactable red marker.
Extra	Activates sub-menu with extra functions.

Source: Own

3.2 Mandatory Features

3.2.1 Augmented Information (Media Boxes)

Show Info. The show info functionality depends on the local anchor system (Subsection 3.1.2). Once the anchors' world transforms are saved and loaded, the show info method will look for each anchor's position and display the dialogs according to the order of anchoring. The dialogs are then loaded as depicted in Fig. 9.



Source: Own

Fig. 8: *Show model environment*

Source: Own

Fig. 9: *Samples of info boxes*

Add Marker. The Add Marker functionality creates a general marker (red) that transforms dynamically (Fig. 10), which means that it can be moved and scaled. This type of marker **cannot be saved**. This feature's purpose is to specifically emphasize some points of interest from the laboratory.

3.2.2 Interactive Zittau Flow Tray Model

Show Model. The Show Model action activates and makes visible a scalable (transform dynamic) 3D Model of the system. When activated, two specific function options will be shown (Fig. 8; Tab. 3).

Tab. 3: *Show model action list*

Name	Action
Lock	Locks the 3D model's world transform properties.
Add L. Marker	Adds a green lab marker.

Source: Own

The lab marker differs from the general marker (red) in that the Lab marker will move and rescale relative to the 3D model's world transforms. The position properties relative to the 3D model's transform properties can be optionally stored to mark key points in the 3D model that can later be automatically loaded.

Extra Menu Action List. The extra interactable activated sub-actions were developed to set up the technical configuration of the virtual environment (Fig. 11; Tab. 4).

Source: Own

Fig. 10: *General marker*

Source: Own

Fig. 11: *Extra menu*

Tab. 4: *Extra Menu Action List*

Name	Action
Remove L. Markers	Removes L. Markers (green).
Save L. Markers	Saves L. Markers' (green) position relative to the 3D lab scan model.
Add Anchors	Creates an anchor.
Remove Anchors	Remove all anchors.
S. Anchors	Saves anchors transform relative to world origin coordinate.
Remove M.	Removes general (red) markers.
Show Anchors	Show anchors as world objects (mesh visible).

Source: Own

3.2.3 Flow Simulation (Mock-Up)

A minimum requirement for the project's duration was the availability of a simulation and visualization of water flow in the ZFT, at least in the holographic 3D model of the PWR. This was achieved through an animated flow of blue dots (water particles) moving from the source to the sink of the ZFT model. This can be seen in Fig. 14 and is accessed via the Real-Time button in the application's main menu (Tab. 2).

The ability to move and scale this holographic object also allows it to be attached to its real-world counterpart in the lab, as demonstrated in Fig. 13. Currently, the flow simulation is not linked to real data. However, it serves as an initial mock-up to "make the invisible visible", taking advantage of one of AR's core benefits.

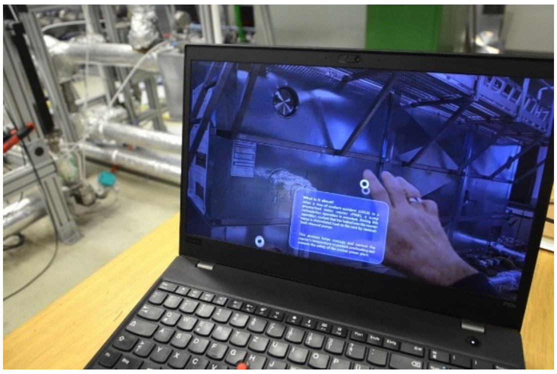
3.3 Expert Evaluation

Following the initial demonstration and testing (Fig. 12, 13, 14), three laboratory staff members, who are ZFT domain experts, provided an evaluation of the AR application.[4] Accordingly, they positively evaluated the system for its user-friendly and intuitive interface. They noted the defects in the 3D geometry caused by reflective metallic surfaces but did not consider them significantly limiting for the intended application.

Even in its current stage of development, the system was deemed suitable for laboratory tours and onboarding sessions for new employees. The staff assessed the efforts required for rescanning after possible modifications of the test rigs as moderate and manageable in everyday operations. The ability to highlight safety-relevant areas and equipment in the virtual model was identified as added value for training and safety briefings, which was not previously considered.

Source: Own

***Fig. 12:** Demonstration of the ZFT AR application in practice*



Source: Own

***Fig. 13:** Live stream of the see-through view including holograms for by-standers on a computer*

Source: Own

***Fig. 14:** See-through view of the AR application with the HoloLens 2 from two different perspectives including the flow simulation in blue*

4 Discussion

Several challenges were overcome in the development of the application, such as selecting and applying a suitable object positioning and reference system to allow, in the end, a truly immersive AR experience for the users and bystanders. Thus, this work contributes to the

[4] https://www.hszg.de/news/durchblick-im-labor-der-zukunft (in German)

establishment of an educational application to explain and make transparent the functionality of a PWR. While other studies have focused on the visualization of radiation in VR (Satu et al., 2024), this work attempts to visualize, among other things, the flow inside a PWR. To achieve this, similar goals are pursued as in Nor et al. (2024), who present sensor data of a water coolant process in AR for maintenance purposes. But this work extends the approach of Nor et al. (2024) with a simulated flow visualization in-situ at the PWR.

Despite the prototype's functionality, not all engineering requirements could be fully implemented as desired. Currently, the technical solution chosen concerning the positioning of the application's reference point still requires the users to stand in the same position when starting the application. Otherwise, the previously stored anchors would no longer appear in the same position.

Due to the shiny (metal) surfaces of the PWT, the 3D scan using HoloLens' built-in functionalities did not provide a sufficient model with enough accuracy. Furthermore, the flow animation in the 3D scan model (Fig. 5 and 12) is only a simulation and not yet connected to the ZFT data in real-time. Finally, the application's usability was just tested through face validity by the involved stakeholders, but it has not yet been tested through a systematic usability survey or similar.

Conclusion

The development of the AR application for the ZFT contributes towards enhancing the educational and practical experience within the long-standing nuclear safety research domain at the HSZG. This project successfully integrated AR technology using Microsoft HoloLens 2, providing users with an immersive and interactive way to understand and interact with the complex processes involved in the sump recirculation operation after a LOCA in a PWR.

Our prototype achieved the core objectives of augmenting the ZFT with static yet movable elements, displaying an interactive 3D model, and simulating flow within this model. These functionalities offer a valuable tool for students and engineers, enhancing their ability to visualize and comprehend the system and its dynamics.

Future research should address the limitations identified in the current prototype and explore avenues for further enhancement and application. Key areas for future research include evaluating the application in practice, improving the anchoring reference system, real-time data and visualization, visualization of the physical object, and the transferability to other devices.

A systematic usability survey would involve testing with a larger and more diverse group of users to gather quantitative and qualitative data on user experience, effectiveness, and areas for improvement. This evaluation will help refine the user interface and overall functionality based on real-world feedback. This can be done already with current and future students and visitors at the Thermal-Hydraulic Test Facilities at HSZG. Further development should focus on a more robust anchoring system to improve the reliability of the reference point positioning, which does not require users to stand in the exact same position each time they start the application.

To fulfil the requirements of real-time data integration and augmentation of the ZFT statuses through cloud services and visualization of accurate system dynamics simulation based on real-time data resources (Subsection 2.1), the flow animation in the 3D scan model should be connected to real-time data from the ZFT. Integrating real-time data will provide a more accurate and responsive visualization, enhancing the application's monitoring and analysis purposes, and for simulation utility. Future research should explore the technical feasibility and methods for seamless real-time data integration and visualization.

Further development efforts should also focus on transferring of the visualization from the 3D scan model to the physical object, the ZFT. This could involve using markers or other tracking technologies to create a MR environment where the flow dynamics are visualized directly on the ZFT. Such an advancement would significantly enhance the applicability in the real-world setting, providing an even more intuitive and tangible interaction for users.

Finally, as the AR technology advances, the application should be adapted and tested on a variety of AR devices. This would ensure that the application remains compatible with the latest hardware and takes advantage of emerging technological capabilities. Research should focus on optimizing the application for different devices, ensuring cross-platform functionality, and leveraging new features to improve user experience. Future research can address these areas and significantly enhance the prototype’s functionality, usability, and applicability, making it a versatile tool for engineering education at the ZFT.

In conclusion, this AR application has laid a foundation for future engineering education and research innovations at the ZFT, demonstrating the possibility of creating an augmented laboratory experience with relatively low resources. We can continuously refine and expand its features to improve how complex engineering concepts are taught and understood, fostering deeper user engagement and comprehension.

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APLIKACE ROZŠÍŘENÉ REALITY PRO POHLCUJÍCÍ LABORATORNÍ ZÁŽITEK: ŽITAVSKÁ PRŮTOKOVÁ VANA

Integrace rozšířené reality (AR) do výuky inženýrství může zlepšit výuku složitých konceptů. Tato studie představuje inženýrský proces a prototyp aplikace AR pro žitavskou průtokovou vanu (Zittau Flow Tray) s využitím Microsoft HoloLens 2 a Unity 3D. Aplikace poskytuje informace o provozu recirkulace v jímce po havárii se ztrátou chladicí kapaliny v tlakovodních reaktorech. Mezi hlavní funkce patří interaktivní 3D modely, simulace proudění a dynamické překryvy informací. Počáteční testování potvrdilo základní funkce aplikace, i když problémy, jako je přesnost určení polohy uživatele a integrace dat v reálném čase, přetrvávají. Budoucí vylepšení se zaměří na zdokonalení těchto aspektů a rozšíření použitelnosti aplikace na různých platformách AR.

EINE AUGMENTED-REALITY-ANWENDUNG FÜR EIN IMMERSIVES LABORERLEBNIS: DIE ZITTAUER STRÖMUNGSWANNE

Die Integration von Augmented Reality (AR) in die Ingenieursausbildung kann die Lernerfahrung durch die Bereitstellung immersiver und interaktiver Tools für komplexe Konzepte verbessern. Diese Studie stellt die Entwicklung einer AR-Anwendung für den Zittauer Flow Tray (ZFT) an der Hochschule Zittau/Görlitz vor. Die Anwendung nutzt Microsoft HoloLens 2 und bietet Informationen über die Sumpfumwälzung nach einem Kühlmittelverlustunfall in Druckwasserreaktoren. Zu den wichtigsten Funktionen gehören interaktive 3D-Modelle, Strömungssimulationen und dynamische Informationsüberlagerungen, die das Verständnis von Studierenden und Ingenieuren verbessern sollen. Erste Tests haben die Kernfunktionen der Anwendung bestätigt, obwohl es noch Herausforderungen wie die Genauigkeit der Benutzerpositionierung und die Echtzeit-Datenintegration gibt. Künftige Verbesserungen werden sich auf die Verfeinerung dieser Aspekte und die Erweiterung der Nutzbarkeit der Anwendung auf verschiedenen AR-Plattformen konzentrieren.

APLIKACJA ROZSZERZONEJ RZECZYWISTOŚCI DLA WCIĄGAJĄCEGO DOŚWIADCZENIA LABORATORYJNEGO: ŻYTAWSKA WANNA PRZEPŁYWOWA

Wprowadzenie rzeczywistości rozszerzonej (AR) do kształcenia inżynierskiego może poprawić jakość nauczania złożonych pojęć. Niniejsze opracowanie przedstawia proces inżynieryjny aplikacji AR oraz prototyp Żytawskiej Wanny Przepływowej (Zittau Flow Tray) przy wykorzystaniu Microsoft HoloLens 2 i Unity 3D. Aplikacja dostarcza informacji o operacjach recyrkulacji z miski olejowej po awarii z wyciekiem płynu chłodniczego w reaktorach wodnych ciśnieniowych. Kluczowe funkcje obejmują interaktywne modele 3D, symulacje przepływu i dynamiczne nakładki informacyjne. Wstępne testy potwierdziły podstawowe funkcje aplikacji, choć nadal istnieją wyzwania, takie jak dokładność określenia pozycji użytkownika i integracja danych w czasie rzeczywistym. Przyszłe ulepszenia skupią się na dopracowaniu tych aspektów i poszerzeniu możliwości wykorzystania aplikacji na różnych platformach AR.

Animation Visualization of a Mobile Radiation Measurement System for Nuclear Waste Containers Using Autodesk Maya

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Abstract

The article presents the development of an animated multimedia presentation for a prototype of a measuring system designed for radiation monitoring of transport and storage containers for radioactive waste. The 3D model of the container was created using the Autodesk Maya software package, utilizing polygonal geometry for modeling. Maya's FX subsystem was employed to simulate both radiation and the movement of the ropes. Post-production was carried out using the CapCut video editor. The final animation will be used for public relations purposes by IPM and to support the next phase of the joint project: "Development and testing of methods for the non-invasive analysis of the inventory status of transport and storage containers during extended interim storage".

Keywords

3D modeling; 3D visualization; Nuclear waste storage; Mobile measurement system; Technical animation.

Introduction

Monitoring radiation from nuclear waste containers is both technically challenging and socially sensitive. Transparent communication about the functionality and safety of such systems is essential for public acceptance and stakeholder engagement. Especially in the nuclear sector — where direct demonstration is restricted — virtual visualizations offer a valuable alternative for illustrating complex processes and interactions.

Despite the increasing availability of advanced 3D modeling tools (Autodesk, 2025a; Autodesk, 2025b; Autodesk, 2025e; Blender Foundation, 2025; Maxon, 2025), a research gap persists in using these technologies specifically for public and interdisciplinary communication of radiation monitoring systems. Most existing studies focus on technical validation rather than how such systems can be visualized in a way that is both scientifically accurate and accessible to non-experts.

This article addresses this gap by presenting an animated multimedia visualization of a conceptual mobile radiation measurement system for the Castor 440/84 container (EWN, 2020; Gartz et al., 1998). The primary aim is to create an engaging, technically grounded animation that supports public outreach, educational purposes, and internal research communication (Guo et al., 2023). The system builds on concepts such as the DCS Monitor II (aseeliger, 2024) and introduces a rope-guided platform for improved measurement access (Kratzsch & Reinicke, 2024; Stephan et al., 2021).

Autodesk Maya (Autodesk, 2025e) was used to model, animate, and simulate mechanical motion and radiation emissions. Maya's FX tools (nParticles, nCloth) and the CapCut video editor enabled the production of a high-quality, coherent visual presentation.

This article's motivation is to visualize a prototype to demonstrate functionality, support visual storytelling, and demonstrate design innovation and operational improvements in a way that static documents cannot. This article demonstrates how advanced 3D modeling and animation tools (such as Autodesk Maya) can be used for engineering simulations. Most studies in this area focus on technical performance, with less attention paid to how these systems are presented to a non-technical audience.

This article is structured as follows: Section 1 presents related research and technical documentation. Section 2 explains the modeling and animation methodology. Section 3 discusses results and visual strategies. Section 4 provides a critical assessment, followed by a conclusion and outlook on future research in visualization for radiation monitoring.

1 Literature Review

In recent years, virtual visualization has gained increasing importance in technical communication, education, and system design. Previous studies have emphasized the role of 3D modeling and animation in conveying complex engineering processes across disciplines such as mechanical engineering, architecture, and energy systems (Rao, 2025; Jasmin et al., 2024). For example, Goldfinger et al. (2024) showed how dynamic visualizations can enhance the comprehension of radiation behavior in containment systems. Similarly, Li et al. (2022) demonstrated the effectiveness of using nParticles in Maya to represent invisible physical phenomena, such as radiation or fluid dispersion, in educational simulations.

Despite these advances, there remains a lack of research that connects detailed modeling of nuclear waste containers—like the Castor 440/84—with accessible visual communication strategies for public and stakeholder engagement. Most existing studies focus either on the mechanical and thermal analysis of such containers (Gartz et al., 1998; EWN, 2020) or on the technical design of radiation measurement systems (Kratzsch & Reinicke, 2024), without integrating these systems into an animated visual narrative that illustrates their operation and benefit. Furthermore, only limited attention has been paid to the role of animation as a tool for bridge the gap between expert knowledge and public understanding.

This article aims to address that gap. While drawing on earlier technical work on mobile radiation monitoring systems (Stephan et al., 2021; Kratzsch & Reinicke, 2024), the authors propos an interdisciplinary approach that uses Autodesk Maya for 3D visualization and CapCut for post-production. This approach combines visual storytelling with engineering precision, extending previous studies' communicative scope.

Key terms used throughout this article include:

- **3D modeling** – creating three-dimensional digital representations of physical objects or systems.

- **Virtual visualization** – the computer-based depiction of systems and processes to improve understanding and communication.
- **Radiation monitoring system** – designed to measure and analyze radioactive emissions from a given source.
- **nParticles (Maya)** – a simulation tool used to create and animate particles that behave like natural or abstract phenomena.

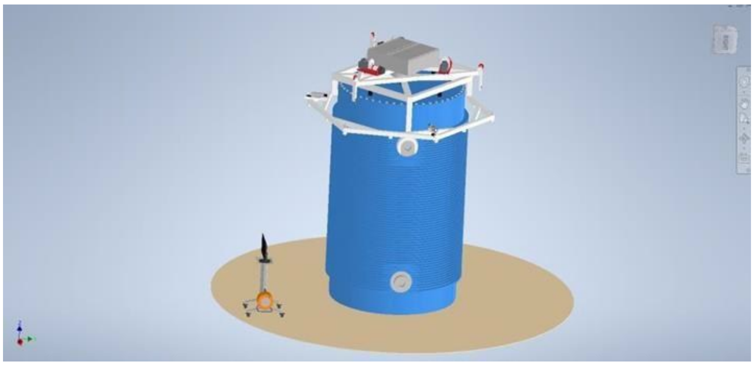
While most literature agrees on the utility of 3D tools in design and simulation, perspectives vary on their role in stakeholder communication. Some argue that technical precision is paramount (Autodesk, 2025d), whereas others advocate for visual simplicity to improve accessibility (Yang, 2024). This balanced article demonstrates how animation can serve both purposes by conveying technical accuracy while remaining visually intuitive.

Project understanding began with the analysis of technical documentation, including dimensional drawings and cross-sections. The Castor 440/84 container is well-documented, with numerous reference images showing its design and storage environment. These resources enabled the creation of a realistic digital representation of the container.

Source: (Kratzsch & Reinicke, 2024)

Fig. 1: *Castor 440/84 and existing mobile radiation measurement system*

The mobile measurement system is a novel concept that has yet to be developed (Figure 1). A 3D model was created for the container and the measurement system to support visualization, enabling a detailed representation of all key components.



Source: (Kratzsch & Reinicke, 2024)

Fig. 2: *3D Model of Castor 440/84 and the conceptual prototype of a mobile radiation measurement system in Autodesk Inventor*

The existing measurement system was analyzed to understand the operational context of the new design (see Figure 2). It rotates around the container and uses sensors to measure gamma and neutron radiation from its surface. This served as the basis for identifying the innovations and potential advantages of the proposed concept in a future research project. Unlike its predecessor, the new system is mounted above the container. Its sensors are positioned on a rope-guided platform, which enables multi-angle measurements (see Figure 2). This approach enhances mobility, reduces required floor space, and may improve measurement accuracy.

2 Methodology

2.1 Software

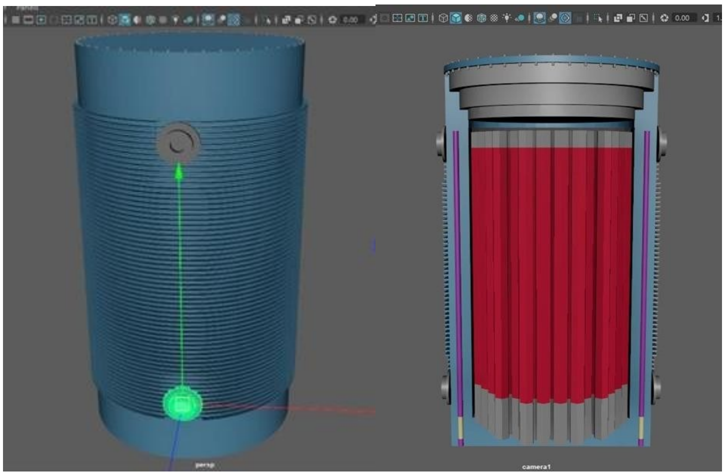
Various 3D software tools are used across numerous industries, including film, animation, gaming, architecture, mechanical engineering, industrial design, advertising, and medical visualization. Prominent examples include Autodesk Maya (Autodesk, 2025e), 3DS Max (Autodesk, 2025a), Unity (Unity, 2025), Autodesk Inventor (Autodesk, 2025b), Cascadeur (Nekki, 2025), and Houdini (SideFX, 2025), among others.

Due to its flexibility and widespread use in industry and academia, Autodesk Maya was used for 3D modeling, animation, and simulation (Rao, 2025). For dimensional accuracy, a reference model from Autodesk Inventor was imported. A scaling factor of 142 mm in Inventor, equaling 1 unit (1 meter) in Maya, ensured correct proportions.

2.2 Container Modeling

The 3D modeling of the container was divided into two main components: the outer structure and the interior assembly. The modeling was performed using polygonal primitives, primarily cylinders and cubes, in combination with Mesh editing tools such as Booleans, Combine, and Extrude.

The outer structure of the container includes the main body, cooling fins, transport brackets, and protective covers. A single fin was created from a cylinder and then duplicated uniformly along the y-axis using the “Edit” → “Duplicate special function” To model the approximately 80 cooling fins along the container wall. The Bevel tool was applied to smooth the edges of the fins and transport brackets, while Extrude was used to give depth to the surfaces.



Source: Own

Fig. 3: *Exterior and interior of a Castor 440/84 in Autodesk Maya*

The interior section consists of a hexagonal frame holding 84 fuel assembly positions, surrounded by 76 steel tubes arranged concentrically around the rim. Each assembly position contains a cluster of smaller hexagons, each with a red circular core representing nuclear fuel; the central hexagon remains empty (EWN, 2020; Gartz et al., 1998; GNS, 2025).

Internal geometry modeling also relied on polygonal primitives and Booleans, Combine, and Duplicate Special to efficiently replicate structures. Each hexagonal element comprises three segments: a top and bottom section (colored gray) and a central core (colored red) to visualize the nuclear material's presence, compared with Figure 3.

2.3 Modeling of the Mobile Measurement System

The mobile measurement system is mounted above the container. It consists of three platforms (Kratzsch & Reinicke, 2024), a rope-based movement system, multiple sensors for detecting radioactive emissions, and control electronics. The components were modeled using a combination of Polygon Primitives and NURBS Primitives in Autodesk Maya.

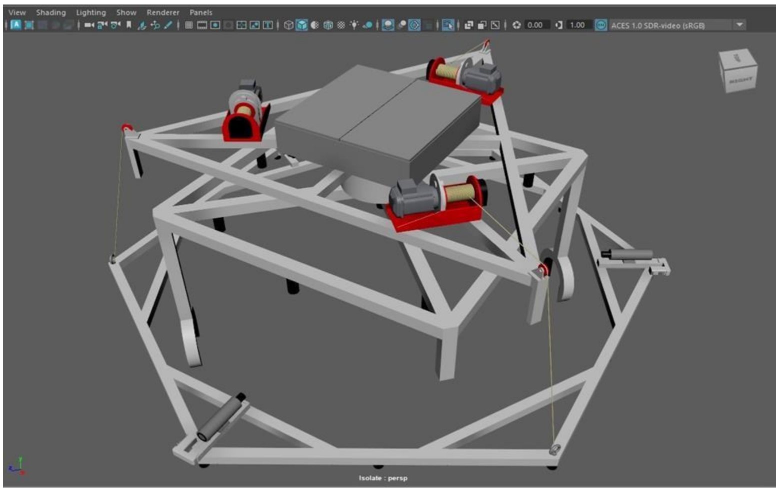
The modeling process began with the three interconnected platforms:

- The first **quadrangular** platform is fixed to the container via transport brackets. It features a rotating wheel that connects it to the second platform.
- The second platform, which is **triangular**, supports three motors used to control the rope's movement. These motors operate in sync with the electronic control unit.
- The third platform is **hexagonal** and serves as the primary measurement unit. It has three radiation sensors, and three circular anchors attached to the ropes. This platform can move and rotate around the container.

The "Boolean," "Extrude," and "Combine" functions were used to model complex elements such as the rotating wheel and the mechanical connectors between the platforms.

A specific modeling challenge was the representation of the rope system. A custom solution was developed using Sweep Mesh to extrude a curve into a cylindrical shape to visualize the ropes. Two separate segments represented each rope:

1. The segment from the motor to the auxiliary spinning wheel remains static but is animated to simulate motion.
2. The segment from the auxiliary spinning wheel to the hexagonal platform is animated to depict actual movement during the measuring process.



Source: Own

Fig. 4: *The conceptual prototype of a mobile radiation measurement system*

This modeling approach allowed for a clear and realistic representation of both the mechanical structure and the movement logic of the mobile measuring system. The result can be seen in Figure 4.

2.4 Simulation of Radiation and Rope Dynamics

The FX module in Autodesk Maya was used to simulate the visual effect of radioactive emissions. The emission was represented using nParticles, configured to appear as small spherical particles. These particles were emitted over time to mimic the dispersion of ionizing radiation from the container surface (Academic Phoenix Plus, 2019).

When animating the rope, nCloth and nConstraint are used (MH Tutorials, 2015). A realistically stretched yet slightly elastic rope behavior was achieved by adjusting physical properties such as stretch resistance and rigidity. The rope was constrained to the platform endpoints, maintaining tension during simulated movement.

The animation was orchestrated along the TimeSlider, beginning at frame 0. Initially, small particles are emitted, gradually increasing in quantity and spatial spread, creating a dynamic visual representation of radioactive activity. Simultaneously, the rope dynamically adapts its shape and tension in response to the animation timeline, reflecting realistic mechanical behavior defined by the simulation settings (Autodesk, 2025c).

2.5 Rendering Techniques and Post-Production Workflow

This project used the Maya Software Renderer due to its flexibility and compatibility with particles, NURBS, and fluid effects, although it entails longer rendering times. While offering high-quality output, Arnold Renderer was less suitable due to licensing constraints and the need for complex lighting adjustments (Autodesk, 2025d).

Post-production was completed using CapCut. Seven individually rendered sequences (converted from AVI to MPG) were enhanced with background edits, text overlays, visual effects, and audio. The result is a coherent animation that effectively communicates the system’s design and functionality.

3 Results

3.1 Material Assignment and Visual Enhancement

Materials and colors were assigned based on real-world conventions to enhance realism and clarity. Most components used Blinn material to achieve a metallic finish; only the ropes used Lambert material for a matte appearance.

The container was color-coded as follows:

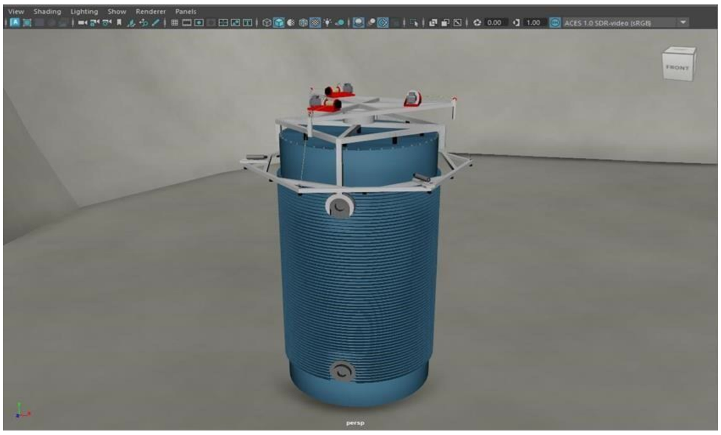
- Blue – the container body, cooling fins, and top cover,
- Red – the nuclear fuel cores,
- Purple – the steel pipes,
- Gray – all remaining structural components.

The conceptual prototype of a mobile radiation measurement system used:

- White – the platforms,
- Yellow – the ropes (hemp),
- Gray – the electronic components and sensors.

A neutral background in the shape of a storage cave was added, textured with a light Lambert material to keep the focus on the central components and provide context. Figure 5 shows the

3D model of the container along with the conceptual prototype of the mobile radiation measurement system, both created in Autodesk Maya.



Source: Own

Fig. 5: *3D model of the container and conceptual prototype of a mobile radiation measurement system in Autodesk Maya*

3.2 Modeling Challenges and Optimization

During the modeling of the interior of the Castor 440/84 container, an initial approach was used to represent the stored fuel assemblies accurately using cylindrical geometries. An initial approach modeled the fuel assemblies using concentric cylinders (blue and red), totaling 182 per compartment across all 84 compartments. This approach significantly increased the computational complexity of the scene, leading to performance issues during rendering. This caused severe performance issues, including rendering failures and application crashes. Sim simplified dual-tone hexagons (gray and red) replaced the cylinders to indicate fuel presence to resolve this issue. This optimization significantly reduced the scene’s polygon count, improving rendering stability and allowing for smoother interaction during animation and editing.

3.3 Simulation of Gamma and Neutron Radiation in Autodesk Maya

Gamma radiation and neutron radiation, which are present inside the container and a small percentage of which escape from it, are invisible. They are visualized to illustrate their emission behavior, using red spherical particles as a metaphor.

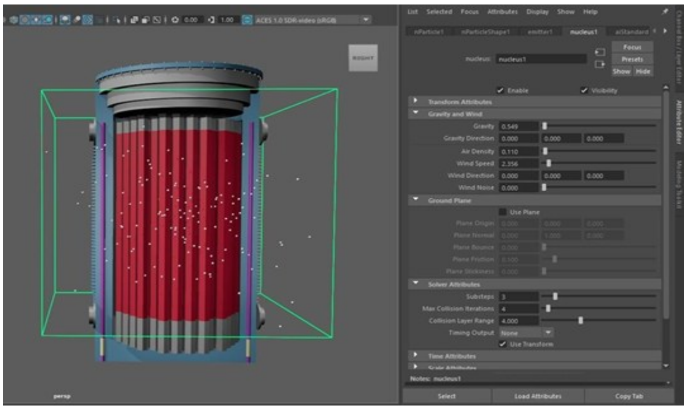


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Fig. 6: *nParticles as a metaphor for radiation and options in Autodesk Maya*

Particle emission was simulated using Maya's nParticles system (FX menu → Create Emitter). During animation playback, this Emitter continuously produces particles, simulating radiation emission from the container (Academic Phoenix Plus, 2019; Riggi et al., 2024).

Parameters such as gravity direction, emission rate, velocity, and spacing were adjusted to achieve a realistic effect. Particles were shaped as small spheres, white in Maya with randomized lifespans, and rendered red to improve visibility.

This approach allows for a visually intuitive representation of radiation fields, supporting communication and understanding of the system's functionality, particularly for audiences without technical backgrounds (see Figure 6) (Goldfinger et al., 2024; Li et al., 2022).

3.4 Storyboard and Scene Structure

The animation process began with creating a storyboard (Rao, 2025), which served as the foundation for visualizing the measurement system in a structured and comprehensible way. The storyboard was divided into four distinct scenes:

- **Scene 1** shows the empty container, which is then filled with internal components and closed with its lids (see Figure 7).

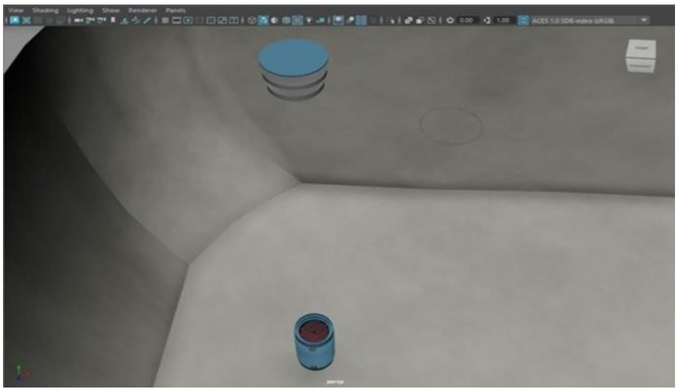

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Fig. 7: *Animation of the first scene (empty container, which is then filled with internal components and closed with its lids)*

- **Scene 2** begins with a cutaway animation of the Castor 440/84, sequentially exposing internal components. These include the fuel assembly hexagons and a simulated radiation emission visualized through red particles. After a brief animation of the emitted particles, they are withdrawn, and the container is closed again (see Figure 8).

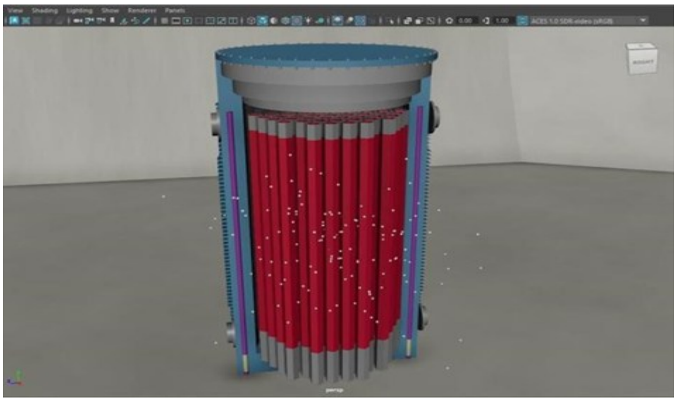

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Fig. 8: *Animation of the second scene (simulated radiation emission visualized through red particles)*

- **Scene 3** illustrates the mobile measurement system being lowered from above onto the container (see Figure 9).

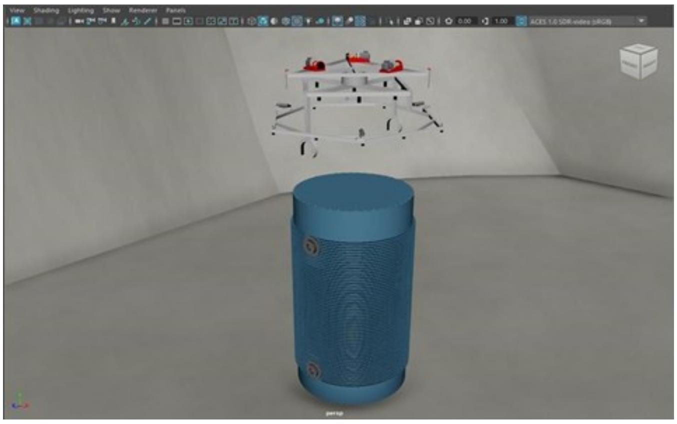

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Fig. 9: *Animation of the third scene (lowering of the mobile measurement system)*

- **Scene 4**, the most critical part of the animation, demonstrates the operation of the mobile measurement system (see Figure 10). It highlights the movement of the platforms, the function of the sensors, and the system's advantages over the previous generation (DCS Monitor II) (Kratzsch & Reinicke, 2024).

Source: Own

Fig. 10: *Animation of the fourth scene (operation of the mobile measurement system)*

The animations were created by placing keyframes at important moments using the "Set Key" function in Maya's Time Slider. This timeline-based approach allowed precise control of object movements and scene transitions (Autodesk, 2025c).

3.5 Rope Animation Using nCloth

nCloth from Maya's FX module was used to animate the rope system connecting the platforms. nCloth is typically used to simulate dynamic cloth-like surfaces. However, a network of connected particles can also be applied to other deformable geometries, such as ropes or cables.

Applying nCloth without constraints initially resulted in a simple gravitational fall, as the rope was not anchored to any object. To realistically simulate tension and attachment, nConstraint – Point to Surface constraints were created at both rope ends: one connected to the auxiliary spinning wheel of the upper platform and the other to the ring structure of the movable platform.

The rope was modeled as a cylinder, and the “looseThickKnit” material preset was used as a starting point. Several Dynamic Properties were adjusted to fine-tune physical behavior, including (MH Tutorials, 2015):

- Stretch Resistance,
- Compression Resistance,
- Deformation Resistance,
- Rigidity.

By carefully calibrating these values, the rope achieved the desired balance between elasticity and structural stability, ensuring realistic movement during animation and interaction with other scene elements (3DMarkAA, 2023). Figure 11 illustrates the visual representation of the hemp element, including the assigned material and adjusted dynamic properties.

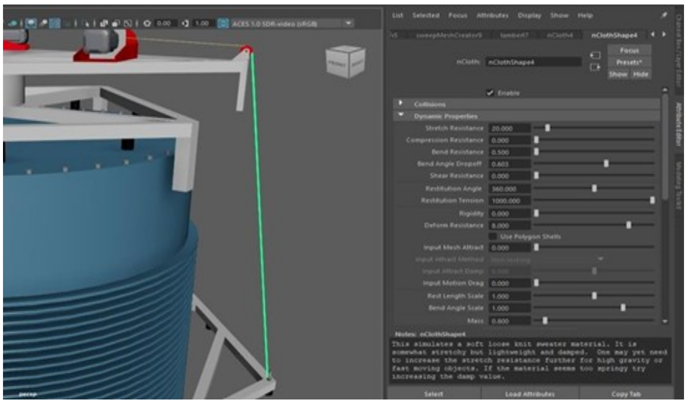

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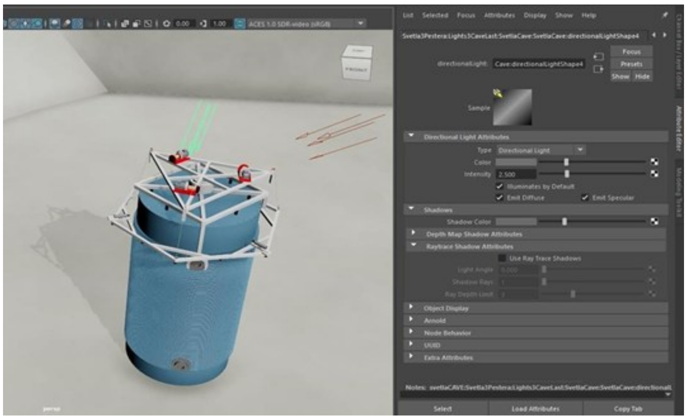
Fig. 11: *Hemp, added material and changed options*

3.6 Lighting and Camera Setup

The final step in the scene design process involved configuring the lighting, camera animation, and rendering settings in Autodesk Maya. Proper lighting was essential to achieve a balanced illumination of both the container and the mobile measurement system.

Two directional lights were added to the scene via Create → Lights → Directional Light (Sir Wade Neistadt, 2018). Figure 12 illustrates the stage illuminated with two configured light sources to enhance depth and visibility in the 3D scene.



Source: Own
Fig. 12: *Lighting the stage with both lights*

The primary light source was assigned an intensity of 3.5, with a light gray color tone for both the light and its shadows. Ray-traced shadows were enabled (Use ray trace shadows) to ensure realistic shadow casting.

The secondary light was positioned above the container to illuminate the interior and measurement system better. It had an intensity of 2.5 and used neutral gray tones for the light and shadows. This light did not use ray tracing, so it did not directly influence the scene's shadows. Directional indicators in the Maya viewport represent both light sources.

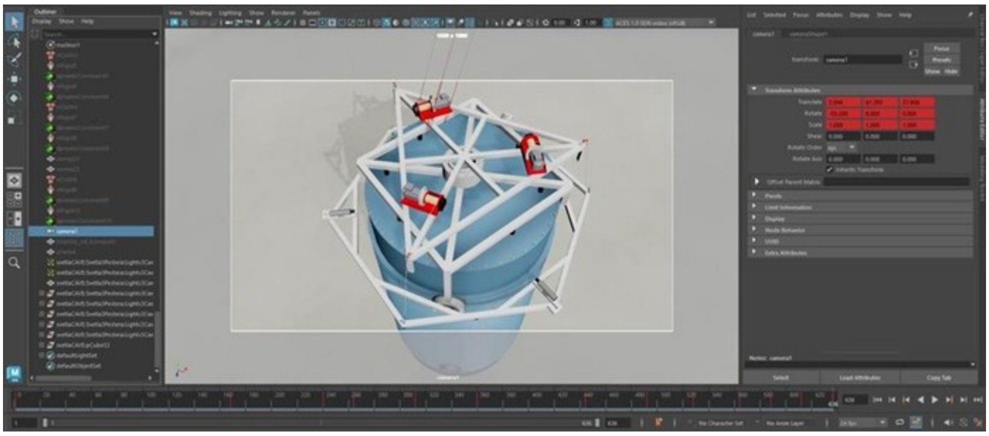
For the camera setup, a single static camera was created (Create → Cameras → Camera), following the structure outlined in the storyboard. The camera was initially positioned in front of the container and animated using keyframes to guide its motion through the scene.

The camera movement included:

- A wide initial shot of the container,
- A zoom-in sequence focusing on a sensor to highlight its function and motion,
- A final framing of the entire mobile measurement system.

Additional keyframes were inserted between the leading camera positions to create smooth transitions. All scenes were animated using a frame rate of 24 frames per second, which is standard for 3D animation.

Scene visualization was managed through the Panels → Perspective → Camera1/Persp. option, allowing toggling between the active camera view and a general perspective view. The final rendering resolution was set to 1920 × 1080 pixels in high quality to ensure clarity and suitability for video presentation and public dissemination. Figure 13 illustrates the final keyframe placement in the fourth scene, marking the last camera frame of the animation.



Source: Own

Fig. 13: *The fourth scene with a key frame in the last camera frame*

3.7 Rendering Configuration and Output Settings

The final step in the animation workflow was rendering the scenes into video sequences using the Maya Software Renderer, which was selected for its ability to produce high-quality-CPU-based output. All rendering parameters were configured via Render → Render Settings, where general and renderer-specific options were defined.

Key parameters included:

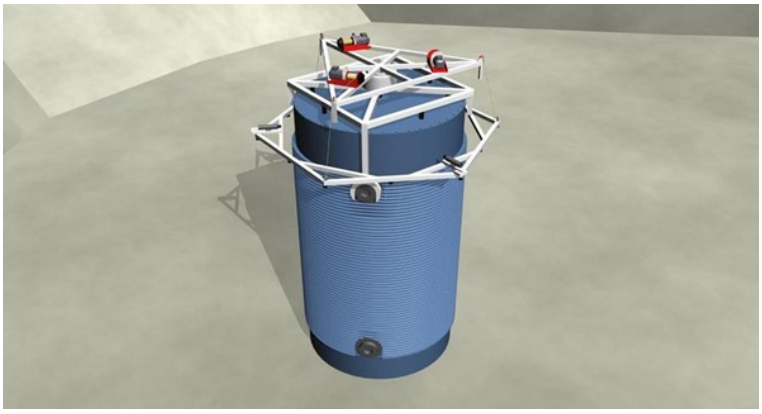
- **Output format**: AVI,
- **Render range**: defined by start and end frames,
- **Camera**: camera1 (as defined in the animation setup),

- **Resolution**: HD 1080 (1920 × 1080 pixels),
- **File name and output directory**: specified for each scene.

Renderer-specific (quality-related) options included:

- **Anti-aliasing quality**: set to High Quality,
- **Multi-pixel filtering**: enabled via Use Multi-Pixel Filter,
- **Raytracing**: enabled, with the following parameters:
  - **Reflections**: 0,
  - **Refractions**: 10,
  - **Shadows**: 10.

These settings were uniformly applied to all four scenes to maintain consistent visual output throughout the final animation. The result was a high-resolution, frame-accurate render suitable for post-production and presentation. Figure 14 shows the rendered image produced using the Maya Software Renderer.



Source: Own

Fig. 14: *Render image in Maya Software*

4 Discussion

This study demonstrates that animated 3D visualization is a powerful tool for communicating complex systems like mobile radiation monitoring units. The primary outcome confirms that Autodesk Maya, in combination with CapCut, enables the creation of technically grounded yet accessible animations. These represent mechanical elements and abstract phenomena such as radiation behavior.

Compared to existing visual documentation in the field, which typically relies on static CAD drawings or text-heavy reports (Goldfinger et al., 2024; Rao, 2025), this animated visualization offers a more immersive and dynamic perspective. Prior approaches often neglected the communicative potential of cinematic sequencing, interactive timing, and symbolic augmentation. By leveraging these techniques, this study contributes to the emerging practice of using 3D storytelling for interdisciplinary and public communication in high-stakes technical domains such as nuclear monitoring.

However, the approach has limitations. The system is still conceptual, and the modeling process was resource-intensive. Some simplifications (e.g., symbolic geometries) may compromise technical accuracy in favor of visual clarity. Moreover, the lack of real measurement data restricts empirical validation.

Conclusion

This article has shown how animated visual storytelling can enhance the understanding and outreach of conceptual radiation monitoring systems. An engaging animation of a next-generation prototype was developed by leveraging Autodesk Maya for simulation and CapCut for post-production. The video highlights advancements over previous systems, such as DCS Monitor II, particularly in mobility, spatial efficiency, and automation potential. It also illustrates how visualization supports stakeholder communication, student engagement, and interdisciplinary collaboration.

Communicating such complex technical systems to a broad audience requires more than traditional documentation. Visual tools such as animated videos, interactive presentations, and 3D models are essential to convey functionality, purpose, and innovation, especially to non-experts. The animated video developed in this project serves as a means of public outreach and a tool to attract potential investors, inspire students, and inform professionals from related fields, including academia and industry.

Ultimately, the project highlighted the importance of interdisciplinary collaboration blending mechanical engineering, nuclear technology, design, and media production to make complex innovations accessible, understandable, and impactful.

Future research should include viewer feedback, engagement metrics, and comprehension assessments to substantiate the assertion that animated storytelling enhances understanding. This data would provide a clearer picture of how effectively such media communicates complex technical information to various audiences. Future articles should also integrate real-world data, validate physical prototypes, and evaluate viewer comprehension. Additionally, this project encourages the broader use of 3D tools in industrial and educational applications beyond their traditional roles in advertising and media.

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VIZUALIZACE MOBILNÍHO SYSTÉMU MĚŘENÍ RADIACE PRO KONTEJNERY S JADERNÝM ODPADEM POMOCÍ ANIMACE V PROGRAMU AUTODESK MAYA

Článek představuje vývoj animované multimediální prezentace pro prototyp měřicího systému určeného k radiačnímu monitorování přepravních a skladovacích kontejnerů na radioaktivní odpad. 3D model kontejneru byl vytvořen pomocí softwarového balíku Autodesk Maya s využitím polygonální geometrie pro modelování. K simulaci radiace i pohybu lan byl použit subsystém FX programu Maya. Postprodukce byla provedena pomocí editoru videa CapCut. Finální animace bude použita pro účely styku s veřejností společností IPM a na podporu další fáze společného projektu: „Vývoj a testování metod pro neinvazivní analýzu stavu zásob přepravních a skladovacích kontejnerů během prodlouženého meziskladu".

ANIMATIONSGESTÜTZTE VISUALISIERUNG EINES MOBILEN MESSSYSTEMS FÜR NUKLEARABFALLBEHÄLTER MIT AUTODESK MAYA

Diese Arbeit stellt die Entwicklung einer animierten multimedialen Präsentation für einen neuen Prototyp eines Messsystems vor, das zur Überwachung der Strahlung von Transport- und Lagerbehältern für radioaktive Abfälle dient. Das 3D-Modell des Behälters wurde mit der Software Autodesk Maya unter Verwendung polygonaler Geometrien erstellt. Das FX-Modul von Maya wurde zur Simulation von Strahlung und Seilbewegung eingesetzt. Eine Kombination aus Keyframe-Animation und physikalischer Simulation ermöglichte realistische Bewegungsabläufe in der Szene. Die Postproduktion erfolgte im Videoschnittprogramm CapCut, in dem Text, Ton und zusätzliche Animationen im MP4-Format integriert wurden. Die finale Animation wird vom IPM für Zwecke der Öffentlichkeitsarbeit und zur Unterstützung der nächsten Projektphase verwendet: „Entwicklung und Erprobung von Verfahren zur nichtinvasiven Analyse des Inventarzustands von Transport- und Lagerbehältern bei verlängerter Zwischenlagerung".

WIZUALIZACJA MOBILNEGO SYSTEMU POMIARU PROMIENIOWANA DLA KONTENERÓW NA ODPADY RADIOAKTYWNE PRZY POMOCY ANIMACJI W PROGRAMIE AUTODESK MAYA

Niniejszy artykuł przedstawia opracowanie animowanej prezentacji multimedialnej dla prototypu systemu pomiarowego przeznaczonego do monitorowania promieniowania pochodzącego z kontenerów transportowych i magazynowych na odpady radioaktywne. Model 3D kontenera został utworzony przy użyciu pakietu oprogramowania Autodesk Maya, z wykorzystaniem geometrii wielokątowej do modelowania. Do symulacji promieniowania oraz ruchu lin wykorzystano podsystem FX programu Maya. Postprodukcja została przeprowadzona przy użyciu edytora wideo CapCut. Gotowa animacja zostanie wykorzystana przez spółkę IPM do celów public relations oraz do wsparcia kolejnego etapu wspólnego projektu: „Opracowanie i testowanie metod nieinwazyjnej analizy stanu zapasów kontenerów transportowych i magazynowych podczas wydłużonego przechowywania tymczasowego".

Classification of Vehicle Routing Problems as a Concept of a Decision-Making Tool in Distribution Logistics

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Abstract

The article follows an extensive investigation of individual variants of Vehicle Routing Problems (VRP) in distribution logistics. The paper aims to use the existing research and the developed VRP classification to design a new concept of decision tool. The research methods are analysis, synthesis, induction, deduction, comparison, and expert interviews. The tool will be able to provide quick information to the professional public and users without prior knowledge based on a created and easily accessible decision-making environment. In this article, user-flexible and fully or partially free options including the structure of concept of decision tool are presented. They will enable developers to prepare an efficient solution that guides the user through the VRP database using the form.

Keywords

Classification; Vehicle routing problem; Decision-making environment; Data filtering.

Introduction

Distribution logistics is a vast and dynamically changing field. In this connection the vehicle routing problem (hereinafter VRP) was chosen for deeper study due to its variety and diversity. The key elements of VRP are capacity, time windows, demand variability, cost efficiency, and overall flexibility. However, the main challenge is to optimize the vehicle's route, which must serve the customer according to his requirements and minimize the total transportation cost while satisfying the constraining conditions. It is, therefore, necessary to plan the route to meet the capacity constraints of the vehicles; respect the (specific) time windows in which customers can be served; adapt the circuit to different amounts of demand; minimize the total cost of operation - fuel, wages, or vehicle maintenance. Thus, flexibility refers to responding quickly to changes or unplanned events. (Tan & Yeh, 2021)

VRP is mainly used to distribute goods, collect waste, deliver food, courier services, supply shops, and perform maintenance and service. Effective VRP solutions ensure cost efficiency, customer satisfaction, and high service quality. These are critical factors for successful logistics operations. Specific impacts of VRP on overall costs include reduced fuel costs, reduced or better utilization of working hours, reduced wear and tear and subsequent repairs of vehicles, optimization of vehicle capacity, reduction in the number of vehicles, minimization of delays and potential fines, improved quality of service and finally reduction of emissions and environmental costs (Tan & Yeh, 2021). Moreover, implementing an efficient VRP leads to significant financial savings. For example, efficient route planning for supplying the business community will reduce transport costs by up to 10-20%. Optimized routes for waste collection and recycling will reduce fuel and labor costs by 15-25%, as reported in (Puri, 2023). Besides, courier companies achieve a 10-15% reduction in overall costs with better route planning (Kant et al., 2008).

In the real world, distribution companies combine intuitive approaches with exact methods because purely algorithmic or expert systems may not always fully cover all aspects of their complex operations. They must be very flexible and react to changes in demand or unexpected situations. This may involve ad hoc decision-making and reallocating resources based on the current situation, rather than strict adherence to predetermined plans. Examples show (Salas et al., 2010) that while distribution companies use technology and expert systems, hands-on experience, intuition, and manual intervention are still a key part of their day-to-day operations. Consequently, managers in distribution companies often use their years of experience and intuition to make decisions supported by data analytics. For example, they can apply their knowledge of historical sales trends when planning seasonal inventory while using forecasting models to validate their estimates.

The author's original intention was to subdivide the VRP offered by the contribution of Plevný (2013). During the analysis, the overview of the essential eight VRPs was supplemented by the periodic VRP, which has experienced a significant expansion in recent years (Gutiérrez-Sánchez & Rocha-Medina, 2022). The often-mentioned environmental restrictions should also be better explained. The uniqueness of this article is explained by the fact that the data collected by the author in the research did not reveal any correspondence with the studies presented before (Tan & Yeh, 2021).

This article explores the development of VRP classification and aims to propose a new decision-making concept. The results of a systematic review of literature related to the topic from 1970 to 2022 are introduced in Subsection 1. The research methodology, including analysis, synthesis, induction, and deduction of theoretical approaches and expert interviews, can be found in Section 2. Section 3 focuses on artificial intelligence applications that aim to assist developers and users in identifying specific VRP variants. It proposes a VRP classification concept structured around three pillars for use in distribution logistics. Finally, this is followed by a discussion (see Section 4) and a conclusion emphasizing the uniqueness of the decision-making tool proposed in the field.

1 Literature Review

Currently, the general public does not have a tool to make it easier to select the type of VRP they seek. Expert systems have this tool, but it is difficult for the general public to access due to the purchase price. For example, **Freight Management Systems** (FMS) allow for the real-time monitoring and management of transport operations. A charming comparison is offered by Škabić et al. (2018), who analyzed three types of FMS – Mobilises, CVS Mobile, and My GPS. Distribution companies use simulation software for traffic modeling. These can be PTV Vistro or VISUM. PTV Vistro is the software mentioned in transportation modeling by Yulianto et al. (2018). Programming languages such as **Python**, mentioned in Benítez-Hidalgo et al. (2019), MATLAB in Farizal et al. (2023), and C++, mentioned in Koguma (2024) have been successfully used directly for solving VRPs. They can find the optimal route and minimize transport costs or transport times.

Specialized tools may be unaffordable for the general public or students. Several cheaper options and approaches may be more affordable for individuals. For example, open-source solutions are available for route optimization (Stančić et al., 2023). These are software tools with the **OptaPlanner** project (Jubé et al., 2023) that can provide comprehensive optimization and planning functions but not for selecting a suitable VRP option based on known model parameters. The primary programming language used in OptaPlanner is Java. Thanks to its interoperability, it is also possible to use the Kotlin programming language. Finally, there are opportunities to contact university departments of transport engineering that can provide computational resources or software for research purposes.

All acquisition-intensive and more affordable simulation, optimization, and planning options are mentioned. Even the more cost-effective alternatives provide some functionality for route optimization and VRP design (Sun et al., 2022; Jena, 2024). However, none of them will allow the general public, without prior knowledge, to access a decision environment where the type of VRP can be easily and freely determined. Thus, this affluent area of distribution logistics is introduced without the need for users to have prior knowledge of VRP issues or to operate the decision environment.

2 Methodology

2.1 Classification of Vehicle Routing Problems

The author has applied the analysis, synthesis, induction, and deduction in this article.

In this case, **analysis** means determining the basic areas of the VRP into individual components and examining to what extent the parts are elaborated and published. It also means examining their interrelation or identifying deviations and differences, i.e., exploring. The analysis was to relate the research work to the literature.

Synthesis required a thorough understanding of the general divisions and the appropriate assembly of the parts into a comprehensive whole. It was also necessary to describe the organizing principles that guided the overall concept to the individual parts.

Induction was used to generalize the data and in the systematic search associated with the VRP concept. The result is the identification of a specific breakdown of VRP types and their grouping according to related features. In addition, the following two methods of inquiry were necessary: **qualitative interviewing** and **expert interview**.

Deduction was used to determine the key specifics of each method. The theory identified so far from the research was applied, and the comparison method was used to assess and compare the relationships between the secondary data obtained from the literature searches and the partially obtained primary data from interviews with subject matter experts.

Moreover, synthesis and induction/deduction were carried out simultaneously or in some sequence. Using synthetic methods, new research areas could be derived for further elaboration by induction and deduction.

To get a comprehensive idea of the area discussed, articles and contributions, both domestic and foreign, were mapped. Duplications were removed from the searched contributions, and relevant outputs were processed into an overview summarizing the issue. For the target classification, subject databases needed to be limited and divided according to the structure of mathematical models and specifications.

The classification is based on nearly 300 articles published from the 1970s to 2022. The first phase of the research was completed in 2022, and the second phase is working on the real use of the VRP classification as a decision-making tool concept. New findings from 2023-2025 will be processed after the second phase is completed and incorporated directly into the existing tool's database. In terms of the review articles themselves, Braekers et al. (2016) are worth mentioning as they presented a taxonomic review of the literature on VRP published between 2009 and June 2015. Dynamic VRP is addressed in Psaraftis's review paper

(Psaraftis , 1995). The paper presents a comprehensive review of the VRP literature for 2015-2021, focusing on applications and solution methods. In the case of robust VRPs (RRVRPs), Min et al. (1998) aim to provide a comprehensive and relevant taxonomy for literature and propose a refined definition of RVRPs.

During the search, VRP has grown considerably in recent years. This is a periodic VRP (referred to as PVRP). Therefore, the division's original intention is extended by modifying this problem according to Gutiérrez-Sánchez & Rocha-Medina (2022) and supplemented with new findings. The basic VRP variants are Capacitated VRP, VRP with time windows, VRP with pick-up and delivery, periodic VRP according to Gribkovskaia et al. (2008), multiply depot VRP, split delivery VRP, stochastic, dynamic and open VRP. The listed types of VRP were further divided into further subclasses. This is a breakdown of the VRP classes listed according to the publications available in the databases of professional articles. For the decision-making process, which includes the mentioned concept, considerable knowledge of VRP variants is necessary, achieved during the creation of the classification itself.

2.2 The Use of Artificial Intelligence

Due to the large number of individual VRP variants, artificial intelligence services are possible. They offer the user several options.

General Artificial Intelligence (GAI) is usually defined as an artificial intelligence capable of performing any intellectual task that a human can. Unlike **narrow AI** systems designed for specific tasks, GAI has broad capabilities and flexibility. However, in the context of distribution logistics and the vehicle routing problem (VRP), GAI will not be foreseen soon.

Another variant is **Machine Learning** (ML) algorithms, used for demand forecasting, inventory optimization, and traffic conditions prediction. These algorithms use historical data and models to learn and improve their predictions (Bai et al., 2023), which can help in VRP decision-making. **Deep Learning** (DL) is a more advanced form of machine learning that uses neural networks with many layers. **Natural Language Processing** (NLP) technologies analyze text data, process customer requests, and automate communications (Chin et al., 2024). In the context of VRP, NLP can help analyze customer reviews, predict demand, and improve customer support.

GAI/Language Processors are also used in VRP classification. For example, large language models such as GPT-4 can help process and analyze large amounts of textual data such as customer orders, feedback, and logistics documents. Decision Support in AI systems can provide recommendations based on historical data and current conditions (Canoy et al., 2023). NLP technologies can interact with customers via chatbots, improving customer service and quickly responding to delivery queries. Further, AI tools can automatically generate and monitor key performance indicators (KPIs) such as delivery cost, delivery time, and customer satisfaction (Klabusayová, 2013). As a concept, GAI is not envisioned for VRP soon, but current AI tools and language processors (NLP) provide significant advantages. They help with data processing, decision support, customer interaction, KPI monitoring, and algorithm optimization. The results of these tools need to be expertly assessed to ensure their reliability and effectiveness in specific logistics scenarios.

Although the possibilities of using **Large Language Models** (LLM) in distribution logistics and solving Circular Transportation Problems (CTP) are still limited compared to specialized optimization tools, several promising directions remain. LLMs can help with pre-processing and structuring textual data relevant to VRP. LLMs can be used as part of a broader decision framework where they prepare data or parameters for optimization algorithms (Tupayachi et al., 2024). LLMs help generate summaries or explanations of complex optimization results

(Ackerman et al., 2024). Overall, LLMs today do not provide a direct VRP solution (they do not perform optimization independently at the level of mathematics and heuristics). However, they can significantly support pre- and post-optimization phases, simplify communication, data, and result interpretation, and make decision-making based on VRP solutions more understandable and flexible.

2.3 Classification of Vehicle Routing Problems as a Decision-Making Tool

Classification represents a significant number of vehicle routing problems that distribution logistics offers. There has also been a significant increase in other modifications of these problems in recent years. The mentioned trend can be expected in the future as well. The professional public or distribution companies are well-informed in this area. In their case, detecting or determining the type of VRP is easy. However, the general public can encounter many pitfalls when making decisions. If the circuit is not correctly set and solved, getting a relevant solution is impossible. Artificial intelligence can be a specific tool. Here, however, it is necessary to recall the necessity of control based on knowledge in the given area.

The goal of the concept is to enable a standard user without prior knowledge to identify the current situation and use the offered solution easily. It will offer rooting of the problem and identify approaches and results for the professional public. It will help to compare one's research with already published works. After a deeper analysis, it will be possible to discover a theoretically unworked problem and work on its formulation further. The article describes the creation of a decision tool concept. Acquisition of knowledge is essential for the mentioned form of creation. They are based on VRP classification and elaborate on it further.

Two options were considered for the correct form of the concept. The first option was to design the work according to the VRP taxonomy of type designations (variants). The second option involved thinking of the problem as a complex group of restrictions and requirements that must be set correctly according to the original classification to select in the next step.

In the case of VRPs, no common standardized system would guarantee an accurate classification in terms of taxonomy. No uniform notation convention is used. In literature, it is common to find a problem whose mathematical model exactly corresponds to another published problem, but the notation is different. During the literature survey, some publications were found, the content of which was very detailed but only at the level of basic types of VRP (Eksioglu et al., 2009) or, in contrast, complex but narrowly specialized (Vidal et al., 2013). Designation of VRP variants by prefixes or suffixes that indicate the presence of restrictions is used mainly for basic types. Identifying other levels is often very difficult, so some variants are given with unambiguous phrases even in the classification. We can find various approaches (Psaraftis, 1995; Min et al., 1998). A very successful proposal for recording problems is presented in the publication (Cherif-Khettaf et al., 2015). The work mentioned proposes a formal notation of problems that would unify and simplify the identification. However, the use in theoretical practice is quite different. Therefore, moving in the direction of decision-making based on the VRP designation proved challenging to implement.

The draft concept is not intended to resolve the taxonomy of VRPs. The comparison of the different types of designations was outlined mainly because it was one of the options for designing the structure of the concept. However, due to the inconsistent notation, it cannot be taken as a classification system. All would have to use taxonomy uniformly. The above-mentioned publications help this. However, if this way of writing is not normatively addressed, the labeling is still different. The concept of three pillars, where the attributes of the VRPs are clearly defined, and sorting occurs based on these attributes, proved to be better.

The second direction is based on the correct distribution of system requirements, the structure of the given problem, and related requirements or optimization goals. Based on the parameters set in this way, a concept was created that includes all the mentioned areas.

The concept is divided into three fundamental pillars that are characteristic of VRP. The first pillar is basic system requirements and resources. The second pillar is the structure of the problem; the third pillar consists of constraints and optimization goals. The concept presented is not a tool for route optimization itself, nor does it explore using optimization methods and models as contributions. This supports an effective search and recognition of the type of VRP or a deeper analysis. Jablonský (2014) addresses a similar issue.

The classification itself serves as a framework for creating the concept's structure. Based on it, three pillars have been developed that contain the basic attributes for defining a VRP variant. A given problem is placed in each category, which, by its very nature, captures the essence of the VRP. Some VRPs are placed in several categories/sub-categories, while other specific VRPs are placed in only one category.

```
from ortools.constraint_solver import pywrapcp

def create_data_model():
    data = {
        'distance_matrix': [...],
        'demands': [...],
        'vehicle_capacities': [...],
        'num_vehicles': ...,
        'depot': 0
    }
    return data

def create_vrp_model(data):
    manager = pywrapcp.RoutingIndexManager(len(data['distance_matrix']),
                                           data['num_vehicles'],
                                           data['depot'])
    routing = pywrapcp.RoutingModel(manager)

    # Adding limitations and rules
def demand_callback(from_index):
        return data['demands'][manager.IndexToNode(from_index)]
    routing.AddDimensionWithVehicleCapacity(
        demand_callback,
        0,  # no capacity
        data['vehicle_capacities'],  # vehicle capacities
        True,  # start cumul to zero
        'Capacity')

return routing
```

Source: Own

Fig. 1: *Example of source code in Python programming language*

The first version is indeed intended for the already existing VRP variants according to the developed classification. The general approach to the extension includes requirements analysis, selection of a suitable open-source tool, implementation of the new type of VRP using available APIs and tools, definition of the new data structure, variables, and constraints, and testing and validation to ensure correctness and efficiency. In the case of this developed concept, the subsequent combination of new species and their integration into the concept structure will follow the following scenario:

1. Definition of categories/sub-categories representing new VRP types, for example, new types of vehicles or customers with new attributes.
2. Definition of the model using Python; new constraints and rules can be added using the API. The general Python code notation is shown in Figure 1.
3. Customizing constraints will require using annotations and custom rules to define new constraints and rules for optimization. For example, new constraints can be added for time windows, vehicle capacities, or special customer requirements.

When creating a concept, an important factor is identifying the target group for which the given tool is chosen. If the form is aimed at the professional public, the wording of the questions will not be understandable for students and the public. It is necessary to find such terms that it will not be necessary for an ordinary user to search for a long time or to get help from experts. The material created has a motivational, informative, and, finally, educational character. The form includes notes and explanations to ensure comprehensibility and overview, which may help understand the question correctly and assign the corresponding requirement or restriction.

Therefore, the tool will fulfill an educational function simultaneously. Due to the need to connect the theory and practice of using the tool, it is necessary to determine the target group to which the created tool can be presented and allowed to be tested. Furthermore, the tool will be subjected to a review to ensure a higher quality of the material created. After incorporating comments, an evaluation of the tool's contribution to theory and practice will take place.

3 Results

3.1 The Concept Structure

The advantage of the concept is the follow-up to the extensive research of VRP variants. The classification shows greater detail, as evidenced by the many sublevel series of VRP variants. The work provides enough information for the intended concept. The VRP variants are divided according to the characters into three main pillars. The listed pillars are processed into components at four levels of categories and subcategories so that each VRP can be included in at least one component. The branching of pillar categories is shown in Figure 2. The processing of information and decision-making materials can take many forms. The electronic version appears promising, considering the purpose of use, content, and importance for further use. In addition to ease of use, this version will ensure future updates.

1. System Requirements and Resources	2. Structure of the Problem	3. Specific Limitations and Objectives
1.1 Capacity	**2.1 Vehicles**	**3.1 Unserved customers**
1.1.1 exceed	2.1.1 one vehicle	3.1.1 one and more
1.1.2 not exceed	2.1.2 more than one vehicle	3.1.2 not exceed
1.2 Time windows	2.1.2.1 homogenous fleet	**3.2 Traffic conditions**
1.2.1 VRP without time windows	2.1.2.2 heterogeneous fleet	3.2.1 stochastic
1.2.2 VRP with time windows	2.1.3 non-specific number	3.2.2 dynamic
1.2.2.1 fixed delivery time	**2.2 Demand**	**3.3 Decision-making authority**
1.2.2.2 simple time windows	2.2.1 number of product types	3.3.1 driver
1.2.2.3 soft time windows	2.2.2 one commodity	3.3.2 dispatcher
1.2.2.4 multiple time windows	2.2.3 more different products	**3.4 Network level**
1.3 Pick-up/Delivery	2.2.4 location	3.4.1 single level
1.3.1 delivery only	2.2.4.1 on nodes (VRP)	3.4.2 two levels
1.3.2 pick-up and delivery	2.2.4.2 on edges (ARP)	3.4.3 three levels
1.4 Period	2.2.4.3 combination	3.4.4 multi-level
1.4.1 one day	**2.3 Cost of service**	
1.4.2 more days	2.3.1 time at the customer	
1.5 Warehouse type	2.3.2 loading/unloading	
1.5.1 depot	2.3.3 fixed costs	
1.5.2 warehouse	2.3.4 costs proportional to the size of the load	
1.5.2.1 backhaul	**2.4 Transportation costs**	
1.5.2.2 cross-dock	2.4.1 proportional distance	
1.5.2.3 combination	2.4.2 proportional to the transport time	
1.6 Stochasticity	2.4.3 another case	
1.6.1 known requirements	**2.5 Reverse logistics**	
1.6.2 random requirements	2.5.1 return services	
1.7 Circuit options	2.5.2 environmental improvement	
1.7.1 closed circuit	2.5.3 local dependency	
1.7.2 open circuit	2.5.4 service	
1.8 Specific requirements		
1.8.1 asymmetry		
1.8.2 priority		

Source: Own

Fig. 2: *The concept structure*

3.1.1 The First Pillar: System Requirements and Resources

The first pillar specifies the basic requirements of the VRP, which is one of the nine main types of VRP offered to the user.

Capacity – The default data for this requirement are the cases where the vehicle capacity is and is not exceeded.

Time windows – In this case, the problem can be solved with and without time windows, and the subsequent specification of the time windows includes a choice of simple time windows and costs that we add to the depot and individual customers, as well as time windows with a fixed delivery time, with a more significant number of time windows, and with soft time windows. The latter requirement allows for a slight discrepancy with the schedule.

Pick-up/Delivery lists two options: whether or not it is possible to return/store the commodity at the customer's place at the same time.

Periodicity – The type of route planning for one day or an extension for several days is considered here.

Warehouse – This is the definition of deliveries from one or more warehouses. Clarification is needed within the terminology. The depot indicates the starting depot from which the circuit is made and to which the vehicle is returned. By warehouse, it meant any warehouse, i.e., especially those located directly on the vehicle's route. As the next level of the Warehouse item, the type will be backhaul, cross-dock, or a combination thereof. The mentioned terms must be concerning their English names explained in the form.

Stochasticity within VRP is characterized by the presence of random data. For effective decision-making, known requirements are offered at the beginning of the process, and a variant is when all requirements are not known at the beginning. So, it is assumed that they will change during delivery.

Circuit options offer a closed circuit when the vehicle returns to the starting depot and an open circuit when it does not return to the starting depot after the end of delivery.

Specific requirements – In this category, VRP prerequisites that do not fall into the previous requirements but clearly define a specific type of VRP were included. This is the VRP asymmetry or customer priority order.

3.1.2 The Second Pillar: Structure of the Problem

The second pillar specifies the next level of the basic VRP selected in the first pillar in more detail based on the problem's structure. This is a classification in the second or third level of classification.

Vehicles must be specified in terms of number: one vehicle, a fixed number higher than one, and an unspecified greater number of vehicles. Furthermore, it is necessary to determine the type of fleet, whether it is homogeneous or heterogeneous.

Demand is represented by four subcategories. The number of product types (1) can be the transport of one commodity or several different products. The location of requests (2) can be on nodes (VRP), edges (ARP), or a combination of both. Service costs (3) can be equal when the vehicle stops at the customer's place, or they can be loaded/unloaded. Costs can be fixed or directly proportional to the size of the load. Transport costs (4) can be proportional to the distance and transport time, or it is negotiated in another case.

Reverse logistics considers the possibility of standard problems with time windows, local dependencies, problems involving service, and a multi-warehouse variant of the problem. The prerogative of reverse logistics is primarily the area of return services and issues related to improving the environment.

3.1.3 The Third Pillar: Constraints and Optimization Objectives

The formulation of specific limitations and objectives characterizes the third pillar. It generally leads to a narrow circle of problems that are privileged or unusual due to their mathematical model.

The number of unserved customers represents a selective limitation of the problem (Cherif-Khettaf et al., 2015). In this variant, not all customers are necessarily served, as the capacity of the vehicles does not allow this.

Traffic conditions must be specified, especially if they are stochastic or dynamic. Default problems do not consider traffic conditions.

Decision-making authority may be a vehicle driver on the route or an experienced dispatcher responding to stochastically or dynamically changing customer requirements.

Number of network levels – Most VRPs consider single-level networks (Cherif-Khettaf et al., 2015). Some variants enable multi-level networks within the management of supplier-customer chains. Intermediate warehouses usually handle this variant.

3.2 Decision-Making Environment

In the first phase, it was important to find the environment where the decision-making process would occur. Software programs have two fundamental disadvantages. The first one is a significant financial requirement. Another disadvantage is the dependence on the development company in case of any system change. Therefore, searching for a freely available environment directly guides users to download a program or application for free. However, this environment must meet the requirements set for it by the author of this publication. There is the option of a decision-making program or application, a web interface, or an environment like an e-shop where users can filter VRP according to various parameters.

3.2.1 Decision-Making Programs and Applications

The first variant is classic processing using **Excel/Google Sheets**, which offers a familiar environment where it is possible to create a table with products and various parameters and then use the filtering and sorting functions in Excel or Google Sheets. The given environment is readily available and, with the help of the other applications, allows for various multi-criteria decision-making options, as reported by Jablonský (2014). With the Excel **Solver add-in** and possibly the **Sanna** application, it is possible to perform multi-criteria evaluation of alternatives.

OpenRefine is open-source software for data editing and cleaning. Suppose the creator of the decision-making environment has programming knowledge in **program R** (Wickham & Grolemund, 2023). It is possible to create an interactive decision-making environment using packages such as **Shiny** (Chilimoniuk et al., 2024), which allows the creation of interactive web applications.

The **Python** programming language offers, as in the case of R, the creation of an interactive decision-making application using libraries such as **Pandas** for data manipulation and **Dash** (Jin et al., 2023) or **Streamlit** for creating interactive web applications.

Likewise the open-source **Anaconda** platform in R or Python (Kadiyala & Kumar, 2017) the **Airtable** platform offers data management options. It combines the properties of spreadsheet systems with database functionality and options for filtering and sorting data according to various parameters.

When creating an environment for deciding and filtering products online, it is possible to use **WordPress** together with the **WooCommerce plugin**, as seen in (O'Riordan et al., 2023). WooCommerce allows easy website management, including filtering products according to various parameters. WordPress is free, but WooCommerce often has hosting costs and plugin payments. With the increasing demands for Android smartphones and apps, this environment is very advantageous from a user perspective and a processing perspective, especially when converting a web interface to an equivalent mobile application (Dehghani & Kolahdouz-Rahimi, 2019).

The above-mentioned variants can offer the creator a space suitable for preparing a decision-making environment according to his needs and preferences. This will enable the creation of a decision-making module for users who will be able to filter individual VRPs according to various parameters.

3.2.2 Web Interfaces

The web interface is currently easily accessible. It offers the user an environment in which he is used to working and having fun, which is very promising. When placing the decision-making environment on a website, one can consider one of the many options offered.

A custom website with its code is the easiest option. VRP filtering is implemented on the web page using **HTML**, **CSS**, or **JavaScript**. This option will provide maximum flexibility but requires knowledge of web development.

Many **Content Management Systems** (CMS) with a plugin or extension allow you to create an environment for product decision-making and filtering. These are, for example, the aforementioned **WordPress**, **Joomla**, or **Drupal**. External services or APIs (services that are directly part of programming applications) provide data filtering and sorting functions integrated into custom web pages.

Creators' choice options are limited by knowledge and budget. Specific solutions can also be obtained by combining the various approaches mentioned. For example, a CMS with a plugin and custom code for further modifications is offered.

3.3 Database of Variants

A database is a table or list of data that allows for recording information and further work with it as needed. The given data must be related. By data, we mean data that specifies a given attribute. An attribute is a property monitored for a given VRP and must be recorded to distinguish it from other types. As a rule, they form table columns; they can take on different (predetermined) values or be of different data types. In this case, especially the verbal description. The primary key that identifies a record is the table row. This is a taxonomic designation or unambiguous phrase that indicates the type of VRP according to the previous classification.

The classification itself is created as a hierarchical data model. Data is organized into a tree structure. Each record represents a variant of the VRP in a tree structure, and the mutual relationship between the records is at several levels of breakdown. Finding data in a hierarchical database requires searching through the basic variant of VRP towards lower levels and back and to the sides to further lower levels. This entails a more complex operation of inserting and deleting records and a higher demand for data organization. The data stored in it must be consistent with the given rules. To effectively use the list, it is necessary to create a table (list) uniformly for all VRP variants. When creating the list, it is necessary to determine what information will be monitored. In the case of a list, these are items with a large amount of information, so the unity of the record is necessary for subsequent filtering. An empty entry cell indicates the selection of all values. Only data that meets the primarily defined criteria can be entered. It is necessary to respect the limitations of admissible information, or the data typeset for the value column. The previously defined three pillars and the subsequent description of the individual pillars' attributes will ensure integrity.

3.4 The Form

The form is a questionnaire that guides the user objectively through the fundamental division of VRP with simple questions. It then clearly specifies the classification of the problem using the questions of the second pillar. If further specification is needed to find the VRP variant, the queries of the third pillar, which brings with it the latest supplementary information, will serve. The form makes it easy for creators to display one whole line that does not fit on one screen. It is thus suitable for both filtering and data entry without having to scroll through many columns. Everything is presented in one dialog window. It also allows a quick entry form for updating databases and the like. Forms are used to work with data listed in the database.

In addition to text fields, forms can contain control elements such as checkboxes, selection lists, selector switches. The arrangement of individual elements in the form must correspond to the practical purpose of the search. A catalogue search engine option is offered when placing the form on the website – it acts with manually sorted lists of links organized into categories according to the type of link. The advantage is the fixed categories according to which the sorting takes place.

3.5 Data Filtering and Record Display

Data filtering is a helpful way to display only the data wanted or data that meets a particular condition or string of conditions. In this case, it will select an entry in the list that meets the criteria specified by the user. In the case of the concept, it will be extended filtering according to the criteria table of categories and subcategories. By selecting the criteria in the individual fields of the form, we specify the resulting condition for the filter.

A table is an area of criteria or conditions. Each record of the table is evaluated based on the given criteria. The record is filtered and displayed to the user if it meets the condition. The user-defined filter itself will not change or delete any of the records.

After filling out the form, the user will be shown possible VRP variants that meet the string of criteria he entered. At the same time, several relevant publications for the given type of VRP and possibly useful links are also displayed, further guiding the user to the selected type. It is also possible to insert a comment with explanatory information.

4 Discussion

Due to the vast number of VRPs and the variety of requirements, constraints, and optimization goals, it is difficult for the general public to specify or pinpoint exactly what problem they are looking for in their needs. For users without previous expertise, this topic is very complex. The trend of recent years is the use of artificial intelligence. The results presented by artificial intelligence need to be properly and professionally evaluated.

The article aims to present a quality elaboration of the concept of a tool for the decision-making process in determining the appropriate VRP variant based on the elaboration of the classification of individual variants of distribution problems. The classification is intended in the first stage to create the structure of the concept. In this phase, its role is crucial. In addition to populating the database with given VRPs, it is also a valuable source of search and supplementary information. As an additional use within the decision tool, it appears to be used to check the novelty of VRPs and classify new VRPs into the concept structure.

The first step is to correctly choose the decision-making environment that will be offered to the user. There are many options. The decisive aspect is user-friendly and simple processing and, of course, the creator's level of technical knowledge.

The working version is on the website created for the plan's layout. From the point of view of the knowledge of the processor, the decision-making environment will be created on the WordPress web interface, which has proven to be the most efficient, especially concerning the considerable number of templates.

Once the database is populated with the VRPs, the final task is to create a form for the user to search across the VRP categories and subcategories. The final step will be to present the user environment to a select group of students in Operations Research I and II courses and then to the public. Any inconsistencies or comments identified will be incorporated to improve the overall quality of the concept.

The concept can serve students to clarify the diverse field of operational research, researchers for deeper analysis and comparison of their research with materials published so far, and also the general public to create an idea. The concept will be freely accessible on the net and guide the user through a simple decision-making process based on the form. Fixed links or terms used directly in the English translation will be defined as notes or explanations. If the tool is intended to be usable by the general public, it is impossible to search for the translation or meaning of the mentioned phrases. With this step, the function of the concept will be upgraded from searching to education. This material can be used to support access to knowledge of distribution logistics and will offer an effective teaching tool. The user can look for connections between concepts in an environment close to him. Digital technology is an integral part of the work process for teachers, students, and researchers. Free web applications offer an efficient way to ensure and improve the quality of teaching.

Similar studies (Chen et al., 2024; Sun et al., 2022; Jena, 2024) have examined VRP classification and decision-making tools and emphasized the role of artificial intelligence in logistics optimization. However, in contrast to their approaches, the approach presented in this paper focuses on creating an accessible, user-friendly tool designed especially for people with no prior expertise.

The limitation of this study lies in its focus on a simplified decision-making process that may not fully account for complex real-world scenarios in which multiple conflicting constraints exist. A solution could be to use classification trees or neural networks instead of filtering.

Conclusion

The presented work is a logical outcome of the previous research on the classification of VRP and offers it as part of the decision tool concept. This is not a tool that optimizes VRP. The concept offers support in formulating the type of problem. Using simple questions, it evaluates the type of VRP and places it in the mentioned classification. It will also offer the user other options that could be the problem. Each result includes a general description and a small amount of research on the identified topic.

The benefit of such a decision-making environment is undoubtedly its educational function. It will offer the public, with no prior knowledge of a broad area of distribution logistics, only the segment that is suitable for the user based on their answers in the form. Thus, there is no need for a lengthy examination and comparison of the different VRP options. In addition to the selected range of VRP, the user will receive information on publications and other useful links related to the topic. This is another tool for students to check their practice in creating a qualification thesis.

The novelty of the research is mainly because it brings a complex topic closer to all those who will need the information, not only to the professional public who are well acquainted with the issue. For the aforementioned field of researchers, it can be beneficial in their own research as an easily accessible and multi-purpose supporting tool.

Fuzzy logic is being considered by the author in the future, which will make it possible to offer more types of VRP that meet the conditions specified by the user and variants with the probability of the correct choice. The user can then evaluate the percentage of his correctly determined problem.

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Ing. Květa Papoušková

KLASIFIKACE OKRUŽNÍCH DOPRAVNÍCH PROBLÉMŮ JAKO KONCEPT NÁSTROJE ROZHODOVÁNÍ V DISTRIBUČNÍ LOGISTICE

Článek navazuje na rozsáhlé zkoumání jednotlivých variant okružních dopravních problémů (VRP) v distribuční logistice. Cílem článku je využít dosavadní výzkum a vytvořenou klasifikaci VRP k návrhu nové koncepce rozhodovacího nástroje. Metodami výzkumu jsou analýza, syntéza, indukce, dedukce, komparace a expertní rozhovory. Nástroj bude schopen poskytnout rychlé informace odborné veřejnosti a uživatelům bez předchozích znalostí na základě vytvořeného a snadno dostupného rozhodovacího prostředí. V tomto článku jsou představeny uživatelsky flexibilní a zcela nebo částečně volné možnosti včetně struktury koncepce rozhodovacího nástroje. Umožní vývojářům připravit efektivní řešení, které uživatele provede databází VRP pomocí formuláře.

KLASSIFIZIERUNG VON TOURENPLANUNGSPROBLEMEN ALS KONZEPT FÜR EIN ENTSCHEIDUNGSINSTRUMENT IN DER DISTRIBUTIONSLOGISTIK

Der Artikel folgt einer umfangreichen Untersuchung der einzelnen Varianten von Vehicle Routing Problems (VRP) in der Distributionslogistik. Ziel des Artikels ist es, die vorhandenen Forschungsergebnisse und die entwickelte VRP-Klassifikation zu nutzen, um ein neues Konzept für ein Entscheidungsinstrument zu entwickeln. Die Forschungsmethoden sind Analyse, Synthese, Induktion, Deduktion, Vergleich und Experteninterviews. Das Tool wird in der Lage sein, der Fachöffentlichkeit und den Nutzern ohne Vorkenntnisse schnelle Informationen auf der Grundlage einer geschaffenen und leicht zugänglichen Entscheidungsumgebung zu liefern. In diesem Artikel werden benutzerflexible und ganz oder teilweise freie Optionen vorgestellt, die auch die Struktur des Konzepts des Entscheidungswerkzeugs umfassen. Sie ermöglichen es den Entwicklern, eine effiziente Lösung vorzubereiten, die den Benutzer mit Hilfe des Formulars durch die VRP-Datenbank führt.

KLASYFIKACJA PROBLEMÓW TRANSPORTU OKRĘŻNEGO JAKO KONCEPCJA NARZĘDZIA DECYZYJNEGO W LOGISTYCE DYSTRYBUCJI

Niniejszy artykuł opiera się na szeroko zakrojonych badaniach nad różnymi wariantami problemu transportu okrężnego (CTP) w logistyce dystrybucji. Artykuł ma na celu wykorzystanie istniejących badań i opracowanej klasyfikacji VRP do zaprojektowania nowej koncepcji narzędzia decyzyjnego. Metody badawcze to analiza, synteza, indukcja, dedukcja, porównanie i wywiady eksperckie. Narzędzie będzie w stanie dostarczyć szybkich informacji profesjonalistom i użytkownikom bez wcześniejszej wiedzy w oparciu o stworzone i łatwo dostępne środowisko decyzyjne. W tym artykule przedstawiono elastyczne dla użytkownika i w pełni lub częściowo bezpłatne opcje, w tym strukturę koncepcji narzędzia decyzyjnego. Umożliwią one programistom przygotowanie wydajnego rozwiązania, które poprowadzi użytkownika przez bazę danych VRP za pomocą formularza.

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Development of an Integrated Software Workflow for District Heating Network Planning: A Structured Methodological Approach

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Abstract

This article outlines the process of streamlining existing methods for conceptualizing and planning district heating networks (DHNs) by designing an integrated workflow. Existing solutions are often fragmented or lack accessibility and transparency. In this article, an integrated methodological approach combines Geographic Information System (GIS) supported spatial analysis of heat demands and potentials, generation and simulation of heating networks, and heat generator dimensioning within a unified workflow. The methodology is validated through case studies and aims to enable transparent and reproducible planning of sustainable heating networks. The developed approaches are the result of a preliminary research project funded by the Saxon State Ministry of Science, Culture and Tourism (SMWK) and they are implemented in the open-source software DistrictHeatingSim, which is publicly available on GitHub.

Keywords

District heating; Heat-supply; GIS; Optimization; Simulation; Pandapipes.

Introduction

The transition to renewable energy sources in heat supply systems is essential for reducing dependence on fossil fuels and achieving climate targets. DHNs are a key element in this transition, as they integrate diverse renewable heat sources, such as industrial waste heat, surface water heat, and large-scale solar thermal energy, with seasonal storage. By utilizing centralized heat production and distribution, district heating enables the economic and renewable heat supply in densely built urban areas by using various renewable energy sources that are not feasible for individual buildings, especially in city centers (Höffner & Glombik, 2024). Additionally, combined heat and power (CHP) systems integrated into DHNs offer higher efficiency, reducing CO_2 emissions and primary energy consumption (Gonzalez-Castellanos et al., 2018). However, planning and optimizing these networks remains a complex challenge that requires the integration of multiple disciplines, including technical, economic, and spatial analyses.

A well-designed DHN must be adaptable to local conditions while ensuring cost-effectiveness and reliability. The planning process involves determining optimal pipe routes, dimensioning generation and storage units and evaluating the economic feasibility of different system configurations. Spatial constraints, fluctuating heat demands, and potential and regulatory requirements further complicate the decision-making process. In this process, advanced computational methods, including thermo-hydraulic simulations and optimization models, are used. (Banze & Kneiske, 2024)

Existing solutions typically focus on specific aspects, such as network hydraulics, GIS-based demand mapping, or techno-economic assessments, but fail to provide an integrated workflow that supports all stages of the planning process. Many proprietary tools limit transparency due to their closed-source nature, restricting their use in research or concise planning (Hilpert et al., 2018; Howells et al., 2011). For many specific tasks, adequate open-source software solutions are available (Lohmeier et al., 2020; Panitz et al., 2022). However, those often lack desired functionalities, a generic data format compatible with other tools, and/or a graphical user interface for the end user.

This article documents the development of the open-source software DistrictHeatingSim for DHN planning that addresses these challenges. The article begins with an introduction to the importance of DHNs in the transition to renewable energy and the complexities involved in their planning. It then reviews existing software solutions, highlighting their limitations and the need for an integrated approach. The methodology section outlines the data integration and processing steps, including GIS-based spatial analysis and heat demand calculation. It also details graph-based algorithms for network generation and thermo-hydraulic simulations for network dimensioning. The techno-economic evaluation section discusses the cost assessment of different network configurations, ensuring economic feasibility. Finally, the results and discussion sections present a case study in Bad Muskau, validating the software's effectiveness and discussing its strengths and areas for improvement. This comprehensive approach aims to establish a standardized process for comparable results, reducing the time and effort required for planning while enhancing the comparison of different variants. It ultimately supports the development of sustainable and efficient DHNs and contributes to the broader goal of decarbonizing urban energy systems.

1 Literature Review

1.1 Scientific Approaches to District Heating Planning

District heating planning has seen significant advancements, with research focusing on network optimization, load modeling, and the optimization of heat generator operation. In a comprehensive study, Höffner & Glombik (2024) evaluated various energy system planning tools, particularly their applicability to urban energy systems and district heating. Their analysis highlighted the predominance of open-source tools utilizing Python or Modelica libraries, which can support various tasks across different planning phases. However, they identified a notable gap in multi-energy system planning in renewable energy integration.

For network modeling and optimization, Banze & Kneiske (2024) introduced the DAVE tool, a Python-based data fusion framework designed to automate the generation of customized energy network models. By leveraging open datasets, DAVE addresses the challenge of restricted access to real network data, which is often classified as critical infrastructure. The tool currently facilitates the creation of GIS-based power and gas networks compatible with standard simulation software, with plans to extend its capabilities to DHNs.

Vieth et al. (2025) present a comprehensive co-planning approach for DHNs that integrates operational considerations and techno-economic optimization. Their method uses real GIS data, a surrogate optimization algorithm, and dynamic simulations in Modelica. Similarly, Fuchs & Müller (2017) propose an automated model generation framework based on OpenStreetMap (2025), offering static and dynamic simulation capabilities. Both approaches provide technically detailed solutions and aim to enhance the accuracy of DHN planning models.

However, these methods are largely optimization-driven and rely on high input detail and specificity, which may not be available during early planning phases. For example, Vieth et al. (2025) apply heat demand data from a heat cadastre top-down to generate a parameterized simulation model. Based on this model, total system costs are calculated using predefined cost functions. While this provides valuable theoretical insights, it is often impractical in real-world planning contexts, especially because segment-specific cost data for DHNs (e.g., pipe installation costs by street segment) are typically unavailable at early stages or vary significantly depending on local conditions.

Wirtz et al. (2020) proposed a mathematical optimization approach for fifth-generation district heating systems. Their methodology emphasizes incorporating renewable energy sources and decentralized storage units to enhance operational efficiency and sustainability. Gonzalez-Castellanos et al. (2018) addressed the complexities of network-constrained CHP unit commitment. They developed strategies to optimize heat and power generation in response to dynamic network conditions, thereby improving the flexibility and reliability of CHP systems within DHNs. Panitz et al. (2022) explored software-supported investment optimization for DHNs using Mixed Integer Linear Programming from an economic and infrastructural perspective. Sollich et al. (2025) investigated pathways for decarbonizing existing DHNs through optimal retrofitting of production units. Their findings offer actionable insights into transforming traditional district heating systems into low-carbon energy solutions.

Sporleder et al. (2022) provide a broader perspective. They conducted a systematic review of optimization methods in district heating system design. Their analysis underscores the importance of integrating low-temperature heat sources, thermal storage solutions, and energy conversion technologies such as geothermal energy and large-scale heat pumps. Further elaboration on these topics is found in Sporleder's dissertation (Sporleder, 2024), which delves into developing tools to optimize district heating system design.

Another essential aspect of DHN simulation is load modeling. Common approaches include using Verein Deutscher Ingenieure (VDI, 2025) standard load profiles and load profiles for gas-based heating demand estimation (BDEW, 2024). Additionally, researchers such as Lombardi et al. (2019), Fischer et al. (2016), Büttner et al. (2022), and Kumpf (2016) have contributed to advanced demand forecasting techniques. However, these models need detailed usage behavior data, which is often unavailable.

These investigations demonstrate efforts to enhance district heating planning by employing interdisciplinary methodologies. By integrating geospatial analysis, thermo-hydraulic simulations, and techno-economic evaluations, researchers develop holistic frameworks for modern energy systems. Nevertheless, the absence of standardized protocols underscores the necessity for a systematic methodology.

1.2 Existing Software Solutions and Tools for District Heating Networks

Various proprietary and open-source software solutions have been developed for DHN planning, each addressing specific network simulation, optimization, or economic evaluation aspects. These tools can be broadly categorized into proprietary commercial and open-source modeling tools and frameworks.

1.2.1 Proprietary Software Solutions

STANET (2016) is traditionally widely used for thermo-hydraulic network calculations, while EBSILON (Iqony EBSILON, 2025) is used for energy system calculations. While both are robust calculation tools, they do not excel in integrated district heating planning. More recent software, like nPro (Wirtz, 2023) and VICUS Districts (VICUS Software, 2025), offer integrated spatial analysis, producer retrofitting and cost calculations. However, nPro lacks transient thermo-hydraulic calculation. VICUS Districts are restricted in delivering an integrated workflow and are more focused on thermo-hydraulic calculation of net and producers and 5th-generation low-temperature DHNs. Also notable are TOP-Energy (2025) and Edgar Energy (Edgar, 2025), proprietary energy system calculation software tools not specialized in district heating planning.

1.2.2 Open-Source Software Solutions

The push for open science and reproducible modeling has led to the development of several open-source tools, although most remain fragmented and do not provide an integrated workflow. Pandapipes (Lohmeier et al., 2020) is an open-source Python library for thermo-hydraulic simulations and delivers a node-based framework for heating network generation and calculation. Scenocalc Fernwärme 2.0 (Solites, 2017) and GHEtool (Peere & Blanke, 2022) offer specialized calculations for solar thermal and geothermal systems, respectively, but are not integrated with district heating planning. The Python software flixOpt (Panitz et al., 2022) enables investment and operational optimization yet is quite complex and requires extensive domain knowledge. EnSySim (Herling et al., 2022), developed in a previous project at HSZG, applies stochastic demand modeling for cellular energy systems. Sophena (GreenDelta, 2025) is an open-source planning tool for district heating with a UI and a database with producers and time-dependent calculations. However, it lacks GIS-based calculations, thermo-hydraulic calculations, and proper results. Additional open-source energy system modeling software such as City Energy Analyst (Fonseca, et al., 2025), oemof (Hilpert et al., 2018), EnergyPLAN (Lund et al., 2021), OSeMOSYS (Howells et al., 2011) provide various functionalities but lack interoperability and require extensive training for efficient usage.

1.2.3 Data Sources Available

Data availability is another critical factor influencing district heating planning. Various public datasets, including the Geothermal Atlas (Sachsen, 2025), PVGIS (EU Science Hub, 2025), Solarkataster (SAENA, 2025), and the new waste heat database (BAFA, 2025) provide valuable inputs for assessing renewable energy potential. Meteorological data from (DWD, 2025) further enhances the accuracy of simulation models by incorporating weather-dependent variations in heat demand.

1.3 Addressing the Need for an Integrated Methodology

Despite the availability of various tools, there is a notable absence of a unified solution that seamlessly integrates GIS-based network modeling, thermo-hydraulic simulation, and techno-economic evaluation. This fragmentation leads to limited interoperability and inflexible workflows, posing significant challenges in current research and practical applications.

Table 1 shows the main gaps identified in existing district heating planning tools and outlines how this work proposes to bridge these gaps.

Tab. 1: Identified challenges and solution approaches in the integrated methodology for district heating networks

Challenges identified	Proposed solution
Limited interoperability Existing open-source tools often focus on specific aspects, such as thermo-hydraulics or optimization, without offering an integrated workflow.	**Modular integration** Development of a modular framework that combines GIS-based spatial analysis, thermo-hydraulic simulation, and techno-economic evaluation into a cohesive workflow.
Restricted accessibility of proprietary software High costs and closed-source models limit the use of proprietary software in academic research and municipal energy planning.	**Open-source accessibility** Creation of a transparent, open-source framework that is freely accessible, promoting collaborative development and widespread adoption.
Lack of user-friendly and interactive solutions Many energy-modeling tools require extensive programming knowledge, making them less accessible to planners and decision-makers.	**User-friendly interfaces** Incorporation of visualization tools and interactive elements, enabling users to explore and optimize various district heating configurations without the need for advanced programming skills.

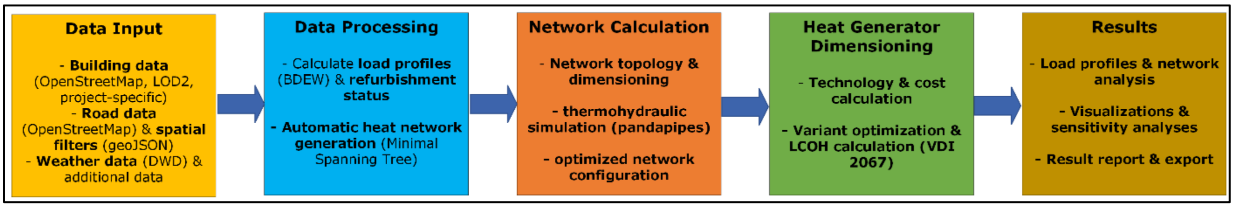
Source: Own

Table 1 highlights significant challenges. While these listed challenges are paramount, calculation algorithms and data processing steps are also critical. The proposed framework aims to directly address these challenges and provide a flexible, scalable, and transparent solution for sustainable DHN planning. This approach not only enhances reproducibility and accessibility but also empowers planners and decision-makers with intuitive tools to facilitate informed energy planning. It is important to note that this work does not aim to develop new optimization methods. Instead, it focuses on streamlining DHN generation, thermos-hydraulic simulation, and heat generation planning by integrating openly available data with project-specific data using automated, reproducible workflows.

2 Methodology

2.1 Data Integration and Processing

The proposed framework integrates multiple data sources and processing steps to enable a structured and transparent DHN planning workflow. As shown in Figure 1, a structured stepwise workflow is established to handle data acquisition, preprocessing, network modeling, and evaluation.



Source: Own

Fig. 1: *Overview of data sources and integration workflow*

The workflow was developed by reviewing previous projects, including one at the Zittau/Görlitz University of Applied Science in Görlitz. The methodology is illustrated using data from this project. Critical data (heat demand in Figure 2) is anonymized.

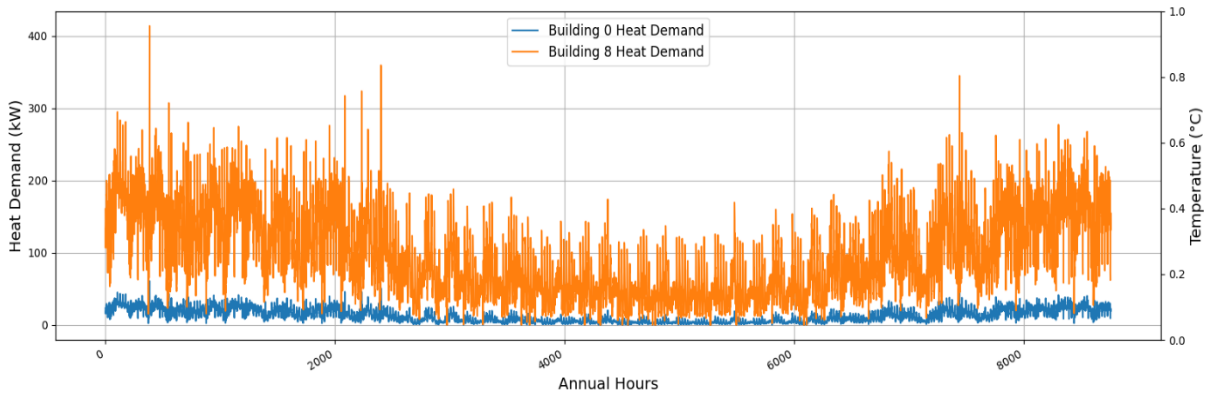
2.2 Data Acquisition and Preprocessing

A structured and consistent data acquisition process is essential for developing an accurate DHN model. The methodology integrates geospatial, infrastructure, and demand-related datasets for reliable network generation and simulation.

The first step in data acquisition involves identifying the buildings that will be part of the DHN. This is achieved by collecting building addresses, which are then geocoded using external services such as Nominatim (Hoffmann, 2025). The geocoding process converts addresses into precise latitude and longitude coordinates, ensuring that each building is accurately placed within the spatial model. Once the project area is defined, relevant geospatial data is retrieved from OpenStreetMap (2025). The two primary data sources include street networks, which provide the basis for pipe routing and building footprints, which define the heat demand distribution and network connection points. All spatial information is automatically converted to a unified coordinate reference system to maintain consistency across datasets. The methodology employs ETRS89 (ETRS89, 2008), ensuring high positional accuracy and compatibility with other geographic datasets.

For a reliable network simulation, heat demand data is required for each building. The most straightforward approach uses existing energy consumption data (e.g., gas, oil, electricity), which is often available for a given project area. This data directly estimates heat demand, simplifying the transition to district heating. The methodology incorporates BDEW standard gas consumption load profiles (BDEW, 2024) to further refine demand modeling. These profiles categorize different building types (e.g., residential, commercial, industrial) and generate time-dependent heat demand curves. This time-series heat demand data is crucial for dynamic simulations of the DHN, allowing for realistic load variations throughout the year.

Two examples of calculated heat demand curves with different building types and total heat demands are shown in Figure 2. Building 0 has a total heat demand of 108,000 kWh and is categorized as “GBD” (“other services”) by definition. Building 8 has a total heat demand of 825,000 kWh and is categorized as “HMF” (“apartment building”) by definition.



Source: Own, plotted in DistrictHeatingSim

Fig. 2: *Building load profiles*

This preprocessing step integrates automated geocoding, GIS processing, and standardized heat demand calculation to ensure a well-structured, accurate, and computationally efficient foundation for the subsequent network generation and simulation phases.

2.3 Network Generation Using Graph-Based Optimization Algorithms

The generation of DHNs in this work is not aimed at finding an optimal or cost-minimal layout in a strict mathematical sense. Instead, the goal is to automatically generate spatially plausible network structures that follow existing road geometries and realistically connect relevant buildings. This allows for a fast and reproducible estimation of pipe lengths, which serves as a basis for subsequent thermo-hydraulic simulation and cost analysis. The proposed method leverages OpenStreetMap street data and building locations to identify feasible pipe routing paths. Since buildings are often set back from the road, each is first connected to the nearest point on the street network to ensure physically plausible pipe entry points.

To construct the network structure, a Minimum Spanning Tree (MST) algorithm is used as a baseline to ensure that all connections are covered with minimal total length. However, the MST is not used as a final network or interpreted as an optimized solution. Instead, it provides a simple and computationally efficient approximation of a connected network. In a post-processing step, the resulting tree is adjusted to better align with the actual street layout using street points as additional nodes for a more detailed MST. This ensures that the resulting pipe segments are technically feasible and suited for further hydraulic modeling using tools like pandapipes (Lohmeier et al., 2020). This approach reduces the modeling effort while maintaining sufficient realism for early-stage cost and performance estimation. Examples of the initial and adjusted network layouts are shown in Figures 3 and 4 respectively.

Source: Own, plotted in DistrictHeatingSim

Fig. 3: *Automatically generated network structure on the example in Görlitz*

Source: Own, plotted in DistrictHeatingSim

Fig. 4: *Post-processed generated network structure on the example in Görlitz*

Despite algorithmic generation, final adjustments may be required based on specific project constraints. The methodology integrates interactive refinement capabilities through a Leaflet.js-based interface (Agafonkin, 2025) embedded in the PyQt5-GUI (Python GUIs, 2025). Users can visualize, modify, and validate the generated network within an HTML-based interactive environment. Additionally, the network can be exported in GeoJSON format (GeoJSON, 2016) for external modifications in other GIS software like QGIS, allowing planners to fine-tune the layout based on site-specific requirements. This combined automated and interactive approach balances computational efficiency and practical adaptability, enabling planners to generate and refine DHNs in a structured workflow quickly.

2.4 Thermo-Hydraulic Simulation and Dimensioning of Supply Systems

The thermo-hydraulic simulation of DHNs is crucial in ensuring efficient and reliable heat distribution. The developed methodology leverages the pandapipes framework to model and analyze network performance under various operating conditions. The simulation involves several key computations like pressure drop calculations across the pipe network to assess hydraulic feasibility and identify potential bottlenecks or temperature distribution analysis, ensuring supply temperatures remain within acceptable limits throughout the network. These calculations allow for a network design that minimizes thermal losses while maintaining operational efficiency.

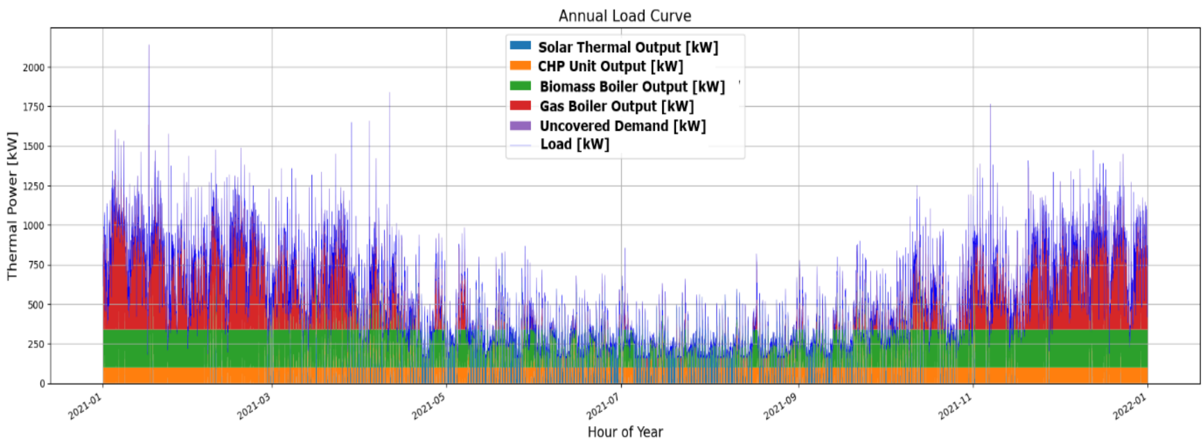
Beyond the core pandapipes capabilities, additional functionalities have been integrated to enhance the simulation process. A direct import of GeoJSON files to a pandapipes net was established for fast data processing, allowing seamless integration of network layouts generated in previous processing steps. Advanced control algorithms to improve system stability under fluctuating load conditions were designed for net calculation with pandapipes. A low-temperature network implementation, including decentralized heat pump integration, was developed to evaluate alternative supply strategies and enhance energy efficiency. These enhancements ensure the simulation framework is adaptable to various district heating configurations. The thermo-hydraulic simulations generate important outputs such as dimensioned pipe networks and calculated heat losses, providing insights into thermal performance and energy efficiency. Further time-series results for supply and demand, allowing for dynamic analysis of network behavior over different operational scenarios, are saved.

During development, extensive testing of pandapipes was conducted to validate model accuracy and identify potential improvements. Issues encountered during simulations were reported back to the pandapipes developers, who contributed to refining the framework and ensuring its robustness.

2.5 Techno-Economic Evaluation

A hierarchical approach is applied to model heat generators and simulate the operation of the energy system, balancing computational efficiency with flexibility. This methodology allows for assessing various configurations, including CHP units, heat pumps, solar thermal collectors, geothermal probes, waste heat, and conventional boilers. Simulations are conducted for an entire year to capture the fluctuations in heat demand and supply, accounting for external factors such as ambient temperature and solar availability. For the resulting load profile, the contributions of all heat generators are accumulated according to their control strategies. More complex control strategies combined with seasonal thermal energy storage are currently under development.

Figure 5 shows an example of a simulated load profile and how the hierarchical control strategy meets the demand at each time interval throughout the year.



Source: Own, plotted in DistrictHeatingSim

Fig. 5: *Load Simulation of Heat Generation*

The levelized cost of heat is calculated according to the VDI 2067 (VDI, 2025) methodology to enable a standardized cost comparison. This metric provides insights into the overall cost-effectiveness of each configuration by considering lifetime energy production, investment amortization, and operational costs. Publicly available cost databases such as (KEA-BW Klimaschutz- und Energieagentur Baden-Württemberg GmbH, 2024) and real-world project data are used to ensure realistic input parameters. The simulation results are presented through interactive dashboards, allowing for scenario-based comparisons of different network configurations. These dashboards visualize key performance indicators such as total investment, annual operational costs, system efficiency, and CO_2 savings. Stakeholders can explore multiple planning options, adjust parameters dynamically, and identify the most cost-effective and sustainable solutions. This approach does not aim to find a mathematical optimum but instead prioritizes flexibility and transparency for stakeholders in exploring planning options.

3 Results

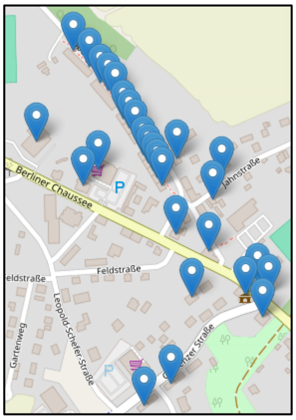
A case study was conducted using real-world data from a district in Bad Muskau, a German city located in Saxony at the Neisse River, where conceptualization of heat distribution options is currently being evaluated in a project between the Zittau/Görlitz University of Applied Sciences and the Ver- und Entsorgungswerke Bad Muskau GmbH (VEWBM, local energy supplier) to validate the developed Software methodology for fast variant generation. The local specifics regarding the study area and data sources are described in Table 2.

Tab. 2: *Bad Muskau's case study specifics*

Geographical scope	The case study covers an urban area with mixed residential, commercial, and public buildings.
Heat demand data	VEWBM supplies all buildings with gas, providing access to annual demand data. A GIS-based analysis incorporating OpenStreetMap data was utilized to estimate the spatial distribution of heating demand.
Heating network infrastructure	There is no existing heating infrastructure in place.
Renewable energy potential	The feasibility of integrating local biomass, profound geothermal energy, and water thermal energy from the Neisse River was examined. Due to space constraints, large-scale solar thermal energy is not feasible, and waste heat sources are unavailable.
Special features	Bad Muskau is part of the UNESCO World Heritage site "Muskauer Park / Park Mużakowski" which presents challenges for establishing heat generation sites due to preservation.

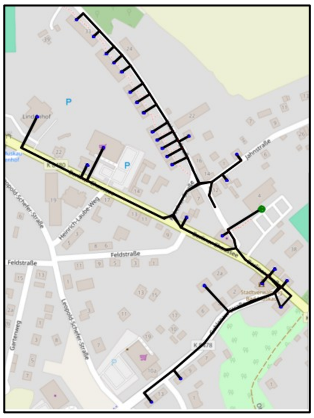
Source: Own

The Methodology outlines that the first step involves collecting the buildings in the considered area. VEWBM provided the buildings, corresponding addresses, and their gas usage for heating and warm water. Figure 6 shows the geocoded addresses. For an initial calculation, the location of a single heat generator was chosen to be at an old supermarket site. The resulting network is shown in Figure 7.



Source: Case study Bad Muskau, plotted in DistrictHeatingSim

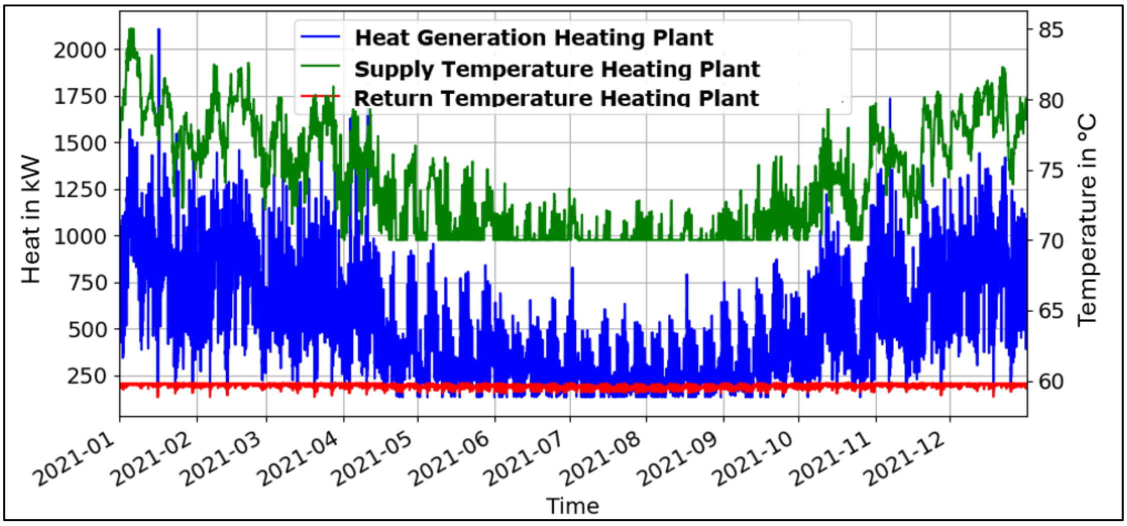
Fig. 6: *Building positions*



Source: Case study Bad Muskau, plotted in DistrictHeatingSim

Fig. 7: *Generated net structure*

A network configuration simulation was conducted with the network generated, providing data on pressure losses across different pipe diameters, temperature profiles, and heat losses along the network. Figure 8 shows the results from the time series calculation within DistrictHeatingSim. The results for the heat generation (heat input in the network), supply temperature, and return temperature are plotted. The supply temperature is calculated using a linear control strategy based on the air temperature from the weather data. In this case, the return temperature is 60 °C for the heat consumers and, therefore, lower at the central return point.



Source: Own, plotted in DistrictHeatingSim

Fig. 8: *Results of thermo-hydraulic net simulation of Bad Muskau*

Based on the calculation results, investment and operational costs were evaluated for different scenarios using VDI 2067 (VDI, 2025) cost models. The scenarios were modeled as shown in the example in Figure 5. With generators dimensioned and heat production calculated, the levelized heat cost was calculated for these multiple configurations. Furthermore, sensitivity analyses assessed the impact of energy price fluctuations and infrastructure costs. The tool was also used to generate different visualizations for the project. Several results can be extracted, but final data is not yet available since the project is ongoing. The developed codebase is available on GitHub as DistrictHeatingSim (Pfeiffer, 2025).

4 Discussion

The georeferencing of heat demand data during preprocessing, combined with the automatic generation of GIS data in the GeoJSON format, enables the rapid creation of a thermo-hydraulic model. Configuration options allow the generation of multiple variants based on input data, which then can be effectively stored. Utilizing the comprehensive framework built around pandapipes, efficient network and time-series calculations are achievable, supporting various network configurations such as decentralized heat pump cold nets and multiple producer locations. The network calculations yield critical key performance indicators, including heat loss and power consumption of circulation pumps.

Following these calculations, the dimensioning of heat generators can be performed using extensive calculation options. Cost calculations for pipes and heat exchangers can be directly derived from the GIS data, assuming cost per meter for pipes and per kilowatt for heat exchangers (installation costs included). Various calculation options are available for generators and optimization processes. The software supports the generation of multiple plots to export the most important information.

The software also supports renewable energy integration by enabling scenario analysis for incorporating waste heat, solar thermal, and heat pumps (using geothermal or aqua thermal heat). This feature is crucial for simulating low-carbon energy systems. Another key strength of the methodology is that it promotes transparent decision-making by providing precise and reproducible results. Planners and policymakers can engage in informed discussions through interactive visualization tools, leading to more effective and inclusive energy planning processes. Another important feature of the developed software is serialization, which enables users to save their work on the file system and load it into the software once they want to continue their work.

The findings align with previous research highlighting the importance of integrated approaches in DHN planning. For instance, Höffner & Glombik (2024) emphasized the need for transparent and reproducible planning processes, a core principle of our developed methodology. Similarly, Banze & Kneiske (2024) demonstrated the benefits of automating network generation using GIS data, a feature central to our framework. While the current work has streamlined and accelerated processes by integrating existing algorithms, which have been effective for steps previously done manually or with various tools, including Excel, it is important to note that the focus was not on optimizing individual calculation steps. Therefore, further comparisons with existing algorithms are not meaningful at this point.

Currently, the computational complexity is limited to smaller DHNs. Large-scale DHNs require significant computational resources, particularly for time-series simulations and optimization models. Ensuring a balance between computational efficiency and model accuracy remains challenging, especially when dealing with high-resolution thermo-hydraulic calculations with pandapipes. The implementation performs slowly for more extensive networks due to inefficiencies in the additional control algorithms integrated into the pandapipes calculation. Some have already been replaced within pandapipes through development going forward. Further improvements in algorithmic efficiency and parallel computing techniques could help address this issue in DistrictHeatingSim. User accessibility is another area for improvement. However, future development should focus on user-friendly interfaces and automated workflows to support non-expert users, making the tool more accessible to a broader audience, including municipal planners and smaller energy providers.

Conclusion

This article presents an integrated methodology for DHN planning that combines GIS-supported spatial analysis, thermo-hydraulic simulations, and techno-economic assessments into a cohesive open-source framework. The developed approach provides a comprehensive and adaptable planning tool. Its modular design ensures flexibility, allowing for region-specific adaptations in the future while supporting the integration of renewable energy sources in district heating systems. By fostering transparency and reproducibility, the framework promotes collaboration and broader adoption, bridging spatial analysis, network modeling, and cost assessment to streamline the planning process. Furthermore, it enhances decision-making for urban planners by providing evidence-based scenario analysis and supporting long-term energy transition strategies.

While the methodology demonstrates significant potential, several areas for further research and development remain. Refining network generation algorithms by incorporating a Steiner tree modeling approach, machine learning, or other heuristic methods could improve network layout generation based on multiple variables. The current algorithm cannot generate meshed networks, which would help optimize net hydraulics. Expanding case study applications across more projects with different boundary conditions will help validate the software's adaptability and effectiveness. Additionally, improvements in automation and user-friendliness, such as intuitive graphical interfaces and real-time data integration, would make the tool more accessible to non-expert users. Further integration with multi-energy systems, including electricity, seasonal storage, and demand response mechanisms, could extend the framework's applicability, particularly in hybrid heating solutions that combine district heating with decentralized technologies. More precise benchmarks must be established for future work to assess process efficiency and enable qualitative and quantitative comparisons with other software tools.

The methodology and software DistrictHeatingSim form a basis for future district heating system research. In the short term, efforts will focus on validating methods and improving data and error handling in the workflow. Long-term goals include optimizing urban energy systems and considering heat, gas, electricity, and buildings. This framework aims to enable sustainable and efficient urban heating systems, contributing to transparent and flexible district heating planning and supporting the move towards decarbonized urban energy infrastructures. The software is available on GitHub for contributions, further information, and documentation (Pfeiffer, 2025).

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Vývoj integrovaného softwarového pracovního postupu pro plánování sítě dálkového vytápění: Strukturovaný metodický přístup

Tento článek popisuje proces zefektivnění stávajících metod koncepce a plánování sítí dálkového vytápění (SDV) prostřednictvím návrhu integrovaného pracovního postupu. Stávající řešení jsou často roztříštěná nebo nedostatečně přístupná a transparentní. V tomto článku integrovaný metodický přístup kombinuje prostorovou analýzu požadavků a potenciálů tepla podporovanou geografickým informačním systémem (GIS), tvorbu a simulaci tepelných sítí a dimenzování generátorů tepla v rámci jednotného pracovního postupu. Metodika je ověřena na základě případových studií a jejím cílem je umožnit transparentní a reprodukovatelné plánování udržitelných tepelných sítí. Vytvořené přístupy jsou výsledkem výzkumného projektu financovaného Saským státním ministerstvem pro vědu, kulturu a cestovní ruch a jsou implementovány v softwaru DistrictHeatingSim s otevřeným zdrojovým kódem, který je veřejně dostupný na GitHubu.

Entwicklung eines integrierten Software-Workflows für die Planung von Fernwärmenetzen: Ein strukturierter methodischer Ansatz

In diesem Beitrag wird die Entwicklung von Methoden und Software für die Konzeption und Planung von Fernwärmenetzen vorgestellt. Bestehende Lösungen sind oft fragmentiert oder es mangelt an Zugänglichkeit und Transparenz. In dieser Arbeit wird ein integrierter methodischer Ansatz vorgeschlagen, der die GIS-gestützte räumliche Analyse von Wärmebedarf und -potenzialen, die Erstellung und Simulation von Wärmenetzen sowie die Dimensionierung von Wärmeerzeugern in einem einheitlichen Arbeitsablauf kombiniert. Die Methodik wird anhand von Fallstudien validiert und zielt darauf ab, eine transparente und reproduzierbare Planung von nachhaltigen Wärmenetzen zu ermöglichen. Die entwickelten Ansätze sind das Ergebnis eines vom Sächsischen Staatsministerium für Wissenschaft, Kultur und Tourismus (SMWK) geförderten Vorlaufforschungsprojekts und sind in der Open-Source-Software DistrictHeatingSim implementiert, die auf GitHub öffentlich zugänglich ist.

Opracowanie zintegrowanego oprogramowania do planowania sieci ciepłowniczej: Ustrukturyzowane podejście metodologiczne

W niniejszym artykule opisano proces zwiększenia efektywności istniejących metod projektowania i planowania sieci ciepłowniczych. Istniejące rozwiązania są często rozproszone lub nie są wystarczająco dostępne i przejrzyste. W niniejszym artykule zaproponowano zintegrowane podejście metodyczne, które łączy opartą na systemie informacji geograficznych (GIS) analizę przestrzenną zapotrzebowania na ciepło i potencjału, tworzenie i symulację sieci ciepłowniczych oraz wymiarowanie urządzeń grzewczych. Metodyka została zweryfikowana na podstawie studiów przypadków i ma na celu umożliwienie przejrzystego i powtarzalnego planowania zrównoważonych sieci ciepłowniczych. Opracowane podejścia są wynikiem projektu badawczego finansowanego przez Saksońskie Ministerstwo Nauki, Kultury i Turystyki i zostały wdrożone w oprogramowaniu open source DistrictHeatingSim, które jest publicznie dostępne na GitHub.

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Barriers and Strategies for Enhancing Eucalyptus Timber Utilization in Ethiopia

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Abstract

Although Eucalyptus was introduced to support Ethiopia's timber production forestry, various barriers hinder its use as an alternative to imported wood. This article's primary aim is to identify key challenges in eucalyptus timber utilization and propose strategies for improvement based on the literature review. The finding indicated technological, economic, social, and policy-related barriers. Secondary data were collected by reviewing scholarly sources from November 2024 to January 2025. Keywords were used to search in Scopus and Web of Science scientific databases and Directory of Open Access Journals (DOAJ). Findings show that the identified challenges limit the utilization of eucalyptus timber. To enhance sustainability, stakeholders should advance wood processing technologies and implement supportive policies and financial incentives.

Keywords

Forest product; Challenges; Approaches; Demand; Wood industries; Ethiopia.

Introduction

Globally, demand for wood products, mainly round wood, is predicted to reach 6 billion m^3 by 2050 and will be the primary driver for expanding industrial plantations (Barua et al., 2014). Plantations, forests, and ecosystems provide essential raw materials, vital habitats, and cultural landscapes that meet diverse social and environmental needs (Rodriguez et al., 2014). Ethiopia has a vast, ancient, and unique repository of non-timber and timber resources, providing the foundations for environmental welfare and rural economic stability (Kebbede, 2016). An important basis for developing various industrial sectors is the availability of predefined basic materials (Stock et al., 2018). Ethiopia is a fast-developing African country, and its economy has been growing smoothly for the last 15 years, with an annual Gross Domestic Product (GDP) growth rate of 7–8%, substantial increases in the GDP contributions of both service and agricultural sectors, and a minor contribution from the industrial sector (Schmidt et al., 2018). The industrial sector accounts for approximately 8% of Ethiopia's GDP, and the country's potential for producing wood and wood products remains untapped (World Bank, 2018). The high rural population provides a strong labor supply that heavily relies on agriculture, leading to significant demands for forest-based products. There has been an increasing demand for wood products, which often depend on imported wood, primarily from pine and oak trees, to meet the population's growing needs. This situation presents challenges in effectively utilizing and managing the abundant eucalyptus tree resources in the country (Bayle, 2019). *Eucalyptus* was first introduced to Ethiopia during the regime of

Emperor Menelik II (1868-1907) in 1895 to solve the critical shortage of fuel wood and construction materials in Addis Ababa and other towns in the country (Bahru et al., 2023; Dessie et al., 2019; Gil et al., 2010). In Ethiopia, eucalyptus species such as *E. amygdalina, E. bicola, E. camaldulensis, E. incrassata, E. globulus, E. melliodora, E. resinifera, E. rudi, E. salubris, E. cladocalyx, E. cornata, E. diversicolor, E. leucoxylon, E. patens,* and *E. tereticornis* were the first to be brought to Ethiopia (Alemayehu & Melka, 2022). Since its successful introduction, eucalyptus species have spread throughout much of Ethiopia, becoming a vital component of most farming systems in the country. They have dominated the landscape and emerged as one of the most significant tree species. Eucalyptus has become widely distributed across the nation. It is utilized as a substitute raw material to meet the increasing demand for various forest products, including fuelwood, composites, and materials for industrial and construction purposes. Eucalyptus wood, known for its strength, resilience, and pest resistance, produces fuelwood, charcoal, poles, posts, essential oils, and other items (Birhanu & Kumsa, 2018; Gil et al., 2010).

The two most common species of eucalyptus in Ethiopia are Eucalyptus camaldulensis and Eucalyptus *globulus*. Eucalyptus *camaldulensis* is more common at lower altitudes, while Eucalyptus *globulus* is more common at higher altitudes (Dessie et al., 2019). Many Ethiopian farmers and wood lot growers now use it as their main species because of its high adaptability, low soil fertility, ability to withstand fire, insect, and browsing animal damage, wide distribution, even on degraded lands, and socioeconomic contribution as a high-yielding cash crop with short rotation.

Ethiopia's wood industries play a crucial role in the country's economy, providing employment opportunities, contributing to national income, and meeting the demand for wood-based products (Daba, 2016). However, the deficit of wood supply in Ethiopia has been a major issue, resulting in significant increases in the price of domestic wood and fuelling a high demand for imported wood products (Girma & Abate, 2021). This situation has prompted the development of the wood industry in Ethiopia to explore potential alternative wooden products. Eucalyptus timber is particularly promising due to its short growth cycle and ability to thrive in various country regions. Given the decline in local timber species and the increased demand for forest products, well-managed eucalyptus species may rank among Ethiopia's best substitutes (Wassie, 2020). Eucalyptus plantations account for 58% of the total area, covering approximately 506,000 hectares (Dessie, 2011; Getahun, 2003). This is followed by Cupressus at 29%, Juniperus procera at 4%, and pines at 2%. In Ethiopia, the species Eucalyptus camaldulensis, Eucalyptus globulus, Eucalyptus grandis, and Eucalyptus saligna are commonly planted (Tesfaye et al., 2020). When these trees are planted in degraded areas with the appropriate density and management practices, they can effectively address the scarcity of wood products for both domestic and commercial use while preserving environmental balance (Muthuri et al., 2023; Pirard et al., 2016; Rajesh Kumar & Rekha, 2024).

Eucalyptus wood is foundational for various sectors, including pulp manufacturing, paper production, and plywood particle board. Due to its strength, it is utilized in joinery, flooring, roofing, and structural framing (Lee et al., 2024; Lee et al., 2022). However, several challenges that must be addressed hinder Ethiopian wood industries from eucalyptus timber utilization (Ghani & Lee, 2021). Many furniture manufacturers in Ethiopia are unfamiliar with the eucalyptus's properties and potential applications in the country's wood industry. Furthermore, the unique characteristics of eucalyptus wood may necessitate specialized processing techniques that are not readily available in Ethiopia. Consequently, eucalyptus is not commonly used for furniture manufacturing in the country despite being a popular alternative to traditional timber species in many other parts of the world (Kaba et al., 2018).

The degradation of land resources is causing severe problems in most highlands and lowlands of Ethiopia. Though magnificent developments are in increasing agricultural production and productivity, the forestry and green energy sectors are still lingering to bridge the energy and construction demand of the growing population (Wassie, 2020). *Eucalyptus* is widely planted due to its ability to meet the growing demand for fuelwood and building materials and its various other uses (Birhanu & Kumsa, 2018; Yimam et al., 2024). For example, in south-central Ethiopia, *Eucalyptus* trees provide over 100% of the construction wood, 20% of the charcoal, and 93% of other wood products (Alemu, 2016). A similar investigation conducted in the Lake Plain area found that *Eucalyptus* was used primarily for fuel wood, income generation, and construction, with little regard for environmental conservation.

Several studies conducted in Ethiopia have emphasized the significant economic importance of the *Eucalyptus* tree (Belachew & Minale, 2025; Zegeye, 2010). Despite prioritizing *Eucalyptus* for various socioeconomic benefits to sustain rural households' income and food security, particularly in harsh conditions, those studies overlook its barriers and strategies of enhancing the Eucalyptus tree for timber utilization. Hence, identifying potential barriers and proposing strategies for enhancing Eucalyptus timber utilization could help intensify the alternative use of wood industries and bring sustainable development to the nation. Therefore, this literature review aims to identify the main barriers to utilizing eucalyptus wood in Ethiopia's wood industry and suggest alternative solutions.

In summary, Eucalyptus plays a crucial role in Ethiopia's economy by meeting the high demand for fuel wood, construction materials, and other wood products, particularly in rural areas. However, the forestry and green energy sectors struggle to bridge the growing energy, and construction demands despite their economic benefits. Studies highlight its widespread use for income generation and construction, but little attention is given to its environmental impact or challenges in timber utilization. The literature review (see Section 1) identifies barriers to eucalyptus timber use and proposes strategies for improvement to promote sustainable development. The literature review methodology (see Section 2) uses keywords searched in reputable scientific databases such as Scopus, Web of Science, and DOAJ. The results (see Section 3) are followed by the discussion (see Section 4) analyzing previous similar research on eucalyptus utilization in Ethiopia, the limitations of this study, and its conclusion.

1 Literature Review

1.1 The History of Eucalyptus in Ethiopia

The name "Eucalyptus" is derived from two Greek words: "eu" meaning "well", and "kalyptos" meaning "hidden" or "well-covered". This name was given by the French botanist Jacques-Julien Houton de La Billardiére, who classified and named the species in 1799. The evergreen species of Eucalyptus are distinct from shrubs and multi-stemmed trees due to their height, with some growing up to 60 meters tall and thriving at altitudes above 1,850 meters above sea level (Belachew & Minale, 2025). In Ethiopia, the natural plantations of Eucalyptus could have disappeared without these benefits. The tree plays a crucial role in the socio-economic dimensions of many Ethiopian communities. For many years, Ethiopians have relied on Eucalyptus as a primary source of construction material for houses. This fast-growing tree has provided goods and services enabling livelihood development and generating income opportunities for various localities.

Eucalyptus was introduced to Ethiopia in the late 19th century as a sustainable solution to the capital city's firewood and construction timber shortages. Over the years, it has proliferated nationwide, creating significant economic opportunities for many households. Additionally, its cultivation has played a vital role in minimizing deforestation, contributing to environmental conservation efforts (Belachew & Minale, 2025). There are over 900 species of Eucalyptus, but only about 100 are economically significant. The tree is widely cultivated for its wood, paper pulp, gum, and medicinal oil (Malakar, 2024). It was first introduced to Portugal four centuries ago and has since become widely distributed throughout Europe, Latin America, Asia, and Africa. Then, at later ages, the tree was disseminated in various highlands of Ethiopia, and it has gained popularity due to its strong potential to adapt to various ecological settings and from fertile to degraded lands. Its fast-growing nature has also made it an economically viable tree species in the country.

1.2 The Importance of Eucalyptus Timber over Imported Woods

Eucalyptus offers numerous benefits to various countries, including fuelwood, charcoal, poles, posts, essential oils, and paper and pulp for manufacturing. It also provides nectar for bees, shade for animals and humans, and serves as a windbreak.

The choice between eucalyptus and imported wood ultimately depends on the final product's specific application, budget, and desired characteristics. Hence, it must address the technological, technical, economic, social, and policy-related barriers hindering the Ethiopian wood industries on eucalyptus timber utilization. It may be beneficial to conduct specific comparisons based on eucalyptus' intended use and local availability versus imported woods. When comparing eucalyptus timber to imported wood products in terms of quality, several factors need to be considered, including physical properties, durability, workability, and suitability for various applications. Eucalyptus wood is known for its high density and hardness, making it difficult to work using traditional and straightforward woodworking tools (Kaba et al., 2018).

2 Methodology

This review article was developed by researching keywords such as eucalyptus, challenges, strategies, demand, supply, and forest products. Relevant information was gathered from reputable journal articles in scientific databases Scopus, Web of Science, and the DOAJ, a unique and extensive index of diverse open access Journals. The data were then organized into a personal EndNote library database. The review article is based on a comprehensive analysis of the related literature from various materials. The secondary data were collected from November 2024 to January 2025 through an extensive review of scholarly articles, reports, books, and online resources. Additional references were identified by examining the bibliographies cited in the collected literature. This review study extracted data from the Scopus, Web of Science, and DOAJ databases. Criteria were established to select publications for a detailed review, focusing on their relevance to the barriers and strategies for improving Eucalyptus timber utilization in Ethiopia.

Twenty-two documents were critically reviewed based on search keywords, such as challenges and prospects for improving eucalyptus timber utilization. The most relevant documents addressed the roles of forests, livelihoods, non-timber forest products, and their implications in Ethiopia. Only documents published in English were considered to ensure consistency in understanding and analysis. Studies published within the last 10 years, from 2014 to 2024, were included to ensure the relevance and timeline of the information. Documents that do not directly discuss the barriers and strategies of eucalyptus timber utilization in Ethiopia and documents published outside the specified date range were excluded, as they may not reflect current trends or knowledge in the field. Non-English documents that could not be accurately translated or understood were also excluded.

3 Results

3.1 Eucalyptus and the Need for Alternative Timber Species

Diversifying the timber supply with alternative species ensures a more resilient and adaptable wood industry, reducing vulnerability to fluctuations in the availability and prices of specific timber species (Girma & Abate, 2021). Although there are more than 300 Indigenous, fast-growing, and exotic tree species that may be used to produce a range of wood products in Ethiopia, 85% of the wood demand has been covered by limited commercially important indigenous timber species and imported woods that were becoming endangered (Kaba et al., 2018; Kaba & Desalegn, 2020).

Alternative timber species with unique properties, colors, and grain patterns offer opportunities for diversifying wood products and meeting consumer preferences in domestic and international markets (Lahr et al., 2018). It also encourages the innovation of wood industries in product development, design, and manufacturing processes (Skorupińska et al., 2024; Stendahl, 2009). According to a study conducted in central Ethiopia by (Alemayehu & Melka, 2022; Daba, 2016), the main reasons why farmers plant eucalypts were the following: the growing demand for wood products, the scarcity of wood, their high biomass production rate, their ease of cultivation and adaptability; the fact that they are not palatable to livestock; the reduction in agricultural land productivity; and the reduction in off-farm employment opportunities.

It can be logged and processed quickly, making it a viable alternative to the limited supply of imported wood products. Additionally, eucalyptus is a sustainable source for generating self-sustained income, supporting the construction of private houses, industries, and infrastructure development. The availability of eucalyptus timber helps address the high demand for housing and commercial needs, bridging the demand-supply gap. This approach helps prevent deforestation and promotes the creation of sustainable and reliable timber supplies in Ethiopia.

3.2 Challenges of Ethiopian Wood Industries Eucalyptus Timber Utilization

Wood is considered a promising raw material for the industrial sector, offering significant competitive advantages over other feedstock due to its non-seasonal growth, high polysaccharide content, availability, and ability to thrive on set-aside land, thereby supporting rural development (Penín et al., 2020). In Ethiopia, the demand for wood products is consistently rising due to rapid economic development, population growth, increasing urbanization, and a growing construction sector (Girma & Abate, 2021; Tesfaw et al., 2021). Ethiopia's forestry industry holds substantial potential, but its ability to produce high-quality wood products is currently constrained. As a result, the country relies heavily on imports to satisfy local market demands for essential forest products, including sawn timber, wood panels, pulp, and paper. The most planted hardwood is eucalyptus, a valuable biomass source for manufacturing materials, chemicals, and fuels.

The rising demand for building materials and firewood has led to robust markets for eucalyptus products. This growing interest in eucalyptus has significantly contributed to the expansion of its acreage throughout the region, reflecting the plant's increasing commercial viability and importance (Dessie & Erkossa, 2011). In Africa, including Ethiopia, eucalyptus trees are significant in various socioeconomic aspects. Ethiopians have been associated with it for a long time because it is the primary source of building materials for homes (Alemu, 2016). Numerous products made from eucalyptus have good economic returns (Gomes et al., 2021). These include fuelwood, poles, construction materials, pulp wood, timber, oil, medicine, tannin, fiber and particle board, livelihood support, honey production, and employment, among many other uses. Four significant eucalyptus species are worldwide (*E. Grandis, E. E. urophylla, Camardulensis, and E. globulus*) (Gomes et al., 2021). Among these species, *E. globulus* and other hybrids cover about 80% of the world (Rockwood et al., 2008).

According to Lemenih and Kassa (2014), demand for wood products is rapidly increasing in Ethiopia due to population growth, urbanization, and economic development. In 2013, the Ministry of Environment, Forest, and Climate Change (MEFCC, 2017) reported that approximately 124 million m^3 of wood products were consumed. Of this amount, 116 million m^3 were used for charcoal and fuel wood, 6.7 million m^3 for the building industry, 0.17 million m^3 for sawn wood, primarily from domestic production, 0.5 million m^3 for round wood, and 0.8 million m^3 for paper and furniture industries. According to Desalegn et al. (2015), the forest products import amount and the corresponding hard currency value between the years 2000-2013 has been 170,721.3 tons costing a capital of 159 million USD.

The wood balance in this construction sub-sector indicates a supply gap of approximately 1.4 million m^3 in volume during the same period, and the supply-demand imbalance reached its peak in 2013 at 38.8 million m^3 (MEFCC, 2017). Belachew et al. (2023) pointed out that if no intervention measures are considered, the import bill by the year 2035 will reach about 3 billion USD. Importing large wood products would demand a sizeable foreign currency, compromising the country's economic development. Moreover, it is projected that over the next two decades, the local wood industries' inadequate productivity, population expansion, and urban development will increase the need for processed wood products in the country (Jaleta et al., 2016).

Consequently, the domestic wood industry will not meet the country's demand for processed wood products. Various wood products have been imported, and several natural forests have been exploited to address the country's growing need for processed wood products. This can be attributed to an absence of a steady supply of raw materials for the wood industry, a dearth of technology, information, and knowledge on the processing and production of various wood products in the domestic wood industry, a scarcity of state-of-the-art machinery in the local wood sector, a deficiency of a proficient workforce in the domestic wood industry, and other various uncertain factors. Studies have indicated that eucalyptus timber species and their innovative manufacturing and utilization technology are among the alternative species and technologies that can be applied for the production of high-quality wood products in the domestic wood products manufacturing industry to minimize the country's demand and supply gap for processed wood products, reduce and replace the importation of wood products, reduce the shortage of raw materials, and so minimize reliance on a few common commercial softwood species in the domestic wood industry (Lee et al., 2022). According to Sori et al. (2023), relying solely on imported timbers is unwise, and alternative sources must be sought to meet this increasing demand for timber.

Eucalyptus plantations are becoming a cash crop supporting income generation and employment opportunities. In Ethiopia, 506,000 hectares of land are believed to be covered by eucalyptus. E. globules and E. *camaldulensis* are the main species of eucalyptus growing in the highlands of Ethiopia (Alemu, 2016). Despite the abundance of wood from this species in Ethiopia, its current capacity to supply high-quality wood products for industrial uses is not vast and faces several challenges. Hence, the imported species satisfy our short-term timber requirements; planning for the local fast-growing tree species like eucalyptus is essential to supply the required timber for the construction and furniture industries. Eucalyptus was introduced for multipurpose use and to rescue the remaining indigenous forests from being destroyed. The forestry sector has prohibited the harvest of *Hagenia abyssinica, Cordia*

Africana, Afrocarpus (Podicarpus) falcatus, and *Juniperus proceora* but allowed obtaining forest products for household use. Laws in later years have also addressed natural resources and the environment. Customized provisions for the private sector's involvement in forestry development have also been made. About 70 species of eucalyptus are available in Ethiopia, most of which are widely spread in many regions. However, most industries (92.9%) still use or depend upon well-known valuable timber species such as *Cordia Africa* for their furniture production across all the towns. Eucalyptus globulus has been studied in Ethiopia for its lumber characteristics by Tadele and Teketay (2014) and for pulp and paper. Waktole et al. (2024) studied the Variation of Physical Properties of Eucalyptus *globulus* grown in Ethiopia; their result suggested using eucalyptus globules for multiple wood products, including pulp and paper.

Using eucalyptus wood in the furniture industry presents several challenges that must be addressed (Ghani & Lee, 2021). Addressing these challenges requires specialized knowledge, equipment, and techniques to effectively utilize eucalyptus wood in furniture making while ensuring quality, durability, and sustainability. Eucalyptus wood is known for its high density and hardness, making it challenging to work using traditional and straightforward woodworking tools (Kaba, 2024). As a result, specialized equipment may be required to cut, shape, and sand eucalyptus wood effectively (Sori et al., 2023). When eucalyptus timber is not properly sawed, seasoned, and dried, it might divide, distort, or break and dry unevenly (Desalegn et al., 2015; Kaba & Desalegn, 2020). Another important problem with fast-growing hardwoods, such as eucalyptus, is dimensional instability (Cao et al., 2023; Vasileios et al., 2017). Attaining accurate moisture content and stability for furniture making requires careful drying and monitoring (Kaba & Desalegn, 2020). Some species of eucalyptus wood can be prone to long-end cracking, primarily if not adequately handled during processing and manufacturing (Famiri et al., 2001). This can lead to challenges in crafting intricate or delicate furniture designs.

Thus, it is an important characteristic for wood quality assessment, and it reflects the suitability of wood for most types of processing and many end-uses (Zanuncio et al., 2022). For example, lower-density wood is preferred for wall panels, which do not have to be strong and stiff, whereas high-density wood is preferred for construction poles and beams, which must be strong and stiff (Sadegh, 2012). Eucalyptus wood is known for its relatively high density, ranging from 450 kg/m^3 to 900 kg/m^3, depending on the species and growth conditions (Gil et al., 2010; Sadegh, 2012). This density contributes to its strength and durability, making it suitable for various structural applications (Kaba & Desalegn, 2020).

Ethiopia's increasing demand for wood products and declining natural forest resources have led to a growing reliance on imported timber. This dependence on imports has significant economic and environmental implications. Eucalyptus plantations, with their rapid growth rate and adaptability, offer a promising alternative to address the country's wood supply needs. However, Ethiopian industries face several challenges that limit the broader application of eucalyptus timber. These issues include technological, technical, economic, social, and policy-related challenges that were the primary barriers hindering the Ethiopian wood industries on eucalyptus timber utilization.

3.2.1 Technological Barriers

In Ethiopia, the forest supply is not well advanced in technology and final Harvested Wood Products (HWP), with most HWP used for products with short lifespans, such as fuel wood. There are numerous species of eucalyptus, but only a few are well-known and widely used (Pirralho et al., 2014). Ethiopia's most commonly used timber species are often the exotic ones introduced from other regions, notably certain varieties of eucalyptus, which thrive in the country's diverse climate (Zerga et al., 2021). Eucalyptus timber is recognized for its excellent physical and mechanical properties, making it suitable for various applications such as edge-glueing, lamination, plywood production, and interior cabinetry (Lee et al., 2022). It is also used in packaging, pallets, and other related uses, supporting local industries and the economy.

3.2.2 Technical Barriers

Not all eucalyptus species exhibit desirable wood properties. Some may have low density, low strength, or poor durability, limiting their suitability for specific applications. Likewise, particular species may be prone to defects like knots, gum veins, and decay, which can reduce the quality and value of the timber. Others can be pretty hard and dense, making working with traditional woodworking tools difficult. Specialized tools and techniques may be required to cut, shape, and finish the wood. Understanding clonal eucalyptus wood shrinkage enables us to implement appropriate measures to lessen their impact (such as collapses) during drying (Amer et al., 2022). A shortage of skilled labor and technical expertise in timber processing hampers the efficient use of eucalyptus timber in Ethiopia. The lack of adequate processing facilities limits the production of high-value products like furniture and construction materials.

Additionally, challenges such as the shrinkage and expansion of eucalyptus wood can lead to dimensional instability in furniture. Inefficient drying techniques contribute to quality issues like warping, cracking, and fungal decay, particularly in species requiring specialized drying methods. Overall, the industry's development is further hindered by the shortage of skilled labor in areas like kiln drying and wood preservation.

3.2.3 Economic Barriers

Establishing eucalyptus plantations in Ethiopia requires significant initial investment, which can challenge small-scale farmers. Costs include land preparation, high-quality seedlings, equipment, and irrigation systems, making it difficult for those with limited resources to enter the market. Eucalyptus trees typically have long rotation periods of 7 to 15 years, delaying returns on investment and impacting economic viability. Additionally, price fluctuations in the timber market can affect profitability, as rising prices can increase revenue while declines can lead to losses. Therefore, monitoring market trends is essential for making informed decisions about eucalyptus operations and investments.

3.2.4 Social Barriers

Uncertain land tenure rights pose significant challenges for Ethiopian wood industries, particularly for farmers in eucalyptus plantations. Farmers may hesitate to invest in long-term tree farming without clear legal rights to the land, prioritizing short-term gains over sustainable practices. This not only limits the growth of the wood industry but also reduces long-term economic benefits for farmers and communities. Additionally, local communities often resist eucalyptus plantations due to concerns over water scarcity, as these trees consume large amounts of water, impacting local agriculture and drinking supplies. There are also fears about soil erosion since eucalyptus roots can destabilize soil in rainy regions, leading to the degradation of arable land. Furthermore, biodiversity loss is a significant issue, as eucalyptus plantations displace native plants and wildlife. These factors contribute to community opposition, stemming from fears of lasting ecological and social consequences.

3.2.5 Policy Barriers

Insufficient policies and regulations can significantly obstruct the growth and progress of the eucalyptus timber industry. When regulatory frameworks are lacking or poorly designed, they can create challenges in sustainable harvesting practices, environmental protection, and market access. Without clear guidelines, businesses may struggle to operate responsibly, leading to overexploitation of resources and detrimental impacts on local ecosystems. Moreover, inadequate policies can impede investment opportunities, stifle innovation, and result in inconsistent quality standards, all of which can undermine the industry's potential for economic development and sustainability in the long term. Besides this, weak enforcement of forest laws and regulations can lead to illegal logging and deforestation, undermining the sustainability of eucalyptus plantations in Ethiopia. Insufficient financial incentives, such as subsidies and tax breaks, can discourage investment in eucalyptus plantations.

3.2.6 Environmental Concerns

Eucalyptus trees are often criticized for their environmental impact, particularly due to their high-water consumption and adverse effects on local biodiversity (Desta et al., 2023; Zerga et al., 2021). Their extensive cultivation can lead to groundwater depletion in water-scarce regions, affecting surrounding ecosystems and diminishing resources for native flora and fauna (Zegeye, 2010). Eucalyptus plantations frequently outcompete indigenous plants, altering local wildlife and threatening species survival, which results in significant biodiversity loss (Ping & Xie, 2009). This situation has led to resistance from local communities and environmental groups against expanding eucalyptus plantations, as many believe the ecological costs outweigh the economic benefits. Therefore, sustainable management of eucalyptus plantations is essential, although achieving this is challenging without adequate training and resources (Birhanu & Kumsa, 2018; Yimam et al., 2024; Rode et al., 2016).

3.2.7 Legal Barriers Hindering Eucalyptus Utilization in Ethiopia

Eucalyptus timber utilization in Ethiopia is hindered by significant legal barriers that impede its cultivation and commercial use. A major challenge is the complexity and fragmentation of forestry regulations, particularly those concerning land use, which often restrict eucalyptus planting due to ecological concerns. Relevant policies aim to preserve indigenous species and prevent land degradation, complicating the establishment of eucalyptus plantations (Gebretsanik et al., 2020). The Forest Law (2018) also adds to this complexity, requiring a management plan approved by authorities for forest use, while emphasizing local community participation in forest management (Article 19(4)) of the Federal Democratic Republic of Ethiopia (FDRE, 2018). These regulations create uncertainty for investors regarding ownership and land use permits, deterring investment and limiting market growth (Tesfaw et al., 2021). The government's stringent environmental policies, aimed at protecting biodiversity, often result in the underutilization of eucalyptus resources valued for their rapid growth (Bayle, 2019; de Carvalho Balieiro et al., 2020). There is a need for a balanced policy review to support both environmental sustainability and economic development (Batra, 2023). Furthermore, a lack of clear legislative guidelines on eucalyptus cultivation contributes to uncertainty for farmers and industries (Tesfaw et al., 2021). Inconsistent law enforcement and bureaucratic inefficiencies further complicate compliance and exacerbate legal challenges, making it essential to streamline administrative procedures for effective eucalyptus timber utilization in Ethiopia.

4 Discussion

Eucalyptus offers significant socioeconomic and environmental benefits in Ethiopia, but constructive dialogue among researchers and stakeholders is essential to assess its impact. While some highlight concerns about its cultivation, others see advantages and consider a balanced evaluation (Dessie et al., 2019). This article reviews the barriers to and strategies for improving Eucalyptus timber utilization in Ethiopia. Key challenges include inadequate processing facilities and a lack of standardized grading systems (Bazzana et al., 2020). Addressing these requires investment in modern processing technologies and establishing national quality standards. Lessons from countries like Brazil and Australia indicate that such advancements can boost utilization rates. Economic barriers, including high production costs and limited market access, hinder investment in Eucalyptus processing (Carias Vega & Page, 2023). Strengthening value chains and providing financial incentives could enhance local production and utilization. Policy barriers are significant, with a lack of clear legal frameworks leading to sustainable harvesting and processing inconsistencies. Establishing defined regulations and enhancing institutional support will be crucial. While environmental concerns exist, such as soil depletion and water resource consumption, research shows that sustainable management practices can mitigate these impacts. Promoting mixed-species plantations and agroforestry can also benefit soil health. The European Union Deforestation Regulation will impact Ethiopia's Eucalyptus sector, requiring producers to ensure their practices do not contribute to deforestation. Compliance may necessitate improved monitoring systems but could also open new markets for sustainably sourced timber (European Commission, 2025; United Nations, 2023). In conclusion, enhancing Eucalyptus timber utilization in Ethiopia necessitates a holistic approach integrating technological investments, market expansion, policy reforms, and sustainable practices. The results presented in this article are limited in scope to Ethiopia and rely solely on secondary data from various databases. Additionally, it has limitations in keyword selection, which may affect the study's comprehensiveness.

Conclusion

The use of eucalyptus timber in Ethiopia has significant potential to meet growing wood product demands, reduce imports, and conserve indigenous forest resources. However, various technological, economic, social, policy-related, and environmental challenges impede this potential. To address these issues, a comprehensive approach is needed, including investments in advanced processing technologies, capacity-building initiatives, policy reforms, and community engagement. Promoting sustainable eucalyptus management and value-added products can strengthen Ethiopia's wood industry and close the timber supply-demand gap. Increasing public awareness and providing financial incentives to small-scale farmers can further facilitate the adoption of eucalyptus. Collaboration among policymakers, researchers, and industry stakeholders is essential for ensuring sustainable eucalyptus timber use. Future research should focus on improving processing techniques, exploring innovative wood applications, and examining the environmental impacts of eucalyptus plantations. Collecting primary data through field surveys and case studies will offer deeper insights into timber utilization. Lastly, enhancing perceptions of eucalyptus, developing supportive policies, and investing in training programs for foresters and entrepreneurs will help overcome barriers to eucalyptus utilization and improve timber quality through breeding and silvicultural practices.

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PŘEKÁŽKY A STRATEGIE PRO ZVÝŠENÍ VYUŽITÍ EUKALYPTOVÉHO DŘEVA V ETIOPII

Přestože byl eukalyptus zaveden, aby podpořil etiopské lesní hospodářství, jeho využití jako alternativy k dováženému dřevu brání různé překážky. Hlavním cílem tohoto článku je identifikovat klíčové problémy při využívání eukalyptového dřeva a na základě přehledu literatury navrhnout strategie pro zlepšení. Zjištění poukázala na technologické, ekonomické, sociální a politické překážky. Sekundární údaje byly shromážděny na základě rešerše odborných zdrojů v období od listopadu 2024 do ledna 2025. K vyhledávání byla použita klíčová slova ve vědeckých databázích Scopus a Web of Science a DOAJ. Zjištění ukazují, že zjištěné problémy omezují využití eukalyptového dřeva. Pro zvýšení udržitelnosti by zúčastněné strany měly pokročit v technologiích zpracování dřeva a zavést podpůrnou politiku a finanční pobídky.

HINDERNISSE UND STRATEGIEN FÜR DIE STEIGERUNG DER NUTZUNG VON EUKALYPTUSHOLZ IN ÄTHIOPIEN

Obschon der Eukalyptus für die Bedürfnisse der äthiopischen Wälder eingeführt wurde, wird dessen Nutzung als Alternative zu importiertem Holz von verschiedenen Faktoren behindert. Das Hauptziel dieses Artikels besteht in der Identifizierung der Schlüsselprobleme bei der Nutzung von Eukalyptusholz, wobei auf der Grundlage einer Literaturübersicht Strategien für eine Verbesserung vorgeschlagen werden sollen. Die daraus hervorgehenden Feststellungen weisen auf technologische, ökonomische, soziale und politische Hindernisse hin. Die Sekundärangaben wurden auf der Grundlage der Recherche fachlicher Quellen von November 2024 bis Januar 2025 gesammelt. Für das Heraussuchen wurden Schlüsselwörter in den wissenschaftlichen Datenbanken Scopus, Web of Science und DOAJ verwendet. Die Ergebnisse zeigen, dass die festgestellten Probleme die Nutzung von Eukalyptusholz einschränken. Zur Steigerung der Nachhaltigkeit sollten die beteiligten Parteien in den Technologien der Holzverarbeitung voranschreiten und eine unterstützende Politik sowie finanzielle Anreize einführen.

PRZESZKODY I STRATEGIE ZWIĘKSZENIA WYKORZYSTANIA DREWNA EUKALIPTUSOWEGO W ETIOPII

Pomimo tego, że eukaliptus został wprowadzony w celu wsparcia etiopskich lasów, jego wykorzystanie jako alternatywy dla drewna importowanego napotyka różne przeszkody. Głównym celem niniejszego artykułu jest identyfikacja kluczowych problemów związanych z wykorzystaniem drewna eukaliptusowego oraz zaproponowanie strategii poprawy sytuacji na podstawie przeglądu literatury. Wyniki badań wskazały na przeszkody technologiczne, ekonomiczne, społeczne i polityczne. Dane wtórne zebrano na podstawie kwerendy specjalistycznych źródeł w okresie od listopada 2024 roku do stycznia 2025 roku. Do wyszukiwania wykorzystano słowa kluczowe w naukowych bazach danych Scopus, Web of Science i DOAJ. Wyniki wskazują, że zidentyfikowane problemy ograniczają wykorzystanie drewna eukaliptusowego. Aby poprawić zrównoważony rozwój, zainteresowane strony powinny rozwijać technologie przetwórstwa drewna oraz wprowadzić politykę wspierającą i zachęty finansowe.