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Research Articles

Research Articles

BIOREFINERY CONCEPT OF THE ZITTAU/GÖRLITZ UNIVERSITY OF APPLIED SCIENCES

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Abstract

This article presents the circular-economy-based biorefinery concept developed by the "Biorefinery" research group at the Zittau/Görlitz University of Applied Sciences. The biorefinery concept aims the holistic utilization of plant raw materials and residues, in orders to exploit their entire value creation potential. The material or energetic utilization of all parts of the plants or plant residues results in significant economic and ecological advantages compared to conventional recycling methods and commonly accepted utilization concepts. The biorefinery process of our research group also envisages feeding products made of or contanining natural fibers after their use to a novel recycling process using saprobionthic fungi. As a result of fungal recycling mycelium-based biocomposites are produced and provided for further applications, e.g. in the construction industry or as packaging material. In this way, carbon can be sequestered in the long term and CO_2 emissions can be avoided.

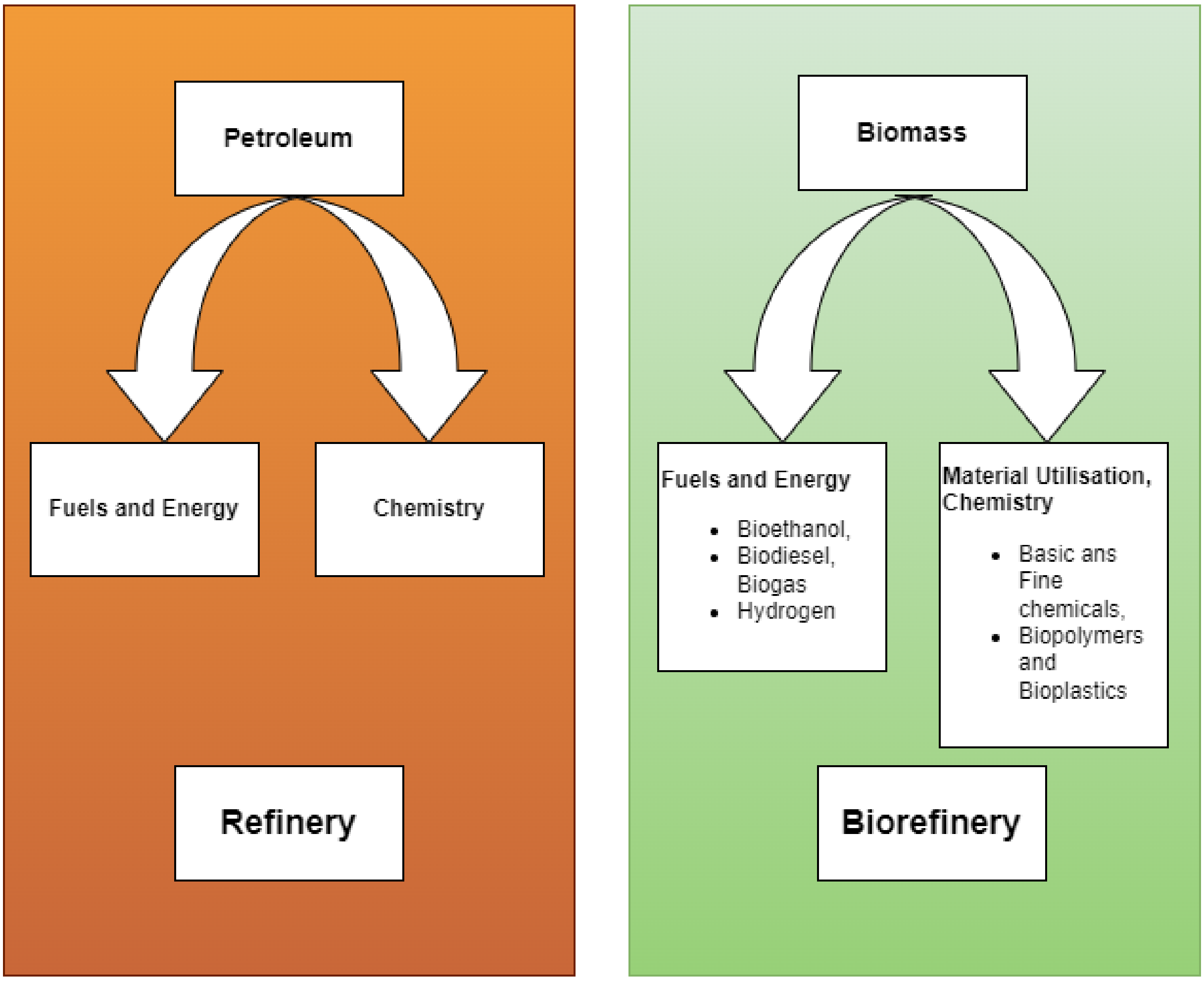
Keywords

Circular economy; Biorefinery; Emission reduction; Plant biomass; Value-added products.

Introduction

There is no single definition for biorefinery that is commonly accepted by scientists or other experts. In general, the term biorefinery stands for producing systems that combine different technologies and processes in order to convert biological raw materials into a range of different valuable intermediates and end products.

Some of the numerous definitions available in scientific (or non-scientific) publications are as follows: "Green biorefineries represent complex (to fully integrated) systems of sustainable, environmentally and resource-friendly technologies for the comprehensive (holistic) material and energetic utilization as well as exploitation of biological raw materials in form of green and residue biomass from a targeted sustainable regional and utilization." The American National Renewable Energy Laboratory published the following definition: "A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power and chemicals from biomass. The biorefinery concept is analogues to today's petroleum refineries (Fig. 1) which produce multiple fuels and products from petroleum." [1]



Source: [1]

Fig. 1: *Comparison of the basic-principles of the petroleum refinery and the biorefinery*

1 Research Subject

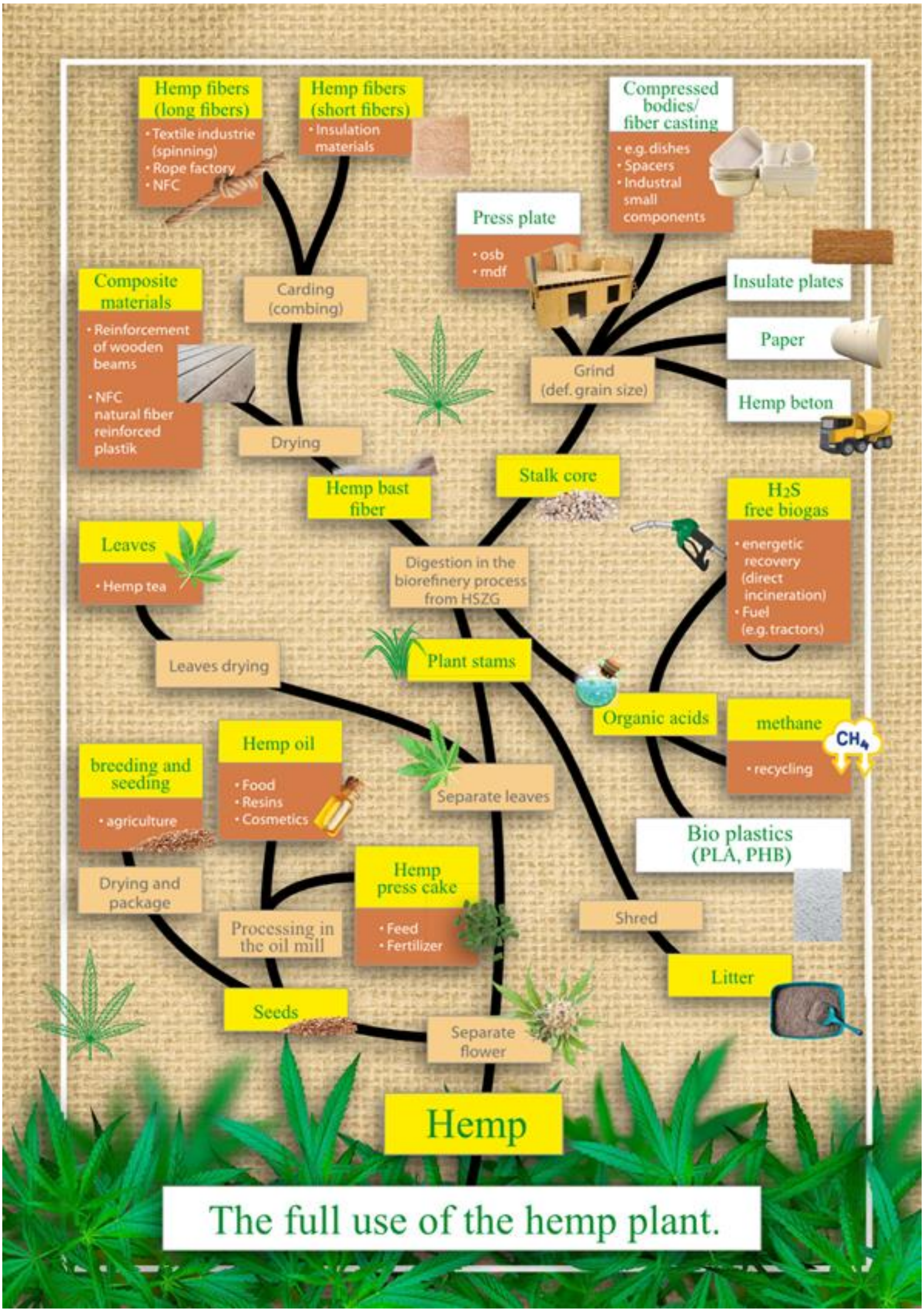
One thing that all definitions have in common is: "biorefineries start with a biomass-feedstock-mix to produce a multiplicity of most various products by a technologies-mix." [1] (Fig. 2)

The idea of biorefineries serves as an essential basis for the work of our research group. We therefore deal with the development and implementation of sustainable concepts for the utilization of plant raw materials and plant-based residues under the premise that all components of the feedstock are used either materially or energetically. In this way, resources can be used efficiently and the value-added potential of the raw materials can be fully exploited. Our research activity has the focus on bringing value chains together to create economic cycles. (This is the basic idea behind circular economy through sector coupling.) Value chains can be assigned to completely different industrial sectors (agriculture, biotechnology, transport system, construction industry, food and non-food industry (Fig. 3)), though they are strongly depending on each other and are therefore tightly interconnected. In addition to closing value chains to economic cycles is one of our fundamental goals to open up new value creation paths (value chains) and to integrate them into existing economic cycles.

Source: Adopted from [1] and supplemented

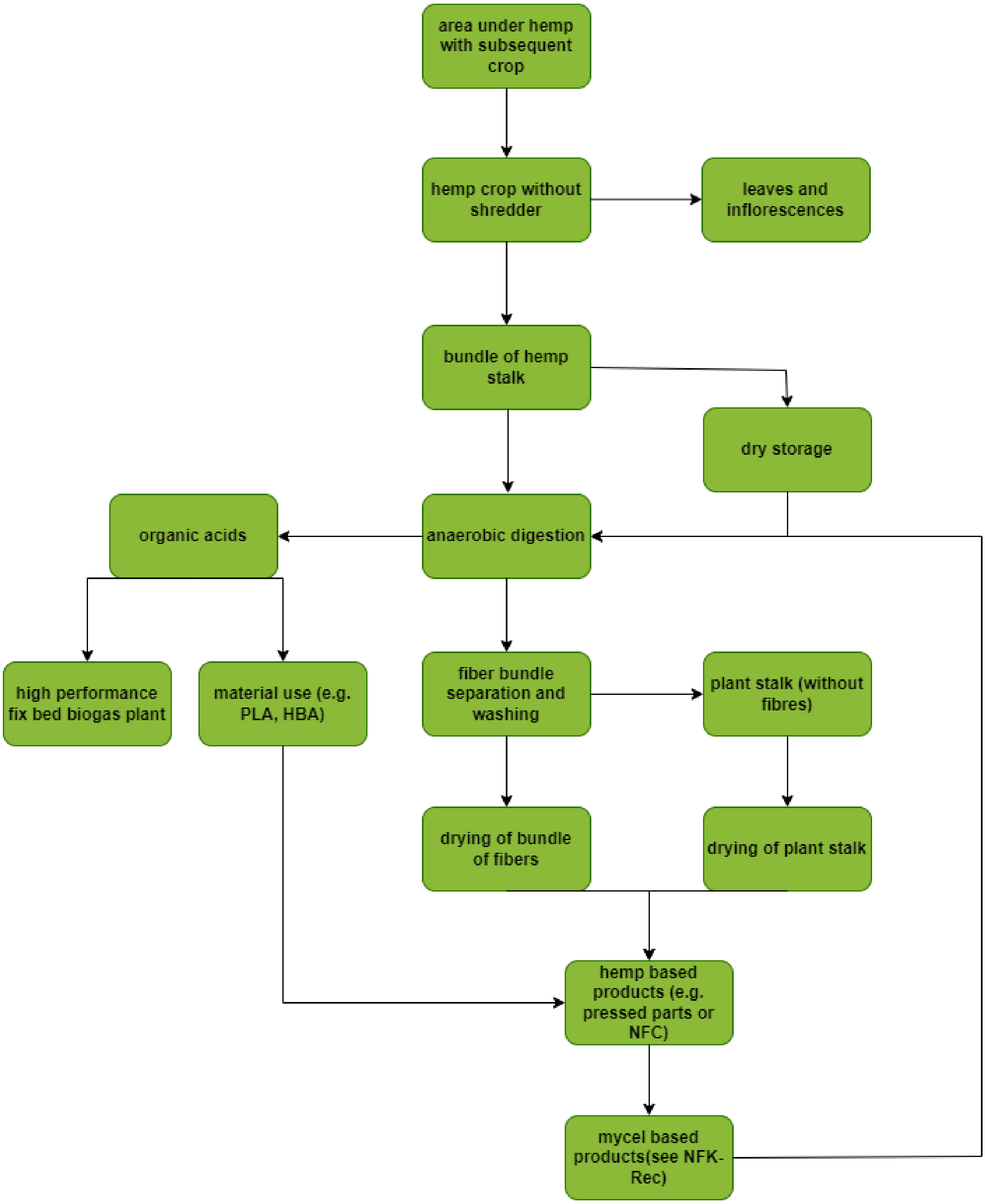
Fig. 2: *Basic principles of a biorefinery from biological feedstocks to substance and energy products, supplements with our substrates, processes and products from our process*

In order to cover/consider the entire life cycle of products made of or containing natural fibers, we also focus on recycling and the possibilities of subsequent uses. In this context, special attention is paid to extending the useful life (time for use and subsequent uses) of the products so that carbon can be sequestered for as long as possible. In this way, the recycling concepts we develop contribute significantly to sustainability and emission reduction.



Source: Adopted from Dr. H. Geilert and supplemented by Matthias Tirsch

Fig. 3: *Hemp plant and their use in various industries*



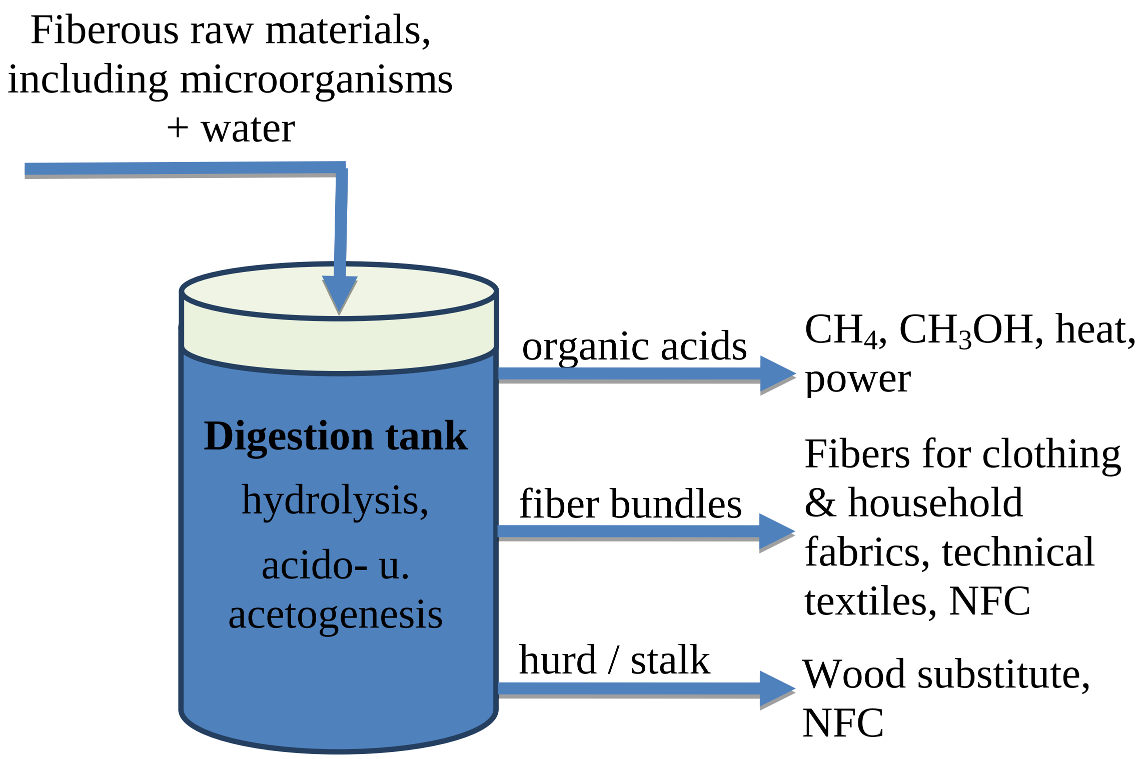
Source: Biorefinery team

Fig. 4: *Flow diagram of Biorefinery process at the Zittau/Görlitz University of Applied Sciences on an example of hemp*

In addition to the ecological aspect, our recycling concepts also offer economic advantages, which result partially from the fact that we work with regionally available raw materials that do not have to be transported over long distances. Especially in the field of natural fibers, cotton fibers – but meanwhile also hemp or flax fibers (or semi-finished natural-fiber-based products) – are imported from abroad, which is of course associated with considerable harmful impacts on the environment [2]. A further significant economic advantage of holistic utilization concepts results from the fact that a wide range of intermediate and end-products can be produced and provided for further processing while keeping the amount of waste (the fraction of raw materials that can be used neither materially nor energetically) at a level near to zero. Nothing is lost, nothing is thrown away – right in line with the principle of biorefineries!

Taking hemp as an example, the holistic utilization concept / biorefinery concept for plant raw materials/biomass can be presented in Fig. 4.

One of the key technologies for the processing of plant-based raw materials is the so called "water retting" which takes place under anaerobic conditions in a tightly closed tank (Fig. 5).



Source: Judit Harsányi.

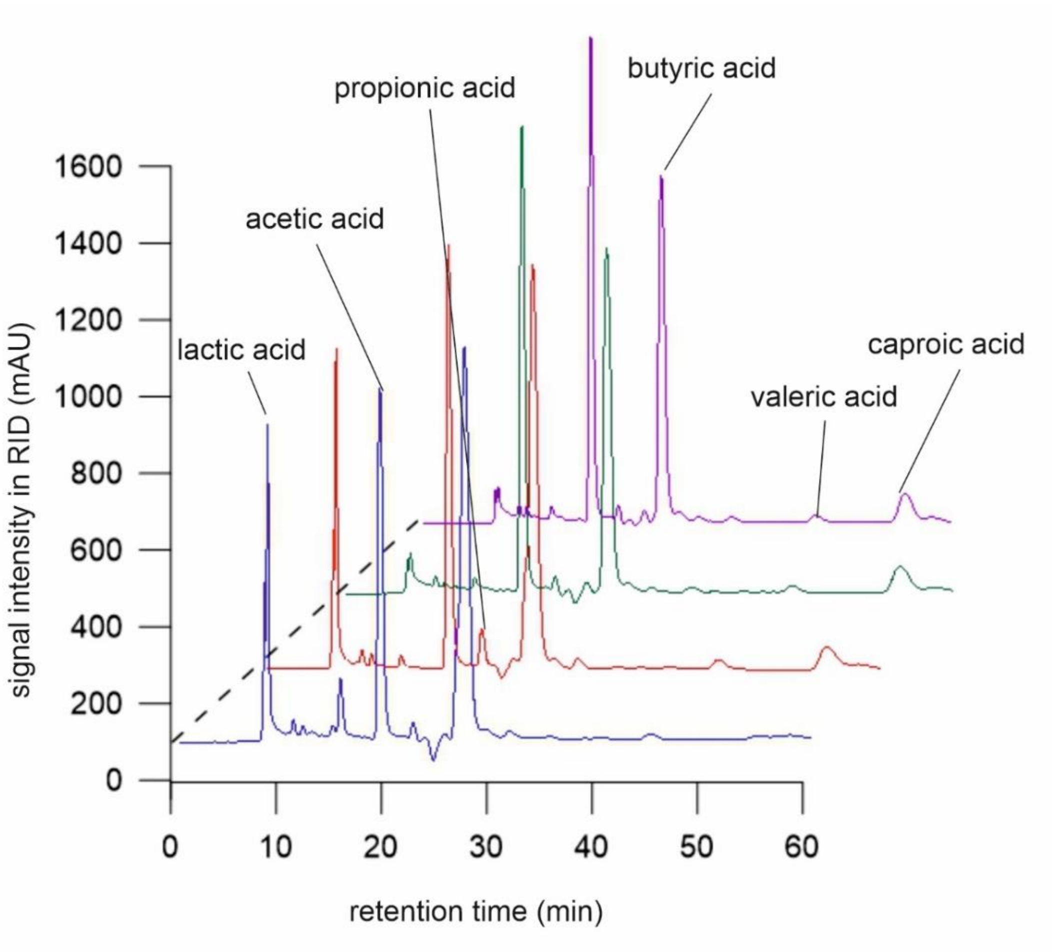
Fig. 5: *Water retting process optimized by the Biorefinery research group with the key product groups*

It is based on the metabolic activity of microorganisms (bacteria) and enables to clearly separate fibers from the woody core (hurd) of the stem of plants. The retting process was developed by our research group on the basis of the technique of traditional water retting (i.e. soaking the plants in either stagnant or moving water to release fibers due to the microbial degradation of glue-like substances like pectin) [3]. Conventional methods for fiber extraction at industry scale involve techniques where fibers (fiber bundles) are subjected to considerable mechanical stress, which consequently leads to reduced stability (tensile strength) and/or severe shortening of the fibers. In addition, fibers may contain shives and dust after mechanical extraction, that have to be removed in subsequent energy-consuming process steps to allow further processing of fibers [4]. In comparison with conventional extraction methods, the advanced technology of water retting developed by our research group provides fibers having no surface adhesions or other contamination due to dust and/or shives (Fig. 6).

Source: Erik Lautzus

Fig. 6: *Examples of hemp products after anaerobic digestion. As a result of water retting clearly separated fiber bundles without surface contamination and clean stalks (hurds) are obtained for further processing.*

Harmful impacts on environment – as they occur especially when applying traditional water retting – can be avoided, too. Water retting in a closed system like a tank allows controlling the retting process at all times. In contrast to this, the traditional retting technology that took place either on the field (field/dew retting) or in water bodies (water retting) is time-consuming and in addition to this, the effects of unpredictable environmental influences can neither be controlled nor avoided, which in turn can lead to reduced fiber qualities. Another particular advantage of water retting in a closed system is the fact that organic acids generated during degradation of organic material (pectin) by microorganisms – can be collected and used for further material or energetic recovery (Fig. 7). This considerably increases the overall economy of plant processing.



Source: Marzena Poraj-Kobielska

Fig. 7: *Example of chromatogram demonstrating composition of acids during anaerobic digestion of biomass (here in example of pineapple leaves) on day 3 (dark blue), day 5 (brown), day 8 (green) and day 9 (purple). At first are build lactic and acetic acid, then butyric acid and valeric and caproic acid in the second week of hydrolysis by elongation of chain from simple acids. [5].*

If required, mechanical techniques are also used for processing the raw materials, either alone or in combination with water retting as described previously. The aim of mechanical processing is either to pretreat raw materials for subsequent water retting or to extract fibers directly. Mechanical pretreatment techniques used in the processing of plant biomass include, for example, pressing between two rollers or carving the plant tissue. The aim of these techniques is to create a larger surface area for microorganisms to attack by opening up the harder tissue layers in which the fibers are embedded. In this way, the retting process can be intensified and a higher fiber yield can be achieved. The so-called ribolyser, see Fig. 8, is used to extract fibers mainly from grass stalks consisting of fine, soft and comparatively short fibers. During pretreatment with the ribolyser the plant tissue is destroyed by friction forces resulting from the sliding of grass stalks against each other. As a result of pretreatment with the ribolyser fibers are released from the plant tissue and are ready for further processing.

Source: Erik Lautzus
Fig. 8: *Ribolyser*

Ribolyser is applied exclusively when processing grass, i.e. plants with short, soft fibers. In the case of plants containing long fibers (e.g. flax or hemp) the ribolyser is not applied, since the fibers could be considerably damaged and/or shortened during mechanical disintegration with the machine. In addition to this, long fibers are likely to tangle more than short fibers, which can lead to damages on the machine or can make subsequent processing of fibers more difficult or even impossible.

The utilization concept presented in Fig. 6 can be transferred or adapted to other plants or plant derived biomass (e.g. residues from beer production) depending on the quality raw material. Thus, we are dealing with the utilization of many regionally growing plants such as flax, nettle, mugwort, palm lily and amaranth. In addition to indigenous plants, we develop concepts also for the holistic utilization of more exotic plants such as banana and pineapple. In the case of these plants, it is not the fruits but the leaf sheaths (banana) or the leaves (pineapple) that are suitable for versatile uses, e.g. as sources of fibers and energy. Both raw materials cause significant environmental and hygienic problems in the corresponding tropical growing regions due to insufficient disposal or utilization.

In order to develop an adequate utilization concept, raw materials are investigated in individual projects. Doing so, our research group is able also to address specific requests and R&D-ideas of regional enterprises. Due to the intensive cooperation with regional – but also with some national – companies, the work of our research group can be highly adapted to the needs and preferences of SME. Due to cooperations with SME we also have better chances to transfer innovations from the laboratory scale into practice.

Some selected biorefinery-projects are presented in the following sections.

2 Industrial Projects

2.1 Project Flachsgarn

Funded by the SME program ZIM of the AiF.

Duration: 1. 6. 2022 – 31. 5. 2024.

The main objective of the project Flachsgarn (= Flax Yarn) is the development of technologies for the emission-free production of goods/items on the basis of flax fibers with high gravimetric fineness. The results of the project will be available for the entire German textile industry.

Within the scope of the project, a novel technology for the gentile extraction of fibers from flax is developed, see Fig. 9. The technology is mainly based on water retting, that takes place in an airtight tank. The advanced technology of water retting and its application for fiber extraction was recently developed by the "Biorefinery" research group at Zittau/Görlitz University of Applied Sciences. Applying the novel water retting technology the fibers can be gently detached from the stalk and they are free of shives and surface-contaminants. Consequently, the fiber bundles obtained in this way are almost white and have an exceptionally fine structure. In contrast to conventional mechanical extraction techniques, no low-quality fibers are produced. The fiber bundles produced can be prepared for subsequent processing, e.g. by drying and cutting them to the desired length. Then, fibers can be processed to a yarn, which in turn can be used for the production of scrims or fabrics with a very high fineness. High degrees of fiber fineness are particularly interesting for textile applications.

Source: Erik Lautzus

Fig. 9: *Flax after anaerobic digestion. Flax stalk (left), flax fibers (in the middle), and flax yarn (right).*

In order to completely exploit the added value creation potential of flax, not only the fibers, but also the by-products generated during fiber processing are subject to investigations within the frame of the project. Thus, the following by-products are assumed to be suitable for further utilization: Stalks for the application as wood substitute (e.g. in paper production or as construction material), organic acids generated during the water retting process for material or energetic use, and seeds that can be used to produce linseed oil.

Participating project partners: Zittau/Görlitz University of Applied Sciences and Netzfabrik Kremmin GmbH.

2.2 Project Biostring

Funded by the SME program ZIM of the AiF.

Duration: 1. 6. 2022 – 31. 5. 2024.

The aim of the project "BioString" is the development of innovative biodegradable natural fiber containing granules for the production of natural fiber-reinforced composites (NFC) using injection molding.

Within the scope of the project fibers from goldenrod are used for the first time as reinforcement in polymer composites, see Fig. 10. 100-120 species belong to the genus goldenrod (*Solidago* sp.), most of which originate from North America. As being an extremely invasive species, Canadian Goldenrod (*Solidago canadiensis*) impacts biodiversity and native species in Europe seriously. Landscape management measures are necessary to stop uncontrolled spread of goldenrod. On the other hand, the plant is cultivated for versatile medicinal purposes.

Source: Photo on the left side: https://www.seven-morning.com/de/kanadische-goldrute.html; on the right side: Erik Lautzus

Fig. 10: *Picture of goldenrod (left), tensile test bars with goldenrod (right)*

Both landscape management measures and medicinal application allow no entire use of the plant. However, residual material can be used for fiber production. Thus, the aim of this project is the development of a technology – in accordance with industrial requirements – for the extraction and processing of fibers from goldenrod. In order to determine the optimal fiber-polymer-ratio, various biobased and biodegradable fiber-plastic-composites are produced and investigated regarding mechanical properties. Here it is of particular importance that the plastic content of NFC-granules (and NFC-products) is reduced to a minimum without affecting product quality. In this way – replacing synthetic plastic with natural fibers – sustainability of NFC production can be significantly enhanced. The fiber-polymer granules are foreseen to be processed with an innovative injection molding system that is to be equipped with a new type of metering unit to provide granules with optimum fiber-polymer-ratio.

Besides NFC-production the project considers also the end-of-life recycling of fiber containing composites. Thus, not only basic investigations on the biodegradability of NFC will be conducted, but also a specific marker will be developed. In contrast to state-of-the-art technologies the marker will allow waste sorting machines to detect and to separate NFC from other waste fractions effectively.

The overall objectives of the project BioString include enhanced sustainability, significant reduction of CO_2 emission and economic viability in the production of natural fiber reinforced composites by using injection molding technology. The efficient use of goldenrod as a valuable natural resource, e.g. by using its fibers for the production of NFC, is another key aspect of the project.

Participating project partners: Zittau/Görlitz University of Applied Sciences and Peiler & Klein Kunststofftechnik GmbH.

2.3 Project Green Fibers

Funded by the SME program ZIM of the AiF.

Duration: 1. 6. 2022 – 31. 5. 2024.

The aim of the project Green Fibers is the development of a new type of natural fiber composite (NFC) on the basis of fibers extracted from hemp by suing a specific and gentle fiber extraction technology (advanced water retting). Due to this novel extraction technology fibers with optimal fineness, length and good mechanical properties can be provided for the subsequent production of yarn, fabrics and NFC, see Fig. 11. The resulting natural fiber polymer composites are characterized by significantly higher tensile and tear strength and twice the bending stiffness of conventional natural fiber-reinforced plastics.

The innovations achieved in the project Green Fibers should contribute to the establishment of new applications for hemp and hemp-based composites, including the application as reinforcement fibers in cladding or structural elements. Thus, a large market may benefit from the results of this research project.

Source: Erik Lautzus

Fig. 11: *Exposed mesh structure of fibers*

Participating project partners: Zittau/Görlitz University of Applied Sciences, PRK GmbH Kunststoffverarbeitung, the German Institute for Textile and Fiber Research Denkendorf and Digel Sticktech GmbH und Co. KG.

2.4 Project NFK Rec

Funded by the SME program ZIM of the AiF.

Duration: 1. 5. 2022 – 30. 4. 2024.

Natural fiber composites are widely used in various industrial sectors. As a consequence of this, the amount of NFC-waste is steadily increasing. Thus, the recycling industry faces the challenge of finding environmentally friendly methods for the recycling of those materials.

The aim of the project NFK-Rec is the development of an ecologically viable technological concept – including the construction of necessary equipment – for the processing and recycling of NFC waste. The technology is based on the application of selected fungi. In a plant, which is similar to a trickle bed reactor, the previously shredded and sterilized NFC-parts undergo a fungal treatment. During that treatment the natural fiber content of NFCs is destroyed. The degradation of natural fibers is supported by a subsequent post-maturing process, where the decomposition of the natural fibers can be completed, see Fig. 12.

In addition to mycelium some of the fungi (e.g., shiitake, oyster mushroom, or king trumpet mushroom) that are foreseen for the application in NFC-recycling, can develop also edible fruiting bodies during the post-maturing process. These can be harvested and sold after appropriate testing for food safety.

Source: Erik Lautzus

Fig. 12: *Fungi growing on shreds of NFC parts. Pleurotus eryngii, Pycnoporus cinebareus and Letinus edodes (left picture), Irpex lacteus in mycoreactor developed and produced in this project (right picture)*

After a while, NFCs, are completely interwoven by the fungal mycelium and are ready for the next process step, i.e. anaerobic digestion in which the biologically degradable part of pretreated NFC is converted into organic acids by microorganisms (bacteria). The organic acids (e.g. acetic acid, lactic acid, etc.) can then be utilized either materially (e.g. for the production of bio-based plastics) or energetically (e.g. for the production of biogas). The plastic fraction left over from the fermentation process can be separated and used as additive in the construction industry, or alternatively it can be re-used for the production of plastic/NFC.

Participating project partners: Zittau/Görlitz University of Applied Sciences, TU Dresden, Weima GmbH and Schmidtberger Maschinenbau GmbH.

2.5 Project Mobile High-Performance Biogas Plant

Funded by the European Regional Development Fund (ERDF).

Duration: 1. 1. 2022 – 31. 12. 2022.

The aim of the project is the development of a compact high-performance biogas plant which – by means of novel fixed-bed fermenters – enables the decentralized and flexible production of biogas from different feedstocks. The biogas with a methane content of at least 70% can be produced in a significantly shorter process compared to conventional large scale biogas plants. Furthermore, investigations with regard to the biochemical conversion of combustion gas (exhausted by a combined heat and power plant) and electrochemically produced hydrogen (from renewable energy electricity surpluses) to methane. The synthesis of methane takes place in an innovatively designed high-performance fixed-bed gas digester in order to minimize the CO_2 emissions of the downstream CHP plant. In addition to the environmentally friendly production of high-quality biogas, also process wastewater is to be treated, e.g. by the recovery of minerals like phosphate. After recovery phosphate can be used for the production of natural fertilizers. The “salt-free” process wastewater thus achieves a quality that allows to discharge wastewater without any concerns into the public sewage system.

The measures presented here – the utilization of exhaust gas from incineration processes as well as the treatment of the process waste water – serve the environmentally viable completion/creation of material and energy cycles.

Participating project partners: Zittau/Görlitz University of Applied Sciences, Haase Tank GmbH, Gedes e.V., Covac GmbH, Rublic & Canzler GmbH.

Conclusion

The implementation of biorefineries, i.e. the basic idea for the generation of a mixture of products from natural resources, in economy is essential, in order to establish a sustainable life. Therefore, it is of fundamental importance to increasingly replace fossil-based products with biodegradable, nature-based products. This should be done wherever the technical requirements of the application can be fulfilled by the natural materials. Moreover, it is essential to use natural resources efficiently. On the one hand, this means that the raw materials (+ residues from agriculture and industry) must be completely utilized – either materially or energetically. On the other hand, the “useful” life of bio-based products should be significantly extended by processing and using them in subsequent applications. In this way, carbon can be sequestered in the long term and CO_2 emissions can be avoided. In order to put all this into practice as efficient as possible, cooperation with industrial partners is of particular importance.

The current and future projects of the research group "Biorefinery" are dedicated to exactly these goals.

Acknowledgements

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KONCEPT BIORAFINÉRIE OD VYSOKÉ ŠKOLY APLIKOVANÝCH VĚD V ŽITAVĚ/GÖRLITZ

Tento článek představuje koncept biorafinérie založený na cirkulárním hospodářství, který vyvinula výzkumná skupina „Biorafinérie“ na Vysoké škole aplikovaných věd v Žitavě/Görlitz. Cílem koncepce biorafinérií je komplexní využití rostlinných surovin a zbytků, aby se využil celý jejich potenciál pro tvorbu nových produktů. Materiálové nebo energetické využití všech částí rostlin nebo rostlinných zbytků vede k významným ekonomickým a ekologickým výhodám ve srovnání s běžnými metodami recyklace a běžně přijímanými koncepcemi využití. Proces biorafinace naší výzkumné skupiny rovněž předpokládá, že produkty vyrobené z přírodních vláken nebo obsahující přírodní vlákna budou po jejich použití podrobeny novému recyklačnímu procesu využívajícímu saprobiontní houby. Výsledkem houbové recyklace je výroba biokompozitů na bázi mycelia, které jsou určeny pro další použití, např. ve stavebnictví nebo jako obalový materiál. Tímto způsobem lze dlouhodobě zachycovat uhlík a zamezit emisím CO_2.

BIORAFFINATIONSKONZEPT ENTWICKELT AN DER HOCHSCHULE ZITTAU/GÖRLITZ

In diesem Artikel wird das von der Forschungsgruppe „Bioraffinerie“ der Hochschule Zittau/Görlitz entwickelte kreislauforientierte Bioraffineriekonzept vorgestellt. Das Bioraffineriekonzept sieht vor, pflanzliche Roh- und Reststoffe möglichst vollständig zu verwerten, sodass ihr gesamtes Wertschöpfungspotential ausgenutzt werden kann. Durch die stoffliche oder energetische Verwertung sämtlicher Komponenten der Pflanzen bzw. pflanzlicher Reststoffe werden ökonomische und ökologische Vorteile im Vergleich zu herkömmlichen Verwertungswegen erzielt. Das Bioraffinationsverfahren unserer Forschungsgruppe sieht weiterhin vor, naturbasierte Produkte nach ihrer Nutzung einem neuartigen Recyclingprozess mithilfe von saprobionthischen Pilzen zuzuführen, in dem myzel-basierte Biokomposite hergestellt und weiteren Verwendungen z.B. in der Bauindustrie oder als Verpackungsmaterial zugeführt werden. Auf diese Weise kann der Kohlenstoff langfristig gebunden und somit CO_2-Emission vermieden werden.

KONCEPCJA BIORAFINERII Z UNIWERSYTETU NAUK STOSOWANYCH W ZITTAU/GÖRLITZ

Niniejszy artykuł przedstawia koncepcję biorafinerii opartej na gospodarce o obiegu zamkniętym, opracowaną przez grupę badawczą „Biorafineria” na Uniwersytecie Nauk Stosowanych w Zittau/Görlitz. Celem koncepcji biorafinerii jest kompleksowe wykorzystanie surowców i resztek roślinnych w celu wykorzystania ich pełnego potencjału do tworzenia nowych produktów. Odzysk materiałów lub energii ze wszystkich części roślin lub resztek roślinnych prowadzi do znacznych korzyści ekonomicznych i ekologicznych w porównaniu z konwencjonalnymi metodami recyklingu i powszechnie akceptowanymi koncepcjami odzysku. Opracowany przez naszą grupę badawczą proces biorafinacji przewiduje również, że produkty wykonane z włókien naturalnych lub je zawierające będą po zużyciu poddawane nowemu procesowi recyklingu z wykorzystaniem grzybów saprobiontowych. Efektem recyklingu grzybów jest produkcja biokompozytów na bazie grzybni, które są przeznaczone do dalszego wykorzystania, np. w budownictwie lub jako materiał opakowaniowy. W ten sposób długoterminowo można wychwytywać węgiel i ograniczyć emisje CO_2.

IMPROVING HUMAN-ROBOT PHYSICAL INTERACTION COMFORT IN MATERIAL HANDLING TASKS USING A SMART PLATFORM

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Abstract

The use of mobile platforms can help employees automate manual processes and streamline operations to save time and perform their tasks safely and accurately. A power-assisted vehicle to move weight around the place – solution: inexpensive, easy to apply, reliable, safe. It can adjust to various tasks, operators' gait, loads up to 500 kg. It is a relatively inexpensive, easy-to-apply, reliable, and safe solution for moving weight. The motivation of the study is to increase efficiency and reduce physical strain on the operator in material handling tasks and to promote the implementation of this smart platform. Artificial intelligence learning methods are applied to adapt to individual operator's experience, resulting in a personalized and more comfortable interaction with the help of Q-learning algorithm with 256 learning outcomes in adjusting controller settings: damping, mass, stiffness.

Keywords

Q-learning algorithms; Smart platform; AI; HRI; Material handling tasks; Human comfort criteria.

Introduction

With the pandemic warehouses growth in number and size [15, 16, 21], the use of mobile platforms can help employees automate manual processes and streamline operations to save time and perform their tasks safely and accurately. There are many types of wheeled devices that we encounter in people's daily lives. Industrial carts and transporters are widely used in various industries and warehouses, while hospitals use bed movers and wheelchairs to transport patients. Supermarket trolleys make shopping easier, and baby strollers allow us to take our children on long walks. Multiple earlier studies [1, 5, 6] demonstrated that the use of manual vehicles can increase human efficiency and reduce stress in manual handling tasks. Many groups of people, including professional workers, parents, disabled individuals, and customers, use some form of mobile vehicle to solve a material handling task at some point in their lives.

Material handling can expose workers to risk factors for low-back disorders, such as lifting, bending, twisting, pulling, pushing, and maintaining static postures. Pushing and pulling activities make up almost half of all manual materials handling [10]. This study focuses specifically on carrying activities using industrial power-assisted carts, which are typically manipulated by pulling backwards and pushing forwards with two hands. Pushing is generally preferred to pulling because it is safer. When pulling, the operator's feet may be run over by the cart, especially if it is powered, and the arm is stretched behind the body in an awkward position that increases the risk of injury. Pulling while walking backwards is also dangerous because the operator cannot see the path of travel. Research has shown that people can usually exert higher push forces than pull forces [13]. While pulling may be necessary in some situations, it should be avoided whenever possible and minimized when necessary.

1 Research Objectives

The goal of the current research is to address the issue of discomfort experienced during interactions between humans and industrial carts. The study is focused on situations where an operator uses a cart to navigate through a space that may contain obstacles and targets (such as a supermarket, warehouse, hospital, or transportation hub). The operator may choose targets and paths that are not always optimal, and their physical and mental state, along with the weight of the load, may change over time. It is aimed to identify criteria that reflect the operator's comfort and satisfaction, and use this information to adjust a support system to improve comfort. To do this, a chain of experiments is designed and conducted involving linear and curvilinear cart movement, using impedance controllers to control both linear and rotational motion in the latter case. The effects of various controller settings on operator comfort are examined and a system that allows adjusting these settings automatically using an optimization method is developed.

The article is organized as follows. The next section reviews the existing literature on the topic, highlighting relevant studies and theories that provide a foundation for the current research. The research design, Q-learning algorithm and human comfort criteria that were used in the study are discussed in methods. The following section presents the findings of the study. The results and their possible practical implications as well as limitations encountered in the current study are listed and explored in the discussion and limitations section. The article concludes with the summary of the work and suggests future directions for research in the field.

2 Theoretical Background

Mechanical impedance control is a control method that involves the manipulation of the mechanical impedance of a system to achieve precise and robust control of its motion. The concept of mechanical impedance control was first introduced by Hogan from the Massachusetts Institute of Technology (MIT) [7, 8]. Mechanical impedance control has had a significant impact on the field of robotics and control engineering. It provides a flexible and robust approach to controlling the motion of robotic systems and other mechanical systems that interact with the environment. By modulating the mechanical impedance of the system, it is possible to achieve a desired motion or interaction with the environment, while also allowing the system to adapt to changes in the load or the environment. Mechanical impedance control has been widely applied in the control of robots and manipulators (see, e.g. [14]), as well as in the development of assistive devices, such as exoskeletons and powered prostheses [3]). It was also used in the development of haptic interfaces, which provide touch feedback in virtual environments, and in the control of rehabilitation devices, such as robotic arm and leg trainers.

There are a few examples of a power-assisted control system based on a compliance controller for exoskeletons, mobile platforms and wheelchairs. The first one was developed at the Rehabilitation Institute of Chicago [2]. The second powered exoskeleton was developed by researchers at the National Institute of Advanced Industrial Science and Technology (AIST) in Japan [20]. These exoskeletons are designed to assist people with lower limb paralysis to walk by providing powered assistance to their legs. The exoskeletons use a compliance controller to adjust the impedance of the powered joints in response to the user's movements and the environment. It allows the exoskeleton to adapt to changes in the user's motion and the terrain, providing a more natural and comfortable walking experience.

Two examples of a power-assisted control system based on a compliance controller for wheelchairs include the HapticMaster developed by researchers at the Netherlands [22] and the Kinetisense developed by researchers at the University of California [18]. Both represent a powered wheelchair that uses a compliance controller to adjust the impedance of the wheels in response to the user's movements and the environment. The compliance controller allows the wheelchairs to adapt to changes in the user’s motion and the terrain, providing a more natural and comfortable ride for the operator. An examples of a power-assisted control system used for mobile platforms and trolleys could be AGV (Automated Guided Vehicle) developed by researchers at the University of Hong Kong [12]. The compliance controller adjusts the impedance of the platform’s motion in response to the load and the environment, enabling it to navigate around obstacles and maintain a stable and comfortable ride for the operator. These types of power-assisted control systems are described in Table 1. All of these projects have the potential to greatly improve the mobility and independence of people with mobility impairments, particularly in challenging environments such as rough terrain or steep slopes and the efficiency and safety of logistics operations.

Tab. 1: *Comparison of the types of power-assisted control systems*

Project name	**Year**	**Research team members**	**Main concept**
Kinetisense	2013	Hargrove, Peshkin	Powered wheelchair with compliance controller for wheels
HapticMaster	2011	Henze, Wahl, Buss, Kohl, Müller, Hertzberg	Powered wheelchair with compliance controller for wheels
Powered exoskeleton	2010	Aoyama, Iwamoto, Nakano	Powered exoskeleton with compliance controller for legs
AGV	2004	Wong, Liu, Leung	Mobile platform with compliance controller for logistics operations
Impedance-controlled exoskeleton	2004	Reinkensmeyer, Herr	Powered exoskeleton with compliance controller for legs

Source: Own

Manipulation with the object of interest requires a physical interaction. In order to fulfil the task requirements, the user chooses desired impedance that can be expressed by equation (1):

$$\mathrm{M_d}(\ddot{x} - \ddot{x}_d) + B_\mathrm{d}(\dot{x} - \dot{x}_d) + \mathrm{K}_d(x - x_d) = -\mathrm{f_e}, \tag{1}$$

where M_d,B_d and K_d are positive constants that represent the desired inertia, damping and stiffness, respectively.

From the equation (1) we can find the acceleration reference (2):

$$\ddot{x}_r = \ddot{x}_d + M_d^{-1} \cdot [-\mathrm{f_e} + B_\mathrm{d}(\dot{x}_d - \dot{x}) + \mathrm{K}_d(x_d - x)] \tag{2}$$

For admittance control, the control force is a position-controller designed to track the trajectory $x = x_d$. Trajectory tracking is implemented using a PD controller with positive gains K_p and K_d (3):

$$\mathrm{f_r} = \mathrm{K}_p(x_d - x) + \mathrm{K}_d\dot{x} \tag{3}$$

The simplified impedance controller could be written in the form (4):

$$\mathrm{M_d}(\ddot{x} - \ddot{x}_d) + B_\mathrm{d}(\dot{x} - \dot{x}_d) = -\mathrm{f_e}, \quad (4)$$

where $\mathrm{M_d}$ is mass, $\mathrm{B_d}$ refers to damping, and external force is $-\mathrm{f_e}$.

The values of $\mathrm{M_d}$ and $\mathrm{B_d}$ depend on the physical properties of the system, and the desired values $\ddot{x}_d$ and $\dot{x}_d$ can be used to specify the desired behavior of the system. Some researchers [4] found that the spring component of an impedance controller does not significantly affect the interaction process.

3 Methods

In robotics, the control of human-industrial cart interaction can be performed using a variety of techniques, depending on the specific application and requirements. In this set of experiments, Human-Robot collaboration approach was used. The platform could interact with the human, for example, by guiding the load to the desired location, assist the human with turns and stops as well as adjust to his driving technique using adaptive control.

In its turn, adaptive control in human-robot collaboration refers to the ability of a robot to adjust its behavior in response to changes in the human operator's behavior, skill level, or preferences. This allows the robot to adapt to the human's abilities and work style, leading to a more efficient and natural collaboration. Adaptive control in human-robot collaboration is currently a multidisciplinary field that combines concepts from control systems, robotics, human-computer interaction, and cognitive science.

In this part of the article, the control algorithm developed for robust and safe human robot interaction is described. An essential component for the solution is the impedance controller [9], which could be used to represent and evaluate human-operator dynamics and to control supporting effort of the mobile platform side during the interaction process. This study aims to improve human-robot physical interaction comfort in material handling tasks by incorporating AI learning methods into a smart platform. As the first step, the human operator's experience and estimation are utilized to adapt to the impedance of the platform, leading to a more personalized and comfortable interaction. This is achieved by incorporating the two strategies demonstrated in previous studies on force field tasks, as described in numerous references [11, 17]. According to these studies, humans adjust their impedance in response to perturbations by applying mainly two strategies:

1) increasing impedance through co-interaction in the case of unpredictable perturbations,
2) learning a feed-forward command to offset predictable perturbations.

By incorporating these strategies into the smart platform, we hope to minimize position error and energy consumption during material handling tasks, leading to improved efficiency and reduced physical strain of the operator.

On the other hand, the smart platform adjusts its own interaction strategy by changing the impedance parameters according to the correlation between detected features and human feelings, such as mass and damping coefficient for the former and level of operator's satisfaction for the latter. This enables the platform to adapt to the operator's individual experience in a timely manner and ensure interaction that is more comfortable. The adjustment process is accomplished using a Markov Decision Process (MDP). An MDP is a mathematical framework that is widely used to model decision-making situations. In the context of improving human-robot physical interaction comfort in material handling tasks, the MDP is used to model the decision-making process of the smart platform in adjusting its impedance parameters. An MDP is defined by the following components:

- A set of states of the world (S), which represent the various conditions or situations that the platform may encounter during material handling tasks.
- A set of actions (A), which represent the different strategies that the platform can adopt to respond to the detected states.
- A transition function (T(s, a, s')), which describes the probability of moving from one state to another state after taking an action.
- A reward function (R(s, a)), which assigns a reward or cost to each state-action pair.
- A policy (π), which defines the strategy the platform uses to select actions in each state, based on the rewards and the transition probabilities.

The platform uses this information to determine the optimal impedance adjustment that maximizes the expected reward over time, leading to improved comfort and efficiency in material handling tasks. The policy is updated iteratively as the platform learns from experience and improves its decision-making process over time. A reinforcement learning algorithm was implemented to include human feelings in the control system. As defined in Sutton and Barto's book '*Reinforcement Learning: An Introduction*' [19],

> *"Reinforcement learning is an approach to learning from interaction with an environment, by trial and error, and receiving rewards or penalties for different actions."* [19, p. xi]

Reinforcement learning algorithms are built on the concepts of MDP. The first task when designing Q-Learning system is to define the environment. The environment consists of **states**, **actions** and **rewards**. The agent uses states and rewards as inputs and generates his actions as outputs. The Q-Learning algorithm was first introduced in the framework of the PhD thesis of Watkins in 1989 [24] and developed later in 1992 [23], which stands for a model-free reinforcement learning algorithm that uses the concept of the action-value function, also known as the Q-function. The Q-function is an estimate of the expected long-term reward for a given state-action pair, and is updated iteratively as the agent interacts with the environment.

3.1 States

The number of states that may occur is limited and finite. Each possible setting of the impedance controllers can be considered as a state, and the agent can only be in one state at a time. This means that only one set of impedance controller settings can be selected and evaluated in each step. The study utilized four parameters for each impedance controller coefficient, which resulted in a total of 256 possible combinations. It is believed that this number of combinations is sufficient to demonstrate the learning process of the platform, although the trade-off between the flexibility of the settings and the time required for the learning process must be considered when determining the number of coefficients to be used in future studies.

3.2 Actions

The number of possible actions is finite. The agent will always need to choose from a fixed number of possible actions as was proved by the results of the regression analysis that was carried out for damping and mass coefficients. A set of possible actions was defined in the following way: the agent could apply two actions (increase or decrease) per each of the four parameters and carry out an additional "do nothing action" when no change was required. The change of inertial and dumping components of the impedance controller leads to a change in the cart dynamics.

3.3 Rewards

The reward system works as follows. The agent checks if the interaction dynamics is positive by comparing values of mean values and standard deviation for the current step and the previous step. Additionally, the agent checks if there is no emergency situation by analyzing the E-stop button state. Peaks of the interaction force have to be avoided as well. If a human operator thinks that the current settings are convenient for him he might give positive feedback. In the end, the rewards for different criteria are totaled. If none of the criteria were met, the reward is set to a negative one.

4 Results

Q-learning algorithm was implemented inside the high-level controller that is Raspberry Pi 4 in our case by using Python. The information about process values (interaction forces, odometry) is supplied to high-level controller from low-level controller using the serial port. Using the same link information about the actual impedance controller parameters provided to low-level controller. Protocol uses a CRC data check. The data of biological markers is read from a smart band using a BLE protocol. The console output of the learning process is shown in Figure 1.

```
Episode 36
Step 189
Current action Mdown
State_num 0
New state [2, 20, 1, 10]
Reward -1
Episode 36
Step 190
Current action Jup
State_num 4
New state [2, 20, 4, 10]
Reward -1
Episode 36
Step 191
Current action Drup
State_num 5
New state [2, 20, 4, 20]
Reward -1
Episode 36
Step 192
Current action Dtdown
State_num 0
New state [2, 20, 1, 10]
Reward -1
Episode 36
```

Source: Own

Fig. 1: *Console output of the learning process*

Information consists of the current episode number, the number of the step inside the episode, the selected action, obtained reward and the new set of impedance controller parameters to be tested. The diagram of the Q-Learning process can be presented in the shape of a pseudo-code shown in Figure 2.

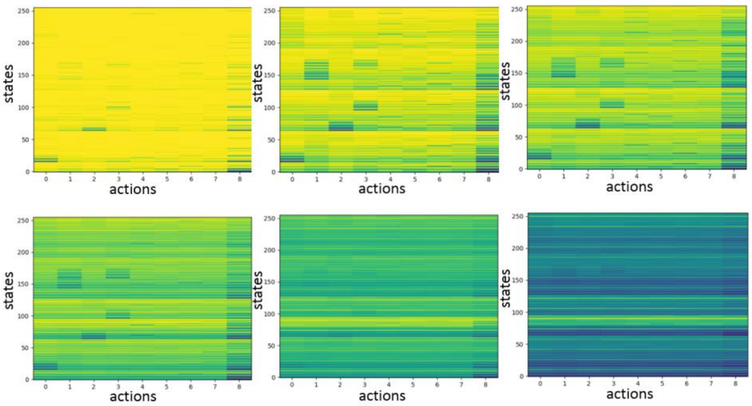
In Figure 3 the graphic visualization of the Q-table values is illustrated. The representation of the high-rating areas is depicted in yellow, while the low-rating areas are shown in blue. At the start of the interaction process, the values in the Q-Table are equal. However, as soon as the algorithm takes action, the system state will change, and the corresponding value in the Q-Table will be updated based on the reward information. The quality and speed of the reinforcement learning process are influenced by the teacher. If the human operator utilizes the user button to provide positive feedback or the e-stop to give negative feedback, it can significantly accelerate the learning process.

Q-learning: Learn function $Q : \mathcal{X} \times \mathcal{A} \to \mathbb{R}$

Require:
Sates $\mathcal{X} = \{1, \ldots, n_x\}$
Actions $\mathcal{A} = \{1, \ldots, n_a\}$, $\quad A : \mathcal{X} \Rightarrow \mathcal{A}$
Reward function $R : \mathcal{X} \times \mathcal{A} \to \mathbb{R}$
Black-box (probabilistic) transition function $T : \mathcal{X} \times \mathcal{A} \to \mathcal{X}$
Learning rate $\alpha \in [0, 1]$, typically $\alpha = 0.1$
Discounting factor $\gamma \in [0, 1]$
procedure QLEARNING($\mathcal{X}$, A, R, T, α, γ)
  Initialize $Q : \mathcal{X} \times \mathcal{A} \to \mathbb{R}$ arbitrarily
  while Q is not converged **do**
    Start in state $s \in \mathcal{X}$
    while s is not terminal **do**
      Calculate π according to Q and exploration strategy (e.g. $\pi(x) \leftarrow \arg\max_a Q(x, a)$)
      $a \leftarrow \pi(s)$
      $r \leftarrow R(s, a)$ ▷ Receive the reward
      $s' \leftarrow T(s, a)$ ▷ Receive the new state
      $Q(s', a) \leftarrow (1 - \alpha) \cdot Q(s, a) + \alpha \cdot (r + \gamma \cdot \max_{a'} Q(s', a'))$
      $s \leftarrow s'$
  return Q

Source: Own

Fig. 2: *Learning function of the Q-Learning algorithm presented in pseudo-code*



Source: Own

Fig. 3: *Dynamic change of the Q-value during the learning process*

The changes in the Q-Table over time can be observed by examining the Q-Learning dynamics. The Q-Table is visualized using a color map (heat map). Initially, the Q-Values are relatively similar, and a significant portion of the color map is depicted in yellow. Over time, the color map becomes darker as the algorithm receives negative feedback about the impedance controller settings. In the long run, the majority of the color map is covered in dark blue and green, indicating the negative impact of the impedance controller setting on the interaction process. Only a tiny yellow line remains, representing the impedance controller settings that are fully responsive to the human operator's intention. The impedance controller settings that correspond to the maximum value of the Q-Table can be obtained by selecting the corresponding state.

By observing and learning from the operator's behavior, the mobile platform can adapt its parameters to match the operator, which can improve its performance in the presence of disturbances and its ability to recover from errors. The mobile platform can learn to anticipate and avoid dangerous situations, such as collisions with obstacles or other vehicles.

Several scientific criteria are used to determine the robustness and safety of a mobile platform. These criteria include performance in the presence of disturbances, recovery from errors, safety, passivity, and efficiency. These criteria have been developed and studied over time by many engineers and scientists and have been formalized in various works, research, and standards. For instance, IEEE and ISO have developed standards for the safety and performance of mobile robots and Automated Guided Vehicles (AGVs). The specific criteria and standards used to evaluate the robustness and safety of a mobile platform will depend on the specific application and environment in which it will be used.

5 Limitations and Discussion

Having specified these criteria, we believe that the current mobile platform might be robust and safe due to the following list of reasons: the maximum speed is restricted to prevent dangerous situations and unexpected behavior. An emergency stop button (E-stop) has been implemented to ensure additional safety. Moreover, the main power switch is available to control the power supply to the system. To further prevent dangerous situations, an interlock has been implemented to avoid instant changes in direction at high-velocity set-points. The system is also designed to slow down, but not accelerate in the opposite direction without reaching a low speed to prevent sudden changes in direction. The control system with the impedance controllers of rotational and translational motion was implemented in the experimental platform. It allows supporting human operator during the linear drive and turns. By analyzing the interaction characteristics, it was possible to obtain the dynamics relevant to the material handling task and to identify the physical measures, emotional feedback and biological markers that were used as additional sources of information to improve interaction. The platform works well with loads up to 500kg. Currently, the learning outcomes include a matrix of 256 components, which is not a limit for the algorithm; however, it is believed to be sufficient for demonstration purposes.

Conclusion

A mathematical and experimental model of the industrial power-assisted cart was developed. A great amount of work was performed in powered mobile platform programming and control system implementation. Therefore, artificial intelligence (AI) methods were employed to adjust the controller settings so that an operator can manipulate an industrial cart loaded up to 500 kg with minimum physical effort and ultimate comfort. Human estimation criteria that characterize the satisfaction and comfort from the human-powered cart interaction process were synthesized. Based on these synthesized criteria, the human-powered cart interaction control algorithm was developed using AI methods (Q-learning). The performance of the proposed solution for the developed industrial cart was tested and verified. The research work contributed the following theoretical input into the field of technical cybernetics – the use of Q-learning algorithm in adjusting controller settings so that the mobile platform could successfully and effectively adapt to the unique gait and tasks of any operator it assists.

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ZLEPŠENÍ KOMFORTU FYZICKÉ INTERAKCE MEZI ČLOVĚKEM A ROBOTEM PŘI MANIPULACI S MATERIÁLEM POMOCÍ INTELIGENTNÍ PLATFORMY

Používání mobilních platforem může zaměstnancům pomoci automatizovat manuální procesy a zefektivnit operace, aby ušetřili čas a mohli bezpečně a přesně plnit své úkoly. Vozidlo s motorovým pohonem pro přemisťování hmotnosti na místě je levné, snadno použitelné, spolehlivé a bezpečné řešení. Dokáže se přizpůsobit různým úkolům při zatížení až 500 kg. Cílem studie je zvýšit efektivitu a snížit fyzickou zátěž obsluhy při úkolech spojených s manipulací s materiálem a podpořit zavádění této inteligentní platformy. Metody učení umělé inteligence se používají k přizpůsobení individuálním zkušenostem operátora, což vede k personalizované a pohodlnější interakci s pomocí algoritmu Q-learning s 256 výsledky učení při úpravě nastavení ovladače (tlumení, hmotnost, tuhost).

VERBESSERUNG DES KOMFORTS DER INTERAKTION ZWISCHEN MENSCH UND ROBOTER BEIM UMGANG MIT MATERIAL MIT HILFE EINER INTELLIGENTEN PLATTFORM

Die Verwendung mobiler Plattformen kann den Angestellten bei der Automatisierung manueller Prozesse und bei der Effektivierung der Operation helfen, Zeit zu sparen und sicher und exakt ihre Aufgaben zu erfüllen. Ein Fahrzeug mit Motorantrieb zur Umsetzung von Masse am Ort ist eine billige, einfach handzuhabende, verlässliche und sichere Lösung. Es vermag sich verschiedenen Aufgaben bei einer Belastung von 500 kg anzupassen. Das Ziel dieser Studie besteht in der Steigerung der Effektivität und der Senkung der physischen Belastung der Bedienung der mit dem Umgang mit Material verbundenen Aufgaben sowie in der Unterstützung der Einführung dieser intelligenten Plattform. Die Lehrmethoden der künstlichen Intelligenz finden zur Anpassung an die individuellen Erfahrungen des Operators Verwendung, was führt zu personalisierten und bequemeren Interaktion mit Hilfe des Algorithmus Q-Learning mit 256 Ergebnissen der Lehre bei der Angleichung der Einstellung des Reglers (Dämpfung, Gewicht, Zähheit).

POPRAWA KOMFORTU FIZYCZNEJ INTERAKCJI MIĘDZY CZŁOWIEKIEM A ROBOTEM PRZY OBSŁUDZE MATERIAŁÓW PRZY POMOCY INTELIGENTNEJ PLATFORMY

Korzystanie z platform mobilnych może pomóc pracownikom zautomatyzować manualne procesy i usprawnić operacje, aby zaoszczędzić czas i wykonywać swoje zadania bezpiecznie i dokładnie. Pojazd z napędem silnikowym do przemieszczania ciężarów na miejscu to tanie, łatwe w użyciu, niezawodne i bezpieczne rozwiązanie. Może dostosować się do różnych zadań z obciążeniem do 500 kg. Celem badania jest zwiększenie wydajności i zmniejszenie obciążenia fizycznego operatorów podczas zadań związanych z transportem materiałów oraz wsparcie wdrażania tej inteligentnej platformy. Metody uczenia sztucznej inteligencji są wykorzystywane do dostosowania się do indywidualnych doświadczeń operatora, co prowadzi do bardziej spersonalizowanej i wygodnej interakcji przy użyciu algorytmu Q-learning z 256 wynikami uczenia się podczas dostosowywania ustawień sterownika (tłumienie, waga, sztywność).

EVALUATING ELECTRICITY CONSUMPTION OF SPECIALISED BATTERY ELECTRIC VEHICLES USING SIMULATION MODEL

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Abstract

Battery Electric Vehicles (BEVs) are widely seen as one of the available options to combat increasing greenhouse gas emissions. However, these vehicles' use is less widespread than conventional combustion engine vehicles. One reason for this is their still relatively short range and long charging times. For this reason, it is becoming increasingly crucial in BEV development to use the most accurate simulation models that allow the impact on electricity consumption to be analyzed based on changes made to individual powertrain components. To this end, the author's dissertation deals with developing a simulation model for estimating the power consumption of a BEV powertrain, describing the definition of the efficiency parameters of the individual powertrain components. The results from the simulation model were then compared with measurements performed in a test facility. The maximum deviation of approximately 8% was measured depending on the driving cycle and parameters.

Keywords

Energy consumption; Simulation; Powertrain; BEV; Efficiency.

Introduction

Battery electric vehicles are now becoming an increasingly common alternative to vehicles with ICE. Their gradual expansion is mainly due to the desire to reduce greenhouse gas emissions and protect the environment. This effort is supported by the European Union's long-term strategy [1], which aims to transform the transport system in Europe by 2050, thereby contributing to reducing emissions and increasing the use of renewable energies. According to the results published in [2], unlike other sectors, greenhouse gas emissions in road transport have increased by 27.8% from 1990 to 2019, and despite the decline caused by the Covid-19 crisis, emissions are expected to increase again briefly in the coming years. However, this increase will be gradually eliminated by better energy efficiency, reduced energy consumption and the use of alternative fuels. In this respect, BEVs offer higher efficiency, i.e. higher energy savings and emission reductions (especially if the electricity is generated from renewable sources). According to the results published in [3], BEVs are more efficient than gasoline or diesel vehicles in terms of emissions in all scenarios considered. In the ideal case where an EV is charged only with electricity generated from renewable sources and is equipped with a battery produced in an environmentally friendly way, EVs are about five times more environmentally friendly than conventional vehicles with combustion engines.

As mentioned in [2], BEVs are expected to reduce their greenhouse gas emissions in the future, mainly due to the increasing efficiency of these vehicles. Simulation models are ones of how this problem can already be accelerated today. Despite advances in EVs, many factors are still to consider, and simulation models are still an essential tool to achieve the best results. These simulation models allow us to calculate how specific changes made to an individual component of a vehicle will affect its performance and electricity consumption based on the exact data of each component. These models can then incorporate many factors into the calculation, which may include, for example, the effect of ambient conditions or the driver's driving style, in addition to the physical parameters of the individual vehicle components. This allows researchers and vehicle manufacturers to create the highest possible efficiency of BEVs.

1 Research Subject

The present work describes the design of the BEV simulation model, a description of the input parameters definition and its validation. With the help of this model it will be possible to estimate the power consumption of the powertrain and thus determine with sufficient accuracy, among other things, the range of the vehicle. All this is to search for the potential to improve its energy efficiency. In contrast to other publications that assume constant efficiency of the individual powertrain components, the effort is to include in this model, as precisely defined as possible, the efficiency maps of the mentioned components as a dependence of torque on speed over the entire range in which the specific component will operate.

2 Methodology

The research in this article is based on a simulation model of the driving dynamics of a battery electric vehicle, which allowed us to define the powertrain consumption of the vehicle during specific driving cycles. The simulation model was created in software Ricardo Ignite [4]. The results from this simulation were then validated in a dedicated facility. The Ricardo Ignite software based on the Modelica programming language is commonly used in the automotive industry to simulate various dynamic phenomena. The software contains many libraries that make it possible to model various powertrain components of commercially available vehicles.

2.1 Simulation Model

Currently, according to [5], two types of simulation models are mainly used to simulate vehicle driving dynamics. These are the forward simulation model and the backward simulation model. The fundamental difference between these simulation models lies in the calculation procedure. In this work, we have used the forward simulation model to calculate the power consumption of the powertrain. In this case, it provides more accurate results than the backward simulation model, albeit at the cost of higher computational time. The architecture of the forward simulation model describing the general arrangement of the elements is shown in Figure 1.

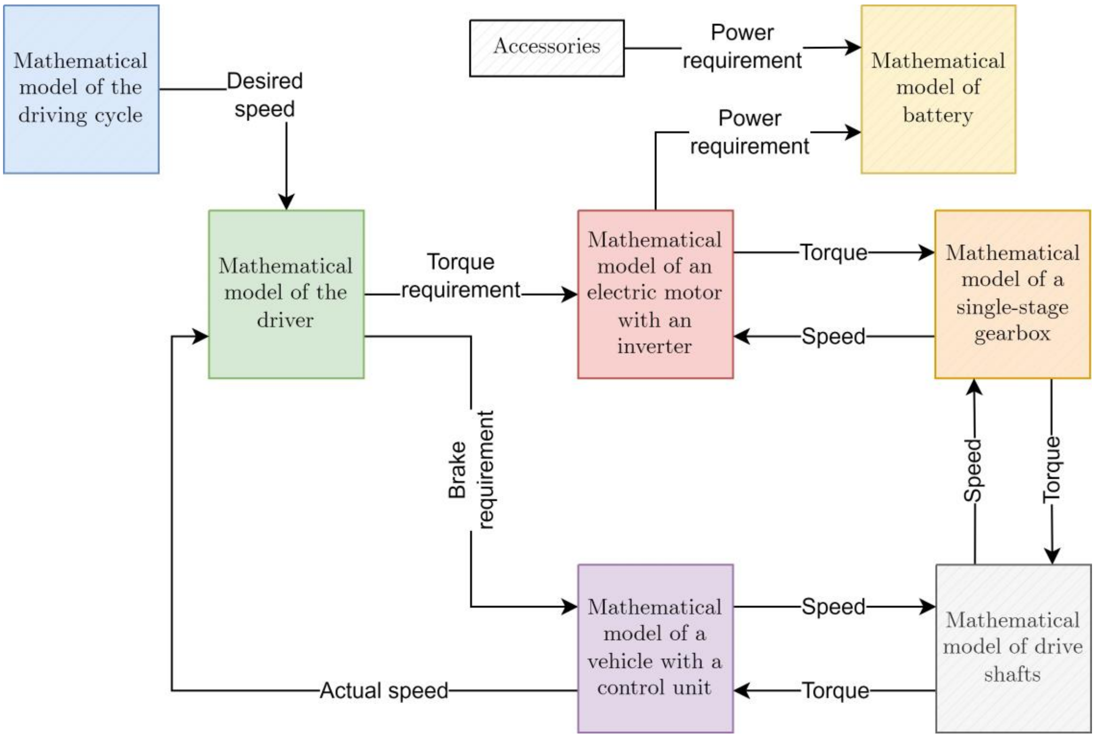

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Fig. 1: *Layout of the simulation model*

2.1.1 Description of Defined Input Parameters

To ensure the desired function of the simulation model, it was necessary to define the parameters of the individual mathematical blocks that make up the model. These elements of the model include various aspects of the vehicle, such as powertrain parameters, environmental parameters and driving cycle parameters, on which the simulation model results are evaluated. The parameters of a specific vehicle were defined through detailed analyses of the different parts of its powertrain, which included, for example, the characteristics of the engines, transmission, and batteries, including a detailed definition of their efficiency at different speeds and different loads. Table 1 lists the basic vehicle parameters considered in the simulation. In addition to these parameters, environmental parameters such as terrain topography, temperature and weather conditions that can affect the vehicle behaviour were also included in the individual models. Another important aspect in developing the simulation model was defining the driving cycle parameters to match the actual vehicle operation as closely as possible. In this case, two driving cycles were simulated, which are the CARB Heavy-Duty Diesel Truck (HHDDT) Creep Segment (CARB-HHDDT-CS) and the NREL Port Drayage Creep Queue Cycle (California) (NREL-PDCQC). Both drive cycles were taken from the Drive Cycle Analysis Tool (DriveCAT) [6], which provides drive cycle data based on real vehicle operations. The CARB-HHDDT-CS drive cycle was developed in California and is used for testing heavy-duty vehicles. The second driving cycle, NREL-PDCQC, is used for testing trucks that are used to transport goods in port areas. This driving cycle focuses on speeds up to 30 km/h and frequent stopping and starting of the vehicle, corresponding to the actual operation of vehicles in port areas.

Tab. 1: *Basic parameters of the vehicle*

Parameter	Value
Rated torque of one electric motor	42 Nm
Rated power of one electric motor	10 kW
Total vehicle weight	3000 kg
Dimensions (h x w x l)	1000 mm x 1925 mm x 3850 mm
Maximum speed	30 kmh^{-1}
Vehicle frontal area	1,82 m^2
Air drag coefficient	0,6
Tyre outer radius	0,362 m
Coefficient of rolling resistance	0,1

Source: Own

A unique feature of the modelled vehicle is that it comprises four identical electric motors and four converters with each electric motor driving one wheel. Related to this is the identical number of single-speed gearboxes and drive shafts. At the same time, the vehicle contains a single electric battery that is common to all the high-voltage electric elements. According to the definition of the powertrain of electric vehicles given in [7], the vehicle can contain four powertrains. For this reason, the results below will only be given for “one-quarter of the vehicle”, i.e. one powertrain. The system of one powertrain mounted on one vehicle axis is highlighted in blue in Figure 2.

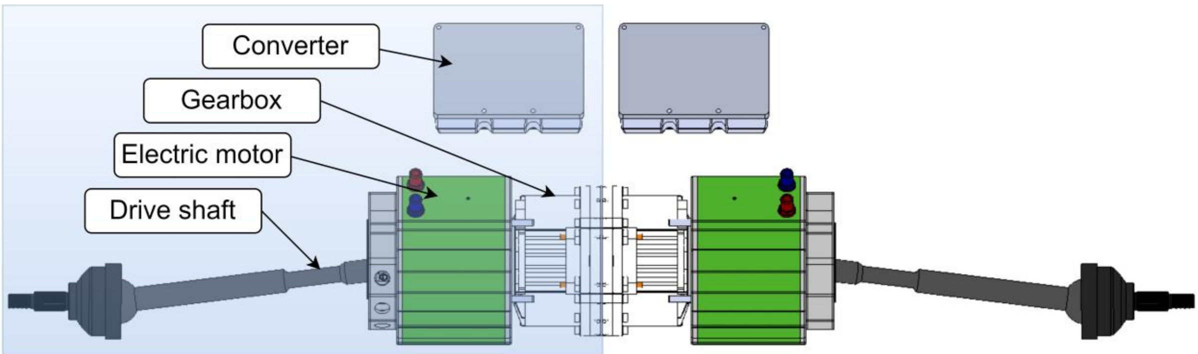

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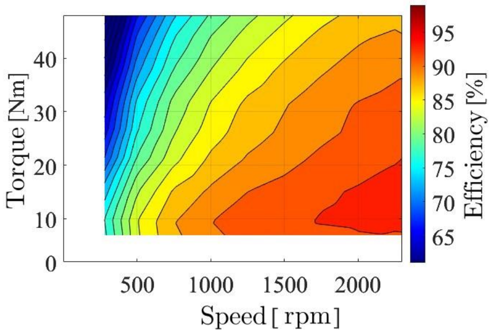
Fig. 2: *Two powertrains on one vehicle axis with the evaluated driveline highlighted*

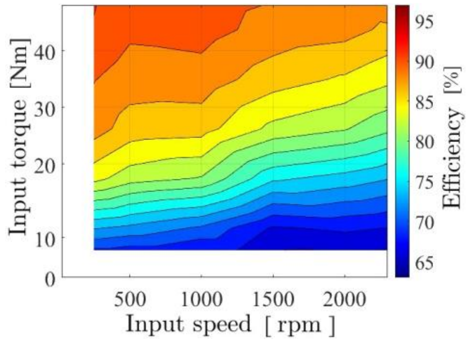
2.2 Determining the Efficiency of Individual Powertrain Components

Along with defining the general vehicle parameters, it was necessary to determine the efficiencies of the individual powertrain components in the relevant mathematical models. Although individual powertrain components currently achieve relatively high efficiencies, the product of these efficiencies across the whole system can significantly impact the vehicle’s overall efficiency. It could adversely affect the results generated by the simulation model. The efficiency of electric vehicles (“Tank to Wheel”) can range from 50% to 80% for BEVs according to study [8]. In order to determine the efficiencies of the individual components in the respective mathematical models, the equipment and test facilities available at the powertrain laboratory of the Technical University of Liberec were used. Among the most crucial equipment we can mention the engine test bench with dynometer HORIBA $DYNAS_3$ LI 250 and the Powertrain test bench designed for long-term tests of the entire powertrain system of all types of vehicles.

In total, three measurements were performed in the experimental part which is shown in Figure 3. The individual sub-figures show the efficiency maps of the individual components of the powertrain of the vehicle under consideration, which are the electric motor system with converter in Figure 3 (a), and the gearbox in Figure 3 (b). These maps represent the efficiency as a dependence of speed on torque.



(a) Efficiency of the electric motor with converter



(b) Efficiency of gearbox

Source: Own

Fig. 3: *Efficiency of the electric motor with converter and gearbox*

The efficiency of the electric motor and converter was measured on a motor station equipped with an asynchronous dynamometer HORIBA DYNAS$_3$ LI 250, to which a shaft coupling connected the electric motor. A battery emulator of a high voltage battery with a DC source ITECH IT6000C realized the power supply of the electric motor and the inverter. This power supply was set to deliver a maximum voltage of 100 V. The maximum current was limited to ± 290 A. The input power was calculated from the voltage supplied and the current drawn. The output power was then calculated from the speed and torque of the electric motor. The electric motor was operated at a certain speed level with a gradual increase in torque. The speed of the electric motor was increased in steps of 250 rpm and the torque of the motor in steps of 5 Nm. The electric motor was operated at each defined point for 40 s. The first 10 s were used for settling the values and the subsequent 30 s for the data recording. From the data thus recorded, an average value was then calculated for each variable, which was fitted into relationship (1), where P_{dyno} is mechanical power measured on dynamometer and P_e is the electrical input power of the assembly of electric motor and the converter.

$$\eta_m(n, M) = \frac{P_{dyno}}{P_e} = \frac{2 \cdot \pi \cdot \frac{\overline{n_{dyno}}}{60} \cdot \overline{M_{dyno}}}{\overline{U_{DC}} \cdot \overline{I_{DC}}} \tag{1}$$

The second step was to define the mechanical efficiency of the gearbox. This efficiency was determined using a method referred to in the literature as “*Back to back electrical*” [9], where the gearbox is placed between two dynamometers, one connected to the input and the other to the output shaft of the gearbox. One of these dynamometers always serves to drive the gearbox and the other serves as a load. For this purpose, the Powertrain test bench, also available in the powertrain laboratories at the Technical University of Liberec, was used. Both dynamometers are equipped with speed and torque sensors used to calculate the power on input and output shafts. As in the previous case, the gearbox was loaded for 40 s, with the first 10 s being used for settling the values and the subsequent 30 s for the actual data recording. From the data recorded in this way the average value for each variable was calculated and then the mechanical efficiency at each measured point was calculated according to relationship (2), where P_{PP} is the mechanical power measured on the front right dynamometer and P_{LP} is the mechanical power measured on front left dynamometer. The measurements were again always carried out for a certain speed level with a gradual increase in torque. The speed was increased in the interval of 250 rpm and the torque in the interval of 8 Nm.

$$\eta_{pr}(n,M) = \frac{P_{PP}}{P_{LP}} = \frac{2 \cdot \pi \frac{\overline{n_{PP}}}{60} \cdot \overline{M_{PP}}}{2 \cdot \pi \frac{\overline{n_{LP}}}{60} \cdot \overline{M_{LP}}}, \tag{2}$$

The last component of the powertrain is the drive shaft. The mechanical efficiency of the drive shaft was not directly measured in this work. The drive shaft usually comprises two joints of the Rzeppa and Tripod type. The overall efficiency of the drive shaft depends precisely on the efficiency of these joints, which depends mainly on their angle. If I consider the zero angle of the joints in this work, i.e. the wheel axis is in alignment with the output shaft of the gearbox, I will take the efficiency of these joints from work [10] where the mechanical efficiency of the Tripod joint was defined as 99.8% and the mechanical efficiency of the Rzeppa joint as 99.5%. Multiplying these values according to the relation (3) gives an overall efficiency of one drive shaft 99.3%.

$$\eta_h(n, M) = \eta_{Tripod}(n, M) \cdot \eta_{Rzeppa}(n, M) \tag{3}$$

2.3 Calculating Energy Consumption Using a Simulation Model

The above-defined efficiencies of the individual powertrain components were then defined in the corresponding mathematical models. Subsequently, a calculation was performed in which the simulation model provided the results of the energy consumed by the powertrain. These results are presented in this chapter. The simulation model calculates the cumulative energy consumption shown in Figure 4.

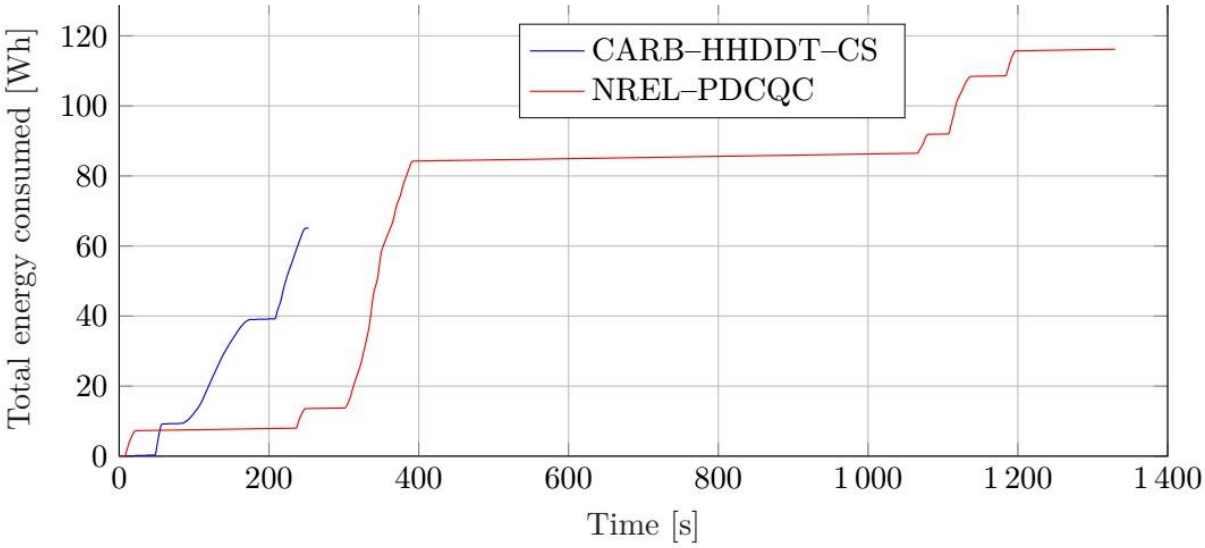


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Fig. 4: *Energy consumption during individual driving cycles obtained from the simulation model*

From the results, we can see that in the case of the CARB-HHDDT-CS driving cycle, which is marked here in blue, the total accumulated energy extracted from the battery was equal to 65.1 Wh, while the driving time of the vehicle on this driving cycle is 253.8 s. During the simulated driving during the second NREL-PDCQC driving cycle, the vehicle moved 1330 s with a total consumed accumulated energy 119.5 Wh.

2.4 Validation of the Simulation Model

The validation of the correct simulation model consisted in comparing its results of energy consumed by the powertrain with the consumption of the real powertrain. For this purpose, the aforementioned Powertrain test bench was used again. The powertrain of the vehicle consisting of the electric motor, the converter, the gearbox, and the drive shaft, including all necessary accessories, was placed on the test bench similarly as described in chapter 2.2. In this case, the gearbox's output shaft was also connected by a drive shaft to a dynamometer in the test room which replaced the car wheel. The electric motor and converter were again powered by a high-voltage battery emulator with a DC power supply ITECH IT6000C. The control system of the testbed controlled the electric motor and dynamometer to accurately simulate the vehicle driving at speeds defined by the speed profiles of the driving cycles under test. The energy drawn from the battery emulator was recorded during these driving cycles.

3 Results

This chapter presents the results of electricity consumption from measurements and simulation for both driving cycles. From the data shown in Figures 5 and 6 it can be seen that the results produced by the simulation model (red) show a relatively high agreement with the results obtained from the measurements (blue) carried out on the Powertrain test bench on both driving cycles. Despite this relatively good agreement, it is essential to note that the simulation model slightly overestimates the powertrain power consumption. This phenomenon was observed for both driving cycles. For the CARB-HHDDT driving cycle, the total measured energy drawn from the battery was 56.9 Wh. In this case, the calculated value from the simulation was 59.9 Wh. The results measured during the NREL-PDCQC run look similar. In this case, the measured total energy consumption was 114.3 Wh, and the calculated value was 123.7 Wh. Based on these data, it can be said that the percentage deviation is approximately 5% for the CARB-HHDDT run and 8% for the NREL-PDCQC run.

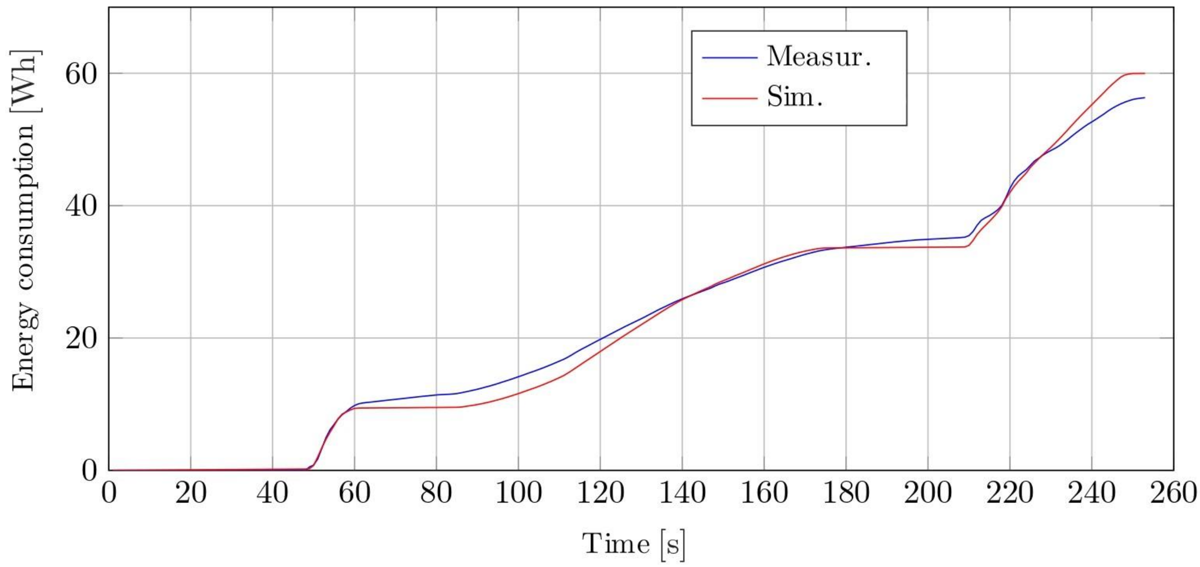

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Fig. 5: *Comparison of cumulative powertrain consumption values from simulation and measurements on drive cycle CARB–HHDDT–CS*

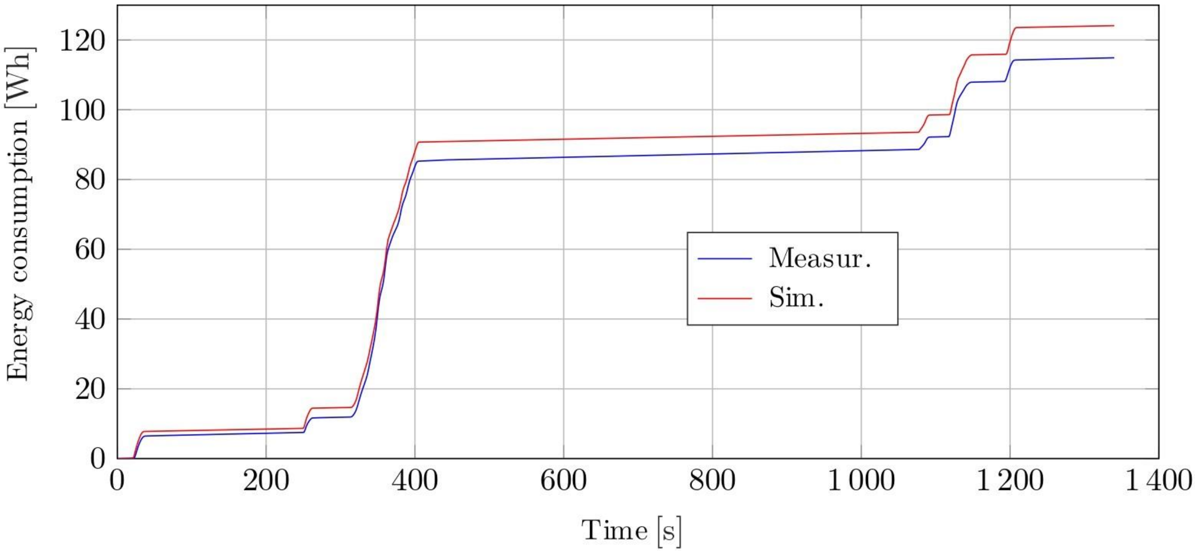

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Fig. 6: *Comparison of cumulative powertrain consumption values from simulation and measurements on drive cycle NREL–PDCQC*

Conclusion

The main objective of this research was to describe and implement a simulation model of a four-motor electric vehicle that would calculate the power consumption of the vehicle's powertrain with the required accuracy.

Evaluating powertrain power consumption using a simulation model and experimental measurements in the laboratory are two different approaches that differ in their advantages and limitations. Different scenarios and vehicle operating conditions can be easily investigated using a simulation model, allowing accurate determination of energy consumption in different situations. Simulations also provide the opportunity to investigate the effect of different components on the overall energy consumption of the vehicle, which can lead to the optimization of the powertrain design. The disadvantage of this solution is that the simulation model needs to be often and adequately tediously tuned so that the results provide sufficient accuracy. On the other hand, measurements made in the laboratory provide results for the specific type of driveline that will be installed in the vehicle, often without the need for further tuning, but the accuracy of the sensors used must be taken into account.

The results of this research have shown that the simulation model thus developed can predict the amount of energy consumed in the vehicle drivetrain with an accuracy of more than 8% (depending on the driving cycle). Although there is still room for increasing the accuracy of the calculation and the related further refinement of the simulation model, I believe that using the proposed simulation model and the described approach for defining the efficiency of the individual elements of the powertrain can be used to evaluate with sufficient accuracy the consumption of the aforementioned four-engine vehicle.

Acknowledgment

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HODNOCENÍ SPOTŘEBY ELEKTRICKÉ ENERGIE SPECIALIZOVANÝCH BATERIOVÝCH ELEKTRICKÝCH VOZIDEL POMOCÍ SIMULAČNÍHO MODELU

Bateriová elektrická vozidla (BEV) jsou v současné době všeobecně považována za jednu z dostupných možností boje proti rostoucím emisím skleníkových plynů. Jejich rozšíření je však stále výrazně menší než v případě vozidel s konvenčním spalovacím motorem. Z důležitých faktorů, které brání jejich širšímu rozšíření, je jejich stále relativně krátký dojezd a dlouhá doba nabíjení. Z tohoto důvodu je při vývoji BEV stále důležitější používat co nejpřesnější simulační modely, které umožňují analyzovat dopad změn provedených na jednotlivých komponentech hnacího ústrojí na spotřebu elektrické energie vozidla. Za tímto účelem se autorova disertační práce zabývá vývojem simulačního modelu pro odhad spotřeby elektrické energie hnacího ústrojí BEV a popisuje způsob definování činnostních parametrů jednotlivých komponent hnacího ústrojí. Výsledky ze simulačního modelu pak byly porovnány s měřeními provedenými ve specializované zkušebně. V závislosti na jízdních cyklech byla naměřena maximální odchylka přibližně 8 %.

BEWERTUNG DES VERBRAUCHS ELEKTRISCHER ENERGIE SPEZIALISIERTER BATTERIEBETRIEBENER FAHRZEUGE MIT HILFE EINES SIMULATIONSMODELLS

Batteriebetriebene Fahrzeuge (Battery Electric Vehicles / BEV) werden weitgehend als eine der machbaren Mittel zur Bekämpfung der Treibhausgase betrachtet. Allerdings sind diese Fahrzeuge bislang weit weniger verbreitet als Fahrzeuge mit Verbrennungsmotoren. Ein Grund dafür besteht in ihrer noch immer relativ kurzen Reichweite und der langen Ladezeit. Aus diesem Grunde wird es bei der Entwicklung von BEV immer wichtiger, möglichst genaue Simulationsmodelle zu verwenden, welche eine Analyse der Auswirkung der an den einzelnen Komponenten des Antriebssystems ausgeführten Änderungen der auf den Energieverbrauch eines batteriebetriebenen Fahrzeugs ermöglichen. Zu diesem Zweck beschäftigt sich die Dissertation des Autors mit der Entwicklung eines Simulationsmodells zur Schätzung des Verbrauchs elektrischer Energie des Antriebssystems eines BEV und beschreibt die Art und Weise der Definierung der Tätigkeitsparameter der einzelnen Komponenten des Antriebssystems. Die Ergebnisse aus dem Simulationsmodell wurden dann mit den in einem spezialisierten Versuchslabor durchgeführten Messungen verglichen. In Abhängigkeit von den Fahrzyklen wurde eine maximale Abweichung von etwa 8 % gemessen.

OCENA ZUŻYCIA ENERGII ELEKTRYCZNEJ PRZEZ SPECJALISTYCZNE AKUMULATOROWE POJAZDY ELEKTRYCZNE PRZY UŻYCIU MODELU SYMULACYJNEGO

Akumulatorowe pojazdy elektryczne (APE) są obecnie powszechnie uważane za jedną z dostępnych opcji walki z rosnącą emisją gazów cieplarnianych. Jednak ich wykorzystanie jest nadal znacznie niższe niż w przypadku pojazdów z konwencjonalnym silnikiem spalinowym. Wśród ważnych czynników, które uniemożliwiają ich szersze rozpowszechnienie, jest ich wciąż stosunkowo niewielki zasięg i długi czas ładowania. Z tego powodu w rozwoju APE coraz ważniejsze staje się wykorzystanie najdokładniejszych modeli symulacyjnych, które umożliwiają analizę wpływu zmian wprowadzonych w poszczególnych komponentach układu napędowego na zużycie energii przez pojazd. W tym celu rozprawa doktorska autora dotyczy opracowania modelu symulacyjnego do szacowania zużycia energii elektrycznej przez układ napędowy APE oraz opisuje metodę definiowania parametrów pracy poszczególnych elementów układu napędowego. Wyniki modelu symulacyjnego zostały następnie porównane z pomiarami wykonanymi w specjalistycznym centrum testowania. W zależności od cykli jazdy zmierzono maksymalne odchylenie wynoszące około 8 %.

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