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INHALT

VORWORT

Die vorliegende vierte Ausgabe des Bavarian Journal of Applied Sciences (BJAS) legt den Schwerpunkt auf Mobilität. Intelligente Mobilität ist einer der Forschungsschwerpunkte an der THD und umfasst sowohl Elektromobilität, Geoinformatik, Verkehrsträgermanagement und Tourismus als auch Logistik. Darüber hinaus knüpfen andere Forschungsthemen, wie mobiles Eye-Tracking und Digitalisierung in der Weiterbildung an diese Mobilitätsthemen an.

Der Eröffnungsbeitrag mit dem Titel „There's No Need to Drive from A to B" ist nur scheinbar provozierend positioniert. Elektronisch unterstütztes Lernen (*E-Learning*) kann dabei mitwirken, das Verkehrsaufkommen zu reduzieren und damit einen Beitrag zu intelligenter Mobilität leisten. Die Arbeit von Andreas Gegenfurtner, Christian Ebner und Nina Schwab setzt sich mit den Bedingungen auseinander, die gegeben sein müssen, damit alle beteiligten Akteurinnen und Akteure von den verschiedenen E-Learning-Formaten tatsächlich profitieren können.

Um den Ausstoß von CO_2 und anderen klimaschädlichen Gase zu senken, ohne notwendigerweise das Verkehrsaufkommen zu reduzieren, wird der Umstieg auf Elektromobilität (E-Mobilität) in Praxis, Politik und Forschung schon seit längerem diskutiert und vorangetrieben. Zwei Beiträge beschäftigen sich mit der Frage, wie E-Mobilität so attraktiv werden kann, dass der Anteil an Elektrofahrzeugen spürbar steigt. Ausgangspunkt für beide Beiträge ist die sogenannte Reichweitenangst, d.h. die Befürchtung, die Ladung des Akkus reiche nicht aus, um von A nach B zu gelangen.

Der Beitrag "Extracting Relevant Points of Interest from Open Street Map to Support E-Mobility Infrastructure Models" von Javier Valdes, Jane Wuth, Roland Zink, Sebastian Schröck und Matthias Schmidbauer beschäftigt sich mit der Ladeinfrastruktur für Elektrofahrzeuge. Wie kann die Planung des Ladesäulen-Netzwerks in ländlichen Regionen geographisch sinnvoll umgesetzt werden? Die Autorin und die Autoren plädieren dafür, in ländlichen Regionen nicht nur kommerziell bereitgestellte Geodaten in die Planung miteinfließen zu lassen, sondern auch freiwillig erhobene und der Öffentlichkeit kostenfrei bereitgestellte Geodaten, so genannte *Volunteered Geographic Information (VGI)*. VGI können aus ihrer Sicht unter bestimmten Bedingungen die Bedürfnisse der Fahrerinnen und Fahrer von Elektrofahrzeugen präziser abbilden. Am Beispiel der *Open-Data-*Plattform OpenStreetMap wird für die Grenzregion Bayern-Tschechien diskutiert, welche Daten auf welche Weise aufbereitet und bereinigt werden müssen, um in ein geographisches Modell zur Planung der Ladeinfrastruktur für Elektromobilität in ländlichen Regionen integriert werden zu können.

Diana Schramm, Nicki Bodenschatz, Markus Eider und Andreas Berl beschäftigen sich mit der Reichweitenangst aus der Fahrzeugperspektive. In ihrem Beitrag „Usage Profiling in Electric Vehicles" stellen sie ein Verfahren vor, mit dessen Hilfe die Berechnung der noch verbleibenden Reichweite des Akkus während der Fahrt präziser und somit verlässlich gestaltet werden kann. In einem ersten Test wurde der Fahrstil mithilfe der Nutzungsdaten des Gas- und Bremspedals bei verschiedenen, vorher definierten Fahrstilen erfasst. Daraus wurde eine Fahrstilklassifikation

The present fourth issue of the Bavarian Journal of Applied Sciences (BJAS) is all about mobility. *Intelligent Mobility* is one research focus area at Deggendorf Institute of Technology (DIT). It includes electromobility, geoinformation and geoinformatics, transport management, tourism and logistics. Research subjects like e-learning in further education and mobile eye-tracking connect nicely to these mobility-related topics.

The fourth issue opens with a contribution dedicated to e-learning in further education, titled "There's No Need to Drive from A to B". This opening headline may, at first glance, seem kind of provocative for an issue on mobility. Electronic learning has a role in decreasing CO_2 and other climate-damaging emissions by reducing the volume of traffic, thus, in a sense, it serves the concept of intelligent mobility. Andreas Gegenfurtner, Christian Ebner and Nina Schwab discuss the conditions under which all participants may gain a real benefit from e-learning offers in further education.

Shifting away from internal combustion engines to all-electric vehicles without necessarily reducing traffic volume is a governmental commitment to cutting CO_2 and other greenhouse gas emissions. This groundbreaking transition is a hot topic for politicians, researchers and the industry alike. Two contributions discuss possibilities of reducing range anxiety. The term range anxiety describes the common worry of becoming stranded with a depleted battery in a vehicle with limited range. It is considered to be one of the major barriers to switching from an internal combustion engine vehicle to an electric one.

The contribution „Extracting Relevant Points of Interest from Open Street Map to Support E-Mobility Infrastructure Models" by Javier Valdes, Jane Wuth, Roland Zink, Sebastian Schröck and Matthias Schmidbauer focuses on EV charging infrastructure. They ask how the geographical distribution of charging infrastructure in rural regions can be planned in a way that meets the needs of EV drivers and complies with their daily routines. The authors suggest combining commercially available geoinformation with open-source *Volunteered Geographic Information (VGI)* to enable sustainable planning in rural regions. VGI is geospatial content generated by non-professionals, accessible for the public at no cost. According to Roland Zink and colleagues, VGI may more precisely map EV users' charging needs. Based on data generated within a research project on electromobility in the Bavarian-Czech border region, they discuss a model that includes VGI from OpenStreetMap. Their paper addresses the conditions under which VGI might be considered in a model for the planning of charging infrastructure and how OSM data would have to be purged and prepared.

In the following contribution „Usage Profiling in Electric Vehicles", Diana Schramm, Nicki Bodenschatz, Markus Eider and Andreas Berl deal with range anxiety from the car's perspective. They present a method for making the remaining range calculation more precise by considering driving behavior. In their tests, the driving behavior was captured by means of characteristic gas and brake pedal operations. Other variables included into their optimized range model were velocity, road topography and weather conditions. The tests confirmed that the continuous integration of driving behavior contributes to making predictions on remaining range more precise and reliable.

VORWORT

trainiert. Diese Daten und die Fahrstilklassifikation wurden in ein optimiertes Reichweitenmodell integriert, welches das Höhenprofil der Route, Wetterdaten und die Geschwindigkeit berücksichtigt. Durch die Integration des individuellen Fahrstils in die laufende Berechnung während einer Fahrt kann die Präzision der Reichweitenanzeige erhöht werden.

Auch im Bereich Logistik geht es gerade beim Einsatz mit Gabelstaplern neben der Reduktion von Kosten um Ressourcenschonung und die Verminderung des CO_2-Ausstoßes. Der Beitrag „A Simulation-Based System for Calculating Optimal Numbers of Forklift Drivers in Industrial Plants“ geht der Frage nach, wie sich der Einsatz von Gabelstablern zeit-, kosten- und ressourcensparend optimieren lässt. Diane Ahrens und Mohammad Alnahhal diskutieren statistische Optimierungsmodelle unter Verwendung der Warteschlangentheorie.

Der abschließende Beitrag von Andreas Gegenfurtner und Kolleginnen und Kollegen gibt eine umfassende Übersicht zu den breitgefächerten Einsatzmöglichkeiten des mobilen Eye-Trackings und befasst sich mit dessen Möglichkeiten und Grenzen. Die Autorinnen und Autoren sehen vor dem Hintergrund der zunehmenden Digitalisierung gerade für anwendungsbezogene Forschung in den Bereichen autonomes Fahren, Gesundheitswissenschaften, Sport und Usability Engineering großes Potential im Einsatz dieser innovativen Technologie.

Die Herausgeber danken den Reviewern aller eingereichten Beiträge für ihre wertvolle Arbeit und ihre Zeit. Für die vierte Ausgabe des Bavarian Journal of Applied Sciences wünschen wir Ihnen aufschlussreiche Einblicke in die anwendungsorientierten Forschungsbereiche und eine anregende Lektüre.

Logistics, specifically material handling by forklifts, is another area where cost reduction but also the reduction of resource consumption and the emission of CO_2 are relevant factors. The contribution “A Simulation-Based System for Calculating Optimal Numbers of Forklift Drivers in Industrial Plants” by Diane Ahrens and Mohammed Alnahhal describes a tool for optimizing forklifts operations with regard to performance, time, costs and resource efficiency. The authors propose integrating queueing theory into the statistical model for optimizing the forklift system.

The final contribution by a group of researchers around Andreas Gegenfurtner provides a detailed synopsis on the multifaceted and ever increasing use of mobile eye tracking in different areas of applied research. It discusses the possibilities and limitations of this technology in autonomous driving, sports/health sciences, augmented/mixed/virtual reality and usability engineering and reflects on potential lines of future research.

The editorial team would like to thank the reviewers of the submitted articles. We very much appreciate the time and effort they invested in providing their reviews. We wish you inspiring insights when reading this new issue of the Bavarian Journal of Applied Sciences.

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“There's No Need to Drive from A to B”:

Exploring the Lived Experience of Students and Lecturers with Digital Learning in Higher Education

Andreas Gegenfurtner* **Nina Schwab*** **Christian Ebner***

ABSTRACT

In many rural regions worldwide, people drive by car or ride a bus to travel to distant cities in which educational training programs are offered. In an era of growing digitalization of higher education and adult training, however, learning environments become increasingly accessible online. Students can thus access digital learning material or attend technology-enhanced training classes from virtually any place worldwide. This increasing ubiquity of training–together with the geographical flexibility afforded by blended distance learning in the form of learning centers, webinars, or virtual courses–reduces the need for automotive mobility in rural regions. The purpose of this study was to explore the experiences of nontraditional students and their lecturers associated with this reduced need for mobility. Grounded in Gibson’s theory of affordances and an interest in the narrative interpretations of lived experience, the study reports qualitative analyses of reflective interview data on how trainees and lecturers experience flexible and ubiquitous synchronous and asynchronous technology-enhanced training programs. Implications of the study for theory development and the practical implementation of digital training for non-traditional students in rural regions are discussed.

In vielen ländlichen Regionen weltweit nehmen Menschen den Bus oder das Auto, um zu Städten zu gelangen, in denen Bildungsangebote und Trainingsprogramme angeboten werden. In einer Zeit wachsender Digitalisierung werden Lernumgebungen und Weiterbildungen jedoch zunehmend auf Online-Plattformen zugänglich gemacht. Studierende haben so Zugang zu digitalem Lernmaterial oder können an technologiebasierten Veranstaltungen von jedem Ort weltweit partizipieren. Diese wachsende ubiquitäre Verfügbarkeit von Bildung – zusammen mit einer geographischen Flexibilität, die Blended Learning in Form von LernCentern, Webkonferenzen und virtuellen Kursen ermöglicht – reduziert die Notwendigkeit von (Auto-)Mobilität in vielen ländlichen Regionen. Der Zweck dieser Studie war, die Erfahrungen von nicht-traditionellen Studierenden und deren Dozierenden hinsichtlich reduzierter mobiler Anforderungen zu explorieren. Basierend auf Gibsons Theory of Affordances und einem Forschungsinteresse in der narrativen Interpretation lebensumweltlicher Erfahrung berichtet die Studie qualitative Analysen von reflexivem Interviewmaterial, das beschreibt, wie Teilnehmende und Dozierende die flexiblen, ubiquitär verfügbaren, synchron und asynchron angebotenen Weiterbildungsangebote wahrnehmen. Implikationen der Studie werden diskutiert hinsichtlich Theorieentwicklung und der praktischen Implementierung digitaler Bildung für nicht-traditionelle Studierende in ländlichen Regionen.

KEYWORDS

Digitalization, training, theory of affordances, higher education, narrative analysis

Digitalisierung, Weiterbildung, Theory of Affordances, Hochschulbildung, narrative Analyse.

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GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

AUFSTIEG DURCH BILDUNG >> OFFENE HOCHSCHULEN

1. Introduction

In many rural regions worldwide, people drive by car or ride a bus to travel to distant cities in which educational training programs are offered. In an era of ever-growing digitalization of higher education and adult training [1–7], however, training materials become increasingly available online. Participants can thus access digital learning material or attend technology-enhanced training classes from virtually any place worldwide [8–13]. This increasing ubiquity of learning and training, together with high levels of geographical flexibility afforded by distance learning in the form of learning centers, webinars, or virtual courses [14–20] have decreased the need for automotive mobility in rural regions and increased participation in educational activities [13, 21–27]. The present study contributes to the qualitative evidence of how trainees and lecturers perceive and experience digital training in geographically rural regions. An analytic interest of the study lies in the lived experiences [28] of students with digital tools and their associated affordances.

1.1. Affordances of digital tools

In his seminal work on how humans perceive the world, James J. Gibson [29] introduced the notion of an affordance. Affordances refer to both the environment and humans, and imply a complementarity of humans and objects they perceive. For example, a chair affords sitting-on-it if one is tired or standing-on-it if one needs to reach for something high or hiding-beneath-it when children play. According to Gibson's theory of affordances, objects have no single use or objective "values" or "meanings"; rather, it depends on individual subjective perceptions of humans how objects in their environment are experienced and used. For instance, depending on the situation, smartphones afford communication when we call each other; they afford photography when we take pictures or selfies; and they afford mass when we need to weigh down a sheet of paper in order to prevent it from being blown off the table on a windy day outdoors. Different objects can offer the same affordances to people [29, 30]. In digital learning, different technological tools–such as desktop computers, smartphones, tablets, or wearables–all offer the possibility to seek and retrieve information. It is thus reasonable to focus on how people perceive objects and to focus on the mutual affordances in the interaction between tools and people [30, 31]. Gibson [29, p. 134] wrote: "The theory of affordances rescues us from the philosophical muddle of assuming fixed classes of objects, each defined by its common features and then given a name. As Ludwig Wittgenstein knew, you *cannot* specify the necessary and sufficient features of the class of things to which a name is given. They have only a 'family resemblance'. But this does not mean you cannot learn how to use things and perceive their uses. You do not have to classify and label things in order to perceive what they afford."

If we follow Gibson's theory of affordances [29], then an interest arises in how people perceive and experience technological tools and systems. More specifically, it is interesting to focus on the lived experiences people have with digital media and objects as they use them. Such a focus foregrounds the subjective nature of human experience and highlights how (digital) objects are utilized; what different tools afford to people; and how technology is lived with and, ultimately, mediates human practices.

In research on technology-enhanced learning, many authors have shared an interest in the lived experiences of learners and how affordances emerge in and shape learning situations [32–36]. For example, Cornelius [15] adopted a phenomenological lens to analyze transcripts from four qualitative, semi-structured interviews with experienced facilitators who used webinars in UK higher education institutions. Reflecting on their experiences, all four interviewees described teaching with webinars as "intense" and "demanding" and how they planned, encouraged, and facilitated interaction during the webinar sessions. Such analyses on how lecturers engage with digital tools are useful because they inform us in how the affordances of virtual learning arrangements intersect with subjective meaning-makings and attempts at creating interactive learning scenarios in the digital.

The present study contributes to this line of research by focusing on how people in a rural region perceive the affordances of distance learning tools. Technology–or more specifically: digital learning formats–offers a unique opportunity for people in rural regions to participate in education and training that would otherwise be hard (or even impossible) to get access to because of the sheer distance between homes and educational institutions. What are the lived experiences of students and lecturers in rural regions when they participate in digital, technology-enhanced training formats?

1.2. Digital, technology-enhanced training formats

Because digital training programs vary greatly, it is reasonable to consider the lived experiences people have with a number of different technology-enhanced training formats. Among frequently used digital formats for adult training and higher education are learning centers, webinars, and virtual courses. Each tool is specified in turn. Table 1 offers a descriptive summary.

	Advantage	Disadvantage
Learning center	Direct social interaction with peers and lecturers, synchronous communication	Temporal inflexibility, traveling to physical environment needed
Webinar	Synchronous communication, ubiquity	Temporal inflexibility, internet connectivity needed
Virtual course	Asynchronous communication, individual learning at one's own pace, temporal flexibility, ubiquity	No direct social interaction with peers or lecturers, temporally delayed communication, internet connectivity needed

Table 1: Description of digital learning environments

First, learning centers are traditional face-to-face classrooms in geographically distant training centers that are connected by video streams. Lectures and discussions are thus synchronously available in and distributed across two or more different places. On monitors, lecturers can observe and react to trainees even if they are not in the same room with them [20]. Learning centers afford social presence and direct interaction between trainees and between trainees and lecturers–but at the cost of geographical flexibility [16]. This is because even if learning centers are installed in multiple rural locations, participants need to leave their workplace or their home and take a ride to attend classes. Still, although learning centers do not afford ubiquitous training, they still reduce the need for automotive mobility because participants can flexibly choose a learning center location that is in high proximity to their home or workplace [22].

Second, webinars and web conferencing systems are digital tools to deliver training through synchronous, audiovisual communication among remotely located training instructors and participants [13, 14, 37]. The digital availability of the webinar environment offers high levels of geographical independence for trainees and lecturers because rides by car, train, or bus to attend lectures in physical classrooms are unnecessary [22]. In recent years, webinars have attracted increasing attention for training and development purposes, largely because of their affordability to connect geographically distant members by offering real-time training communication [38, 39].

Third, virtual courses afford the highest level of ubiquity, that is: the digital learning materials are accessible from anywhere and are not contingent on specific geographic locations (given internet connections are available). In virtual courses, trainees work on prepared assignments on their computing devices and lecturers correct or provide feedback to task solutions [22]. Trainees can learn at their own pace and flexibly access training where, when, and how often they prefer [16]. This geographical flexibility and ubiquitously available learning opportunities reduce the need for automotive mobility because learning is not contingent to the physical boundaries of classrooms or training institutes.

Digital learning environments afford varying degrees of geographical flexibility. While some environments are completely online, which offers an absolute level of ubiquity, some environments are in line with a blended learning approach, which offers a reduced need for traveling but does not absolutely eliminate traveling to physical spaces (e.g., the nearest learning center). It is important to note that levels of geographical flexibility are not the affordance of the learning material itself but of the digital learning / pedagogical arrangements designed for the training. Therefore, it is necessary to conceptualize learning materials as being embedded within educational learning environments; these learning environments for digital training–more specifically: learning centers, webinars, and virtual courses–emerge at the nexus of education and technology (see Figure 1).

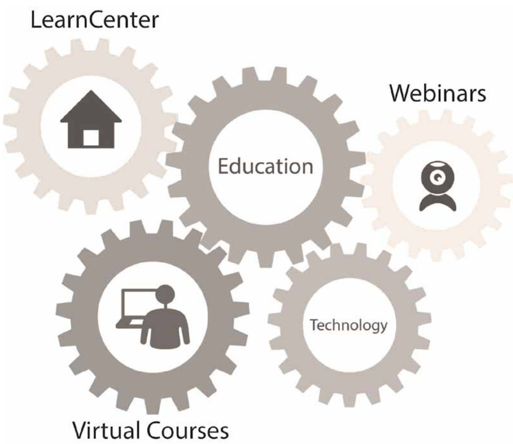

Figure 1: Digital learning environments at the confluence of education and technology

1.3. Aims and research question

The purpose of the present study was to explore the lived experiences of trainees and lecturers with the affordances of digital, technology-enhanced training programs. A particular focus was on how the ubiquitous availability of training material that is embedded in digital learning arrangements affords reduced levels of mobility and, more importantly, how trainees and lecturers perceive this afforded geographical flexibility. Because digital training programs vary greatly, the study considered three different training formats: learning centers, webinars, and virtual courses. Grounded in the theory of affordances [29, 30] and an interest in the narrative interpretations of lived experience, the research question was: How do trainees and lecturers experience the geographical flexibility and ubiquity afforded by digital, technology-enhanced training programs?

2. Methods

2.1. Participants and training formats

The study employed a qualitative methodology and examined the lived experiences of trainees and lecturers who were all engaged in off-the-job training programs designed and administered at a large training center for adult and continuing education adjacent to the Bavarian Forest, a rural region in Southern Germany. The training center is part of a higher education institute and offers numerous academic courses for non-traditional students on evenings and weekends that participants attend off-the-job in lieu of their regular work duties. Non-traditional students are students who are typically older than regular students, have family and / or work duties, and return to higher education to obtain academic degrees [38, 40]. The study focused on training programs that were technology-enhanced and included digital elements that afforded ubiquitous access to training. Three programs were considered: The first training program was a 9-month course on supply chain management; the second training program was a 9-month course on industrial management; and the third training program was a 5-month course on early childhood education. Participation in these programs was voluntary [41]. All these training programs included the three instructional formats learning centers, webinars, and virtual courses. Among the instructional activities planned in the training curricula were both learner-centered and knowledge-centered activities, including lectures, discussions, demonstrations, and small group activities. Participants in the study were twenty-three persons–15 trainees and 8 lecturers–recruited from the three training programs. Among them were (a) four trainees (one woman, three men) and three lecturers (one woman, two men) recruited from supply chain management; (b) six trainees (three women, three men) and three lecturers (one woman, two men) recruited from industrial management; and (c) five trainees (four women, 1 man) and two lecturers (1 woman, 1 man) from early childhood education. Trainees and lecturers volunteered to participate in the study and received no compensation. Anonymity and confidentiality were guaranteed for all responses.

2.2. Data collection

Grounded in a qualitative research methodology, data for the study were collected with semi-structured face-to-face reflective interviews [42, 43]. A total of 23 interviews were performed by a trained interviewer with a standardized set of questions in individual sessions that ranged from 11:26 to 41:18 minutes. Total interview time was 326:36 minutes for trainees and 305:17 minutes for lecturers. In addition to the standardized set of questions, interviewer and interviewee were free to talk and discuss other aspects not covered in the question guide. The main purpose of the interviews was to evaluate the attended training programs. From the collected interview material, a major research interest for the present study was in the lived experiences of the participants and how they perceived the ubiquity and geographical flexibility afforded by the digital, technology-enhanced training programs. A semi-structured interview guide with a set of prepared questions was used for collecting data. Among the set of questions, we selected some questions and their associated answers for the analysis in the present study. These questions were (a) for the trainees: Why have you decided to participate in this program? How have you experienced the learning centers, webinars, and virtual courses? and (b) for the lecturers: What were your experiences with the learning centers, webinars, and virtual courses? If you consider your trainees, how do you think they experienced the learning centers, webinars, and virtual courses? Interviews were performed within one week after each training program has ended. Talk during all interview sessions was recorded; a trained student assistant transcribed the interview recordings verbatim.

2.3. Data analysis

Based on an interest in the narrative accounts of lived experience [28], qualitative analysis of the interview transcripts sought to explore how students and lecturers intersubjectively perceived and experienced the digital training formats. The analytic approach took as starting point the empirical realm of everyday lived experience [28, 42, 43]. Analysis was identical for both training roles: trainees and lecturers.

Following the procedures of the circular deconstruction [44], data analysis included three steps. First, the individual interview transcripts were summarized and paraphrased. Next, the summarized and paraphrased interview transcripts were further condensed to deconstruct predominant themes and subthemes as they relate to geographical flexibility and reduced needs for automotive mobility. These two analysis steps were performed on the level of a single interview and identical for all 23 interview transcripts [44].

Finally, the deconstructed themes from each individual interview were compared and contrasted across transcripts to develop categories. In the present study, the developed categories mirrored the three instructional training formats learning centers, webinars, and virtual courses. These three categories unveil the lived experiences of students and lecturers associated with the geographical flexibility afforded by the digital learning environments. To guide the reader through the analyses, the three categories learning centers, webinars, and virtual courses are used to structure the first paragraphs of the following Results section.

3. Results

How do trainees and lecturers experience the geographical flexibility and ubiquity afforded by digital, technology-enhanced training programs? The following sections present results from the interview analyses separately for each of the three training formats: learning centers, webinars, and virtual courses.

3.1. Learning centers

Learning centers afford participation in classroom activities close to the trainees' homes. This high geographical proximity between learning centers and home is a positive aspect for many trainees. As ST1 argued: "For me, this was optimal because it was so close to my home, to have classes right in front of my front door, so to speak, with very short distances. This was a huge advantage for me". And TT1 said: "It was great that the training program was offered at the learning center close to my home. Because, if you have to drive around in the evening… I simply was here for class". Along these lines, also KT1 said that similar training programs do not exist in her rural region; the installment of a learning center close to her home thus afforded her participation in the training program.

Trainees communicated to their lecturers how learning centers afforded them to integrate work duties, family duties, and training participation. For example, the lecturer KL3 argued that she did not think that learning centers–with a distance of 50 kilometers only–would have been significant enough to facilitate training participation because she thought that this small distance can be bridged easily by car. At multiple occasions, however, her trainees expressed that they would not have started the training program if they had to drive 50 kilometers on evenings or weekends to regularly attend classes. These multiple statements seem to suggest that the regional proximity offered by learning centers indeed promotes training participation.

3.2. Webinars

Webinars afford a high level of ubiquity because participants can attend webinars flexibly at any place with internet connection. This geographical flexibility was perceived very positively by trainees. For example, TT2 stated: "Generally, I like webinars quite a lot because I can do them at home on my sofa". KT3 said that webinars even make redundant the already short drive to the nearest learning center. ST4 argued that, for webinars, "you could attend them at home. There's no need to drive from A to B. I think that, for most, this made it easier to integrate the whole issue with your daily work duties". ST2 said: "Well, so, what was really handy for me was that you could do this from home. You didn't have to drive to attend classes but could do it in your kitchen or living room. This is an immense benefit“.

Not only trainees, but also the lecturers enjoyed the ubiquity and geographical flexibility afforded by webinars. KL2 articulated that "webinars are great because we say let's do them in the evening after work when nearly everyone has time (…) trainees and also we lecturers don't have to drive to class again." This high level of ubiquity thus reduces car or bus rides for both lecturers and trainees.

Although webinars afford ubiquitous learning spaces, some trainees raised critical voices associated with webinars. Specifically, KT2 argued: "(…) I have to honestly say that a webinar will never replace a personal talk. Because it offers a limited perception only. And not like when you sit next to each other and can perceive all other facets of human communication. So this is a limitation."

3.3. Virtual courses

Virtual courses afford asynchronous ubiquity of the training material. Trainees perceived this local and temporal independence and flexibility of virtual courses very favorably because, as KT5 said, she could easily coordinate work, family, and training activities: "I like that I can be autonomous in when I do what, how much I do (…) temporally and geographically totally free". The possibility to access training from virtually anywhere was also appreciated by ST3; he stated: "I have to say that, at the moment, I have lots of stress at work and so it was great that I could access the learning content in the evenings or on weekends at home and follow things up. Even if I did not understand something immediately, I had the peace to sit at home and repeat exercises and look up things and that was the ultimate best for me".

In addition to trainees, also lecturers enjoyed the flexibility that virtual courses afforded. For example, KL1 articulated that virtual courses are great for those who work on a daily basis because "virtual courses minimize the need for travels, rides, and drives to attend classes." Along these lines, SL1 said: "I think that an apparent benefit is that trips are shortened. Like, not only driving to class, but the whole think around it. I don't have to rush out of work to get to class". In summary, both trainees and lecturers appreciated the advantages of ubiquitously available learning material that virtual courses afford.

3.4. Differences per training role, content, and gender

A closer analysis on similarities and differences was performed to compare answers as a function of training role, age, and gender. First, training role was defined as trainee or lecturer. Considering the given responses, both trainees and lecturers appreciated the geographical flexibility afforded by the digital learning environments; no dedicated qualitative differences emerged. Second, content was defined as supply chain management, industrial management, and early childhood education. No qualitative differences in the articulated experiences emerged as a function of content. Third, gender was defined as male or female. Prior research examined gender as a moderator for training participation [45] and training motivation [46]. In the present analysis, no differences between women and men emerged in either of the two training roles.

4. Discussion

4.1. Main findings

The purpose of the present study was to explore how training participants and their lecturers in a rural region perceive the affordances of digital training formats that make training ubiquitously available and thus reduce the need for automotive mobility [28–31]. Because technological tools for digital training vary greatly, the study considered three different formats: learning centers, webinars, and virtual courses [22]. Analyses of qualitative interview data [43] suggest that both training participants and training lecturers appreciate the geographical flexibility and ubiquity afforded by distance learning. This was a consistent finding for all examined digital tools, including learning centers, webinars, and virtual courses.

Learning centers close to trainees' workplaces or homes reduced the time needed for traveling to formerly very distant educational institutions. This higher proximity affords time savings that could alternatively be spent for work or family obligations. Even more drastically, some trainees articulated that they started the training programs only because learning centers were installed close to their homes; they would not have participated in training if they had needed to drive 50 kilometers to access physical face-to-face classrooms. In terms of Gibson [29], learning centers afford closeness in a rural region and participation in training that was previously precluded due to geographical distance.

Webinars brought the training program directly into the homes and workplaces of training participants and lecturers. While learning centers decreased the time for driving and traveling, webinars made drives obsolete. People perceived no need to leave their homes or workplaces because the webinar environment afforded digital access to all training content, material, and lecturers. Following Gibson's theory of affordances, webinars afforded synchronous participation in training with high levels of geographical flexibility. Participants appreciated and benefited from webinars because this tool saved even more time from traveling than learning centers did.

Finally, virtual courses afforded identical levels of ubiquity and geographical flexibility like webinars. In addition, however, virtual courses also afforded temporal flexibility. That is, the asynchronous communication patterns and time-independent access to training were experienced as possibilities to engage with the training content whenever and wherever needed. These benefits that virtual courses afforded were perceived by both trainees and lecturers alike. In both groups, the minimized (and even removed) need to take a ride to get to class was strongly appreciated. The narrative analyses of the lived experiences highlight that virtual courses contributed to continuous training participation and learner satisfaction with educational activities in rural regions.

4.2. Theoretical and practical implications

Implications of the study for theory development include analyses of digital technologies and how they are associated with levels of training motivation. Particularly, it can be speculated that easier access to training thanks to ubiquitous learning material can promote interest [47, 48], mastery goal orientations [49, 50], or motivation to transfer [51, 52] because experiencing lower physical barriers (in Gibson's terms: negative affordances) to training and the positive affordances of geographical flexibility might be associated with increasing levels of affective reactions from trainees and lecturers. However, these directions for future research need to be theorized, conceptualized, and put into the focus of further empirical research.

Implications of the study for educational practice center on the installment of more learning centers. If people strongly appreciate the geographical proximity of learning centers–and the educational activities they afford–then it seems intuitive that more learning centers in more rural regions would offer access to training for more participants. A second implication for educational practice is to design, deliver, and implement more webinars and virtual courses in concert with improved broadband infrastructure and internet connectivity in these regions. Webinars and virtual courses afford geographical independence–even without buses or cars, training becomes accessible for people, regardless how rural and remote they might live. Particularly for regions with long distances to educational activities, webinars and virtual courses can afford unique possibilities to engage with training and participate in adult education. Ultimately, this increased level of participation and access to educational training activities can benefit not only the people, but also entire rural regions, including the one examined in the present study: the Bavarian Forest.

4.3. Limitations and directions for future research

Limitations of this study relate to the qualitative approach to data collection and analysis. Specifically, based on a limited sample, the study utilized 8 lecturers and 15 trainees. While this is a small number of research participants if one adopts a quantitative perspective on empirical research, qualitative research often uses an even smaller number of participants to reach data saturation and to reconstruct case evidence [15, 28, 42, 43]. As such, the presented qualitative evidence is robust but we still note that additional follow-up studies using quantitative survey methodologies can be employed to triangulate the qualitative interview findings.

Another limitation of this study relates to the study focus. If we consider the sheer amount of collected interview material of more than 300 minutes each for the groups of trainees and lecturers, then numerous focal analyses would be possible. In the present manuscript, a decision was made to highlight the experiences associated with the afforded geographical flexibility and the reduced need for mobility. On one hand, this decision was made because of the focus of this special issue on mobility. On the other hand, this decision was made because both trainees and lecturers articulated repeatedly–in all interviews–how favorably they experienced the ubiquitous nature of the attended digital training programs. It was thus obvious to highlight analytically what was articulated empirically in the qualitative interview material.

Directions for future research relate to replications of these analyses in different rural regions in different countries to examine how stable the described experiences are in changed contexts. Similarly, as the present study focused on non-traditional trainees [40, 53], future research can investigate experiential differences with digital learning between nontraditional and traditional students in higher education. One could assume that positive experiences relate with positive levels of motivation and transfer–an assumption that needs to be tested empirically in further studies [45, 54, 55], particularly with regard to the commitment level that could act as a moderating variable. Finally, this study considered two training roles: trainees and lecturers. More training roles exist, such as training designers [22], evaluators [56], or technologists [20] whose experiences can also be collected and analyzed in lieu the views of trainees and lecturers. Future research can thus triangulate multiple perspectives when examining the intersubjective nature of affordances of digital training environments in higher education.

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Extracting Relevant Points of Interest from Open Street Map to Support E-Mobility Infrastructure Models

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ABSTRACT

In addition to commercial geodata, Volunteered Geographic Information (VGI) is gaining more and more importance in research. Platforms like Open Street Map (OSM) meanwhile provide an enormous amount of geodata. At the same time, however, new questions arise regarding the quality and the possibilities of using OSM data for research matters. Therefore, in the field of spatial planning, data require further validation processes and data cleaning frameworks. This paper presents a method of data processing in the context of electric mobility (e-mobility) research with a focus on a charging station placement model. The presented methodology is divided into pre-validation, to gather the relevant data set, and data processing, that specifies the relevant Points of Interest (POI) for further research by deleting all possible complications arising in OSM data. The validation process is customized to the model that determines the demand of electric charging by categorizing POIs into the four time slots living, work, shopping and recreation. By processing data in the presented way, the electric vehicle charging model is filled with improved input data, which allows to reduce the bias associated to the particularities of the OSM production process. A case study in the Bavarian-Czech border area demonstrates that the error correction rate through the model is at about 10%.

Neben kommerziell bereitgestellten Geodaten nehmen freiwillig erhobene geographische Daten (VGI, volunteered geographic information) in der Forschung einen wachsenden Stellenwert ein. Plattformen wie OpenStreetMap (OSM) bieten inzwischen eine enorme Menge an Geodaten, deren Qualität und deren Mehrwert für die Forschung zunehmend kritisch betrachtet werden. Besonders dann, wenn es um räumliche Planung geht, müssen die Daten vor der Anwendung angemessen validiert und bereinigt werden. In diesem Artikel wird ein Datenverarbeitungsmodell vorgestellt, mit dem OSM-Daten so aufbereitet werden können, dass der Bedarf an Ladeinfrastruktur für Elektroautos über von Nutzern eingetragene Point of Interests (POI) räumlich möglichst genau erfasst und abgebildet werden kann. Zunächst erfolgt eine Selektion relevanter Datensets durch eine Prävalidierung. Im zweiten Schritt werden die wichtigsten POI selektiert und spezifiziert. In einem dritten Schritt werden alle OSM-immanenten Schwierigkeiten beseitigt. Das hier vorgestellte Datenverarbeitungsmodell ist auf das Thema Elektromobilität zugeschnitten, für welches POIs in die vier Zeitkategorien Arbeit, Leben, Einkaufen und Freizeit eingeteilt werden, um so den Bedarf an Ladeinfrastruktur zu erheben. Durch dieses Modell der Datenverarbeitung soll die Energienachfrage für Elektroautos räumlich möglichst realistisch dargestellt werden und Rohdaten mit ihren bekannten Fehlern durch den OSM-Datensammlungsprozess bereinigt aufbereitet werden. Anhand einer Fallstudie, die im bayerisch-tschechischen Grenzraum durchgeführt wurde, wird gezeigt, dass die Fehlerrate durch die Implementierung validierter Daten um ca 10% reduziert werden kann.

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KEYWORDS

Electric vehicle charging station, spatial modelling, Open Street Map, data validation

Ladestationen für Elektrofahrzeuge, räumliche Modellierung, Open Street Map, Datenvalidierung

1. Introduction

Recent technological progress, especially in battery research, increases the electric vehicles' (EVs) competitiveness compared to conventional vehicles. Many governments are promoting EVs in order to reduce the carbon footprint of their respective country, which is pushed, among others, by the European Commission. Different subsidies and incentives have been established at several levels to raise the awareness for EVs and to increase their popularity in the public. In Germany, for instance, the government is paying a sustainability bonus ("Umweltbonus") to private users purchasing an EV and is granting tax deductions on company cars, among other measures [1]. In addition to the financial incentives, municipalities and regional actors also try to increase the attractiveness of e-mobility through economic and regional development concepts such as purchase subsidies, free parking or reserved parking spots and free bus lane use for EVs [2]. Currently, the focus of these concepts is put more on purposefully integrating e-mobility infrastructure into existing structures and less on substituting the latter by entirely new forms of mobility.

Given the objective of integrating EVs into the existing transportation and energy distribution network, creating the required infrastructures for recharging EV batteries poses new challenges to regional governments, municipalities and individuals, as well as to distribution grid operators. These challenges result from the high importance of implementing a charging infrastructure fitting to the regional needs of customers. This is due to the significant differences from conventional refueling as charging EV batteries takes considerably longer. Compared to fossil fuels, the high time expenditure on EV charging means that charging processes have to be embedded into the daily schedule and route planning of users, but also into the already existing regional energy supply structures. This is why it is highly important to find answers to the question of where charging stations (CS) have to be set up.

With the ability of spatiotemporal modeling, Geographic Information Systems (GIS) can be utilized to support answering this question. In addition to the GIS functionalities, the spatio-temporal approach requires a comprehensive database for finding suitable sites for CS. Nevertheless, due to the complexity of the collection methods and the high amount of information needed, there is still no database available that has been designed to assist the planning of charging infrastructure. The methodology presented in this paper draws the attention on how to use and ensure the quality of collaborative mapping platforms data for spatiotemporal modeling in the context of e-mobility. A big advantage of OSM compared to commercial geodata and other collaborative mapping platforms is that OSM is the most complete free open source database available for everyone. Moreover, OSM is constantly being updated, constantly growing and open to be edited by all potential actors involved.

Using OSM data offers a broad database with great potential, however, also involves some inconveniences. Even though collaborative mapping platform data is versatile enough to be used in a variety of applications, it has not primarily been designed to be used for scientific purposes. OSM, and other crowdsourced geographic data sources in general, are known to be partly incomplete or incorrect [3–8]. This study focuses on the extraction of relevant Points of Interest (POIs) from OSM to support e-mobility infrastructure models as in Zink et al. [9]. Unlike earlier quality assessments based on the quantitative and statistical characteristics of OSM data, this study contributes to the literature about OSM data, presenting an innovative method for extracting valuable information based on qualitative criteria and a data processing methodology. The results show the potential of qualitative studies and their complementarity with conventional statistical approaches to VGI quality assessments. The second contribution of this study is related to the literature on CS placement. Unlike most of the previous studies on CS locations, the reference regions are rural areas with a focus on the road from Písek (Czech Republic) to Deggendorf (Germany), whose future suitability for EVs is currently being evaluated. As previous studies show that OSM biases are greater in areas with lower population density, focusing on this area allows to assess the robustness of the methodology under diverse conditions – it contains both rural and small urban areas – and to open up an avenue for research on CS locations models based on VGI.

The rest of the article is structured as follows: the next section presents an overview of rural e-mobility models and the possibilities for using OSM. Section 3 presents a methodology for selecting and processing OSM data for e-mobility projects, and section 4 shows results of applying the methodology in rural areas stretching over two countries, currently facing demographic exodus. In section 5 the findings are concluded.

2. Spatial localization for charging stations and OSM-based studies

Overall, models for the optimal EV charging infrastructure can be studied in many different directions, starting from the inside (battery lifetime analyses, driving distance enhancements or consumption needs of single tools) and leading to outside factors (CS infrastructure, willingness to buy EV or awareness of natural impact improvements). Although EVs have already become a reality in many countries and cities, the research effort devoted to generating optimal models for CS infrastructure planning is still in its infancy. Developing new approaches is of primary importance, as several studies indicate that range anxiety is a central inhibitor to going electric [10–12]. A sufficiently developed CS infrastructure could contribute to diminishing this inhibitor [13] and foster the trust in EV technology.

The lack of studies on the optimal placement of CS in rural areas is in strong contrast to the increasing attention on optimal allocation and modelling in urban areas. In a recent review of the literature, Shareef et al. [14] found that more than 100 articles with a focus on the optimal placement and sizing are published every year in specialized research journals, all aiming at urban areas. These studies are in many cases based on geographical information of different complexity. For instance, Huang et al. [15] proposed a model for the placement of CS in urban areas based merely on geographical correctness. This means that CS are not located depending on the actual demand but on the geographic distances from each other to tackle possible driving/battery range anxieties. Frade et al. [16] define the demand for CS on the basis of the 2001 census data and apply their demand model to an area in Lisbon, Portugal. In comparison, Chen et al. [17] base their CS location model on the travel distance while bearing in mind the re-charging requirements of consumers with respect to the existing transportation network and its efficiency. Funke et al. [18] compare demand-driven localization models with a coverage-driven one. They state in their results that planners should first find out on what matter to put their focus: on the demand-driven amount of needed CS or the distribution of CS pursuing the coverage aspect. All mentioned studies propose CS locations depending on different factors, however, always in urban, very densely populated areas.

The vast availability of studies shows the wide range of options and possibilities for locating CS depending on the characteristics of drivers, EVs, locations, needs and charging technologies. However, to the authors' knowledge, only a few number of studies have been carried out in rural areas to describe important characteristics and they are based on GPS recorded data. For instance, Triebke et al. [19] collected data on more than 15.000 charging events in both rural and urban areas and their statistical analysis shows that although the charging behavior in urban areas is predictable, it is rather random in rural environments and occupancy rates are low compared to urban areas. In a more recent study, Gasde et al. [20] also found that although EVs offer socially and environmentally promising perspectives in rural areas, the economic drawbacks of current e-mobility solutions are a barrier for EV expansion. These case studies reveal the difficulties in implementing EV solutions in rural areas. The challenge is even greater when the model's scope is extended to covering multiple municipalities given the complexity of GPS-based collection methods and the recourse-intensive data collection method.

Data collection, or more specifically, the collection, assembling and dissemination of geographic data, is the focus of collective mapping and VGI databases. The increasing availability of data sets of freely available VGI has led to strong interest from researchers and practitioners in the usability of these data, both their limitations and their potential. Although VGI offers an alternative mechanism for the acquisition and compilation of geographic information, it requires many individuals to participate. Some authors argue that researchers should analyze but not complement VGI [21]. The collection of data should be done by the overall public which leaves researchers more space and time to focus on quality checks. Those quality checks have been realized by many studies in a variety of ways. The unconventional way in which data are being produced as well as their richness and heterogeneity have resulted in a range of different research questions on how to assess, mine, enrich, or just use these data in different domains and for a wide range of applications. In the area of e-mobility, to the authors' best knowledge, only the study of Zink et al. [9] is based on OSM data. Similarly to Frade et al. [16], they locate CS infrastructure at places where the potential demand for electricity for transport reasons is the highest, but instead of using census data they used OSM data to allocate the demand. Using OSM allowed Zink et al. [9] to generate a CS location model for a large low-density area like the studies of Triebke et al. [19] and Fournier et al. [20]. Finally, Wanger et al. [22] also developed a model for demand location for car sharing, in this case based on Google API; they included 180,000 POIs as well as demographic data in order to identify POI categories that substantially influence variation in car sharing activity.

OSM and crowdsourced geographic data sources in general are known to be partly incomplete or incorrect, and many studies were performed to analyze data characteristics of different VGI platforms [3–8]. In the following, we focus on OSM which today is the platform with the highest number of registered users and the largest crowdsource-based data volume [3]. The methodology discussed in this paper attempts to make it possible to use these data for research, that is to say, they need to be cleaned and verified. Senaratne et al. [3] provide a summary of articles in the area of VGI Data Quality Analysis. Quality measures for VGI as defined by the International Organization for Standardizations (ISO) are completeness, logical consistency, positional accuracy, temporal accuracy and thematic accuracy. Besides these qualitative criteria, quantitative criteria are introduced, namely purpose, usage and lineage. For all these different criteria, Senaratne et al. [3] have executed analyses in order to define the level of correctness of different data sources. However, these authors did not introduce data cleaning processes on a larger scale.

Regarding specific OSM data studies, several research projects focus on different OSM data sets and analyze different layers. For Germany, Fan et al. [23] compare road data in OSM with official data while Zielstra and Zipf [5] compare road data with commercial data acquired by navigation service providers. The results of both studies indicate medium to high levels of completeness and quality of the examined data, depending on the population density. Moreover, they show how fast the OSM data set is increasing over time. Between July and December 2009, the road data provided on OSM in the specified research regions increased by 20%. Neis et al. [6] show that OSM data in several cases even exceed the data pool used by car navigation systems in 2011. Arsanjani et al. [7] compared OSM data with pan-European GMESUA data and Dorn et al. [8] compared OSM data with official German administrative data updated every 3 months, both putting a focus on land use and land cover (LU/LC) data. Asanjani et al. [7] conclude that LU/LC OSM data lie within a correctness and completeness level of 40%-60%. Dorn et al. [8] reveal that concerning LU/LC data, the quality and completeness of OSM data strongly depends on the feature classes observed. Forests, for example, show a large completeness and correctness level in the study area in southern Germany. Other classes of data such as farmland or urban areas/characteristics are often incomplete although the information provided is of high quality. In other cases, the quality of data is low while the level of completeness is high [8]. Barron et al. [24] focus their research on quality assessments of OSM by reviewing the history of OSM data. They state that it is possible to evaluate the quality of the observed data solely by assessing the history of the data generated and without using external sources.

These examples demonstrate that many research efforts have been realized in different use cases to define the degree of quality of OSM data. A variably applicable cleaning and verification process for a better usage of OSM data, however, has not yet been introduced. The next section introduces a validation methodology in order to fill this gap and to increase the application of these freely available data for specific research topics.

3. Methodology for data validation

The data validation methodology presented herein was developed for an e-mobility demand model based on OSM data which was developed by Zink et al. [9], however, it may also be tailored to other mobility-related models as the one by Wagner et al. [22]. To facilitate the logic behind the data validation process presented in the following section, figure 1 displays the modeling approach by Zink et al. [9]. As described in the previous section, the aim of this site planning model for e-mobility is to place CS infrastructure at locations where the potential demand for electricity for transport reasons is the highest. It is therefore based on existing transportation patterns and current transport infrastructure and not on the current system based on gas stations. Due to the long periods needed for charging EV, the main idea behind the model is to create charging infrastructure at existing parking locations instead of using the current model of isolated gas stations. The charging demand calculation is based on a spatial statistical methodology considering demographic parameters and maximum walking distances from the CS to selected POIs according to four age groups. It furthermore contains the average time use per activity per day, dwelling time at one POI, the penetration rate of EVs and POIs from OSM. The walking distance determines the optimal location within a region with high energy demand by minimizing the average walking distance to the surrounding POIs. Therefore, the optimal location is found while simultaneously considering high parking demand and short walking distances. If there is only one POI within the user's maximum walking distance, the charging location is as close to the POI as possible, but always bound to the street.

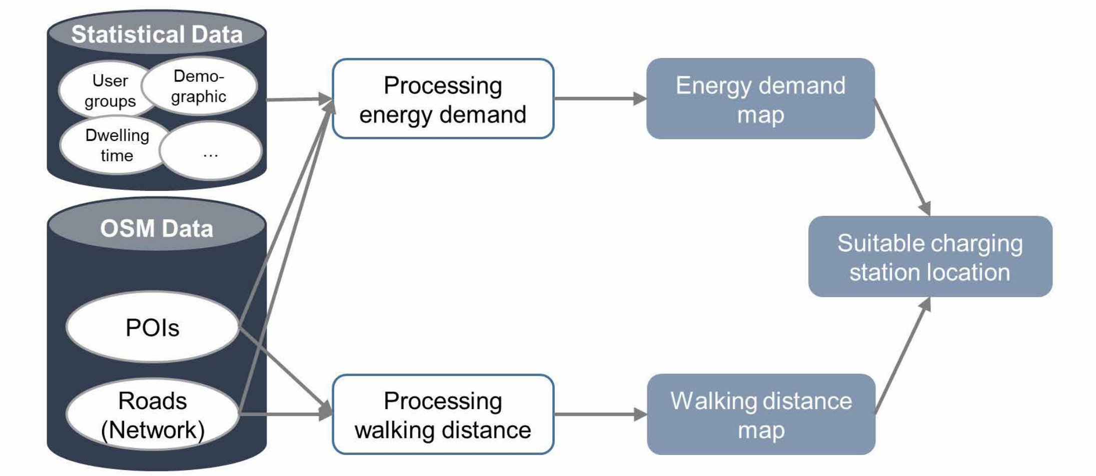

Figure 1. Electricity demand and site planning modeling approach

POIs from OSM are included in the model to define the areas where demand is highest. As already described, in OSM, gathering data depends on the users, this means that anyone who finds a certain spot on the map that is not yet classified, such as a fuel station, can add it accordingly and tag it with the category of their choice. Consequently, a personal bias might be in place for each single location defined in OSM. Thus, a qualitative review and data validation process is necessary to assess the quality and relevance of the input data.

Furthermore, POIs like, for instance, kindergartens or schools can have a point-like or a polygon shape in OSM. As an example, figure 2 shows a screenshot from the OSM web map with a query about schools. On the left hand side, a point is selected that represents *Staatliche Berufsschule Deggendorf* (public vocational training school). The screenshot on the right hand side visualizes the selection of the entire building (polygon), including four other schools (so 4 points in one polygon). For modeling, this raises the question as to which dataset the location search should be based on: on one school or on four schools. In the electric demand modeling approach, the number of POIs is the determinant of EV's charging demand, which induces the need for inserting the number of POIs into the model that is closest to reality. The methodology presented herein reviews necessary processes for validating OSM data before including it into an e-mobility model.

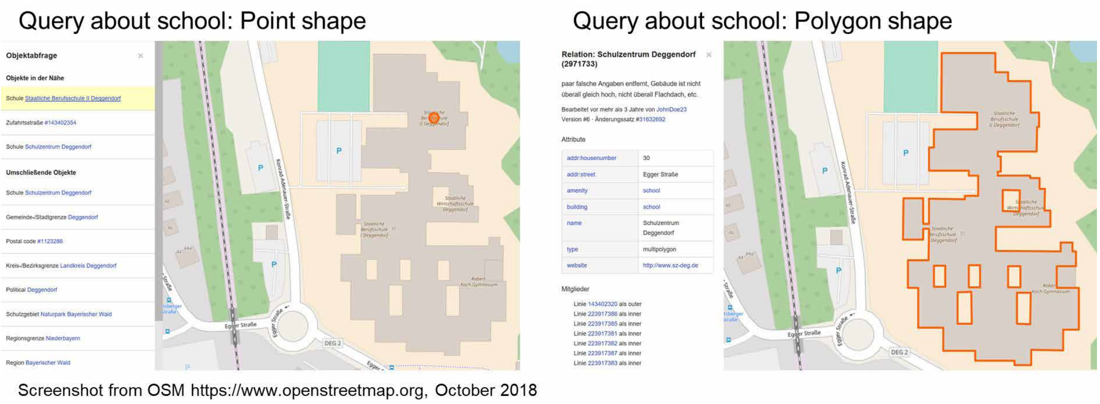

Figure 2. Screenshot of OSM web map

3.1 OSM data characteristics

In OSM data, different POI categories like buildings, roads, water, etc. are classified and they are further divided into sub-categories, which are also called feature classes (f-classes) by Geofabrik, the provider of OSM data used in this study. F-classes are, for instance, tree, school or bank[1]. The decision to add a new location to a specific category in the OSM data depends on the judgement of the volunteers. As it is possible for everyone to participate in adding data to OSM, the map is highly user-reliant, depending heavily on individual preferences as well as on the socio-economic and geographic characteristics of each region. In order to reduce this source of bias, the OSM community maintains a large OSM wiki page and implemented a series of quality checks as well as reviews of the dataset. However, users mainly add new features to the map for regions they know well. As a consequence, every tree and every bench in a park have been added for some regions, while the mapping for other regions is rather poor. Regions and POIs attracting more people are mapped with more detail and are more complete while, for instance, important POIs in rural regions are missing. This pattern is also observable with regard to the distribution of mapped parking spaces. A decrease in the percentage of mapped parking areas is observable the further away the parking space is from regions that are highly interesting. The propensity for higher data correctness and completeness depending on population density is also very well represented in the analysis of Dorn et al. [8]. Due to these patterns, it is necessary to clean and validate the data before using OSM data and in order to assess the level of correctness. The validation process presented herein is specifically designed for the requirements of the OSM data and can be applied to OSM data from other regions with minor adaptations. It consists of two main steps, namely (1) pre-validation, which includes selecting relevant data for the project, and (2) data processing, which considers the cleaning of data and the preparation of one complete data set.

3.2 Pre-validation

In the first step of the validation process, the main goal is to extract only data that are relevant for the e-mobility model described in figure 1. The first questions that needs to be answered is whether (1) the feature class (f-class) is relevant for the model's goal. The second question is whether (2) the f-class is distinguishable enough for use within the model. The criteria for the f-classes to be chosen are dependent on the model specification and the research objective. In this model, as explained above, different time categories were defined. The POIs need to be classified into one of these classes according to their main purpose. It is therefore necessary to ask (3) whether the f-class is defined narrowly enough so that it can be categorized into one of the four time classes. Figure 3 lists these questions including criteria that need to be met in order to fit into the model.

[1] See: https://www.geofabrik.de/data/geofabrik-osm-gis-standard-0.7.pdf

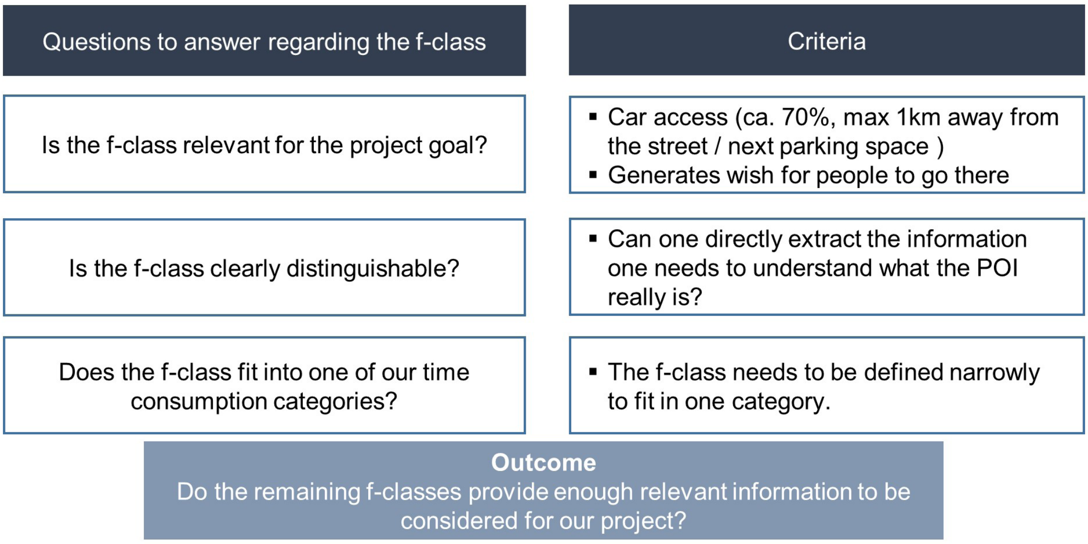

Figure 3. Pre-validation process

Besides these three initial questions for data selection, additional qualitative criteria have to be met in order to further process the relevant data. These criteria do not apply directly to the entire f-class but to the single features within f-classes. The first criterion is related to the location's geographical characteristics. In the model it is assumed that at least 70% of the POIs per f-class needed to be close to streets or parking spaces. A range of 1km is defined as the maximum distance. The maximum distance refers to 1km on paths or tracks, not necessarily passable by car, however, accessible by foot, bicycle or other means of transport. Additionally, the f-class considered in the model needs to be exactly categorized in its additional information. For example, the POI category "building" can be any type of building, ranging from family houses over public administrative buildings to convenience stores. Thus, if additional information about the type of the building is missing on the platform, it is neither possible to define the kind of demand for CS infrastructure for this f-class, nor can the POI be defined according to the model's needs. The correct pre-validation yields a list of f-classes which should be relevant for the model and can be further evaluated in the second validation step.

The following quantitative and qualitative criteria are developed in order to define the OSM data that are relevant for the EV CS demand-model:

i. Distance to roads or parking spaces

Walking distances is a central concept in a model for transportation and public health and it is the major factor in the context of parking choice [25]. Overall, research on the exact distance and duration of walking trips for different purposes and across diverse population groups remains limited. For Germany, it is difficult to obtain estimates of the distribution of walking distances from parking places to final destinations. As to research in other countries, it is difficult to assess the validity of the results based on survey data. These limitations arise because of the discrepancy between perceived distances and objective distances [26, 27]. Based on these studies and for the purpose of the model applied, the maximum walking distance to the next parking place or street is set to 1km.

ii. Relevance

Different time categories for weighting the relevance of POIs are applied in the e-mobility model. These time categories are based on surveys that collected information on the time spent on daily activities in Germany and the Czech Republic [9]. The f-classes are considered relevant for the model if they can be classified into one of the activities depicted in the time surveys. For instance, the f-classes "school" or "courthouse" can be classified within activities concerning the time category "work", other f-classes such as "tree" or "bench" cannot easily be allocated to one certain activity as they describe street furniture and vegetation. In order to assess the significance of this criterion, a literature review was conducted to see whether the charging events recorded on pilot projects and used to model EV driving behaviors are consistent with the time usage model applied in this project. The results of the literature review show that current charging behavior in urban areas is strongly determined by the activities of EV drivers [19]. Studies point out that the distribution of charging events in function of the location of the CSs (for instance: working places, homes and recreation locations) are consistent with the users' use of time [12, 27].

iii. Differentiability

Differentiability is a key element to the purpose of e-mobility models and is related to the way in which data are recorded and classified. It accounts for the capacity of distinguishing within and between the classes. The f-class "swimming pools" provides an idea of the capacity to differentiate within classes. It characterizes whether the data recorded respond to a common structure and whether their characteristics are identifiable. In the case of the swimming pools, the data is considered to be non-differentiable as it does not allow to draw a line between public or private swimming pools. Another issue can be displayed by the f-class "commercial". This class does not allow to be differentiated from other f-classes such as shops, restaurants or clothes. Therefore, such f-classes are also not considered to be differentiable among f-classes.

iv. Classifiability

As OSM data are integrated into the model with data of different origins, the classifiability of each class is paramount. In the OSM e-mobility model, instead of basing demand for each CS on the current behavior of EV users, the model uses the amount of time that both members of the German and the Czech population spend on different activities. The classifiability criterion represents the possibility to allocate the f-classes to those activities. Therefore, an enterprise or a city hall are classified as places of work, a restaurant is classified as a recreation location and any kind of shop is allocated to shopping activities.

3.3 Data processing

The data processing phase consists of several steps, all building on one another in order to identify whether the locations represented in the OSM data correspond to real sites and to make sure that duplicates are erased. Figure 4 displays the different steps of this process and the resulting actions. In order to do so, it is first necessary to check the geographical intersections between points and polygons to see whether there are points that are as well included in the form of a polygon, both referring to the same POI. This first step in the analysis is done across all f-classes, simultaneously checking for duplicates within and between the f-classes. There are some classes that are likely to be used as substitutes, like "observation tower" and "viewpoint". The extracted list of duplicates is further separated into three categories, namely "exact matches", "approximate matches" and "possible coexistence". In the first two groups, the corresponding polygons are erased in order to reduce the amount of duplicates. In the group containing the inconsistencies, both the points and the polygons indicate two different sites and thus must remain in the data set. The "possible coexistences" are left aside in this step, as it is liable to believe both OSM tags are relevant.

After erasing all irrelevant polygons or points identified in this step, polygons get transformed into points and one large data set is created for further analysis. A common issue with OSM data is that different users may consider the same location for different f-classes. This results in one data point, with one OSM data ID, represented in different f-classes. Therefore, when considering more than one f-class, two or more data points with the same OSM ID at the same location but in different f-classes are possible to arise. Thus, the intermediate step is to erase points that have the same OSM ID and indicate the same spot. As already explained, some f-classes have a broader definition than others, a point "commercial" can cover various topics that are specified in other f-classes like "clothes", "hairdresser", "supermarket" or "restaurant", just to name few. Thus, a list of priorities is introduced that deletes the second or third data point with the same OSM ID, always leaving the most specific point in the data set. For example, a religious location with the f-classes church, Catholic, cemetery, work-art, Christian and garden is reduced to church.

For further data processing, data points are compared considering the belonging to an f-class. Further duplicates may exist even after comparing points directly situated in polygons and deleting double OSM IDs. This can happen if the same location appears as a point and as a polygon without any overlap, for instance, it may be the case of a polygon representing an edifice that is surrounded by a garden and also of a point, representing the street number of the edifice and being located on the sidewalk. These duplicates can best be found by geographically estimating rational distances between points of interest. A wastewater plant, for example, is usually not located directly next to another one, clothing stores, however, are mostly grouped together in a particular part of the city center. Thus, a special distance is allocated to each feature class in which one point would normally not occur twice. For that, f-classes representing features that could be used equivalently are grouped. A common example would be the f-classes graveyard and cemetery. Simultaneously, to make sure former polygons are represented according to their size, this analysis was made by introducing three different polygon sizes. Either 0, 50% or 100% of the former shape is represented in the form of a buffer around the points. A comparison between the three different results are made in order to estimate the best fitting solution for each f-class. Double entries are thus deleted accordingly while points of different origin are not erased by mistake.

In the last step of data processing, buffers of different sizes are laid around each remaining point in the data set to analyze in purely geographical manner whether points are close to each other. This final step is done without limiting the comparison to inter-f-class consolidations. Results indicate the most mapped areas within the data sets. This step is undertaken to find and manually delete remaining duplicates. Besides being the final step of data processing, it simultaneously represents a quality assessment of the previous steps. If many duplicates occur that still need to be erased manually, it is possible to identify which parameters of the former steps need to be adjusted in a way that allows for a more qualitative result.

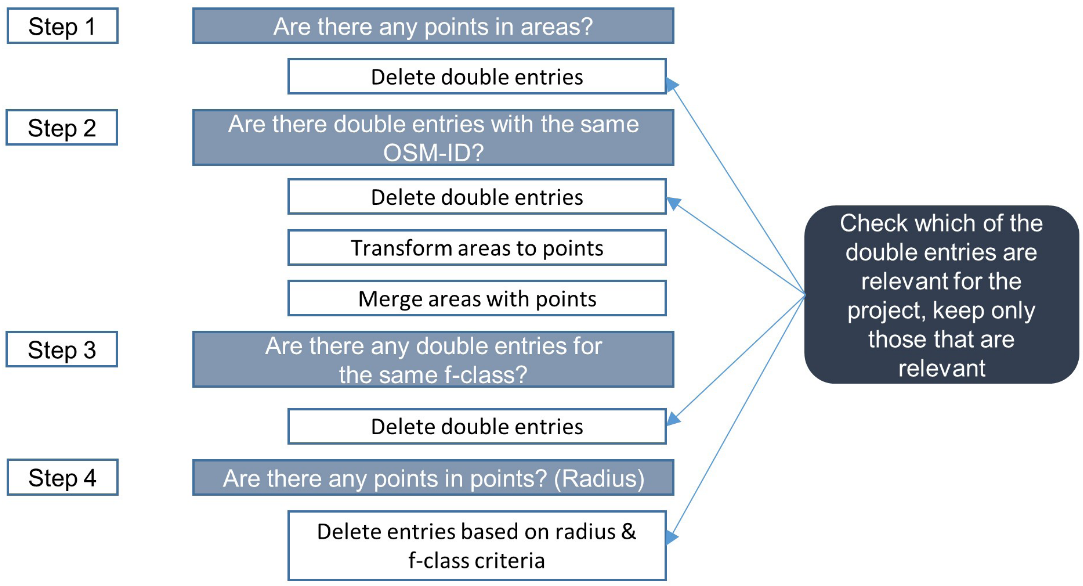

Figure 4. Data processing

4. Case study eRoad: Deggendorf – Písek

The presented methodology is applied to an area at the German-Czech border (see Figure 5). The regions involved around Deggendorf and Písek are facing particularly large challenges: on the one hand, population numbers are decreasing due to the absence of basic amenities or the general lack of employment opportunities in rural areas. On the other hand, there is a flow of migration of new citizens coming from towns in a process of deconcentrating population also called "counterurbanization" [29]. Under such a scenario, municipalities are lacking fitting infrastructure and their competence in areas related to mobility is often not sufficient in order to react to the ongoing e-mobility transition with a mature concept. As preferences and needs of habitants from these regions do not correspond to those of urban citizens, there is a need to adapt existing e-mobility solutions to the characteristics of this area. A concept covering all relevant topics can only be realized when municipalities ensure basic infrastructure for their population that satisfies current and future demands. The concept moreover needs to provide attractive incentives and possibilities for the economic development of the area and, at the same time, offer an attractive quality of living. Therefore, the selection of POIs to be implemented in the CS demand model should be based on such characteristics and present an appropriate response to the potential citizens' needs.

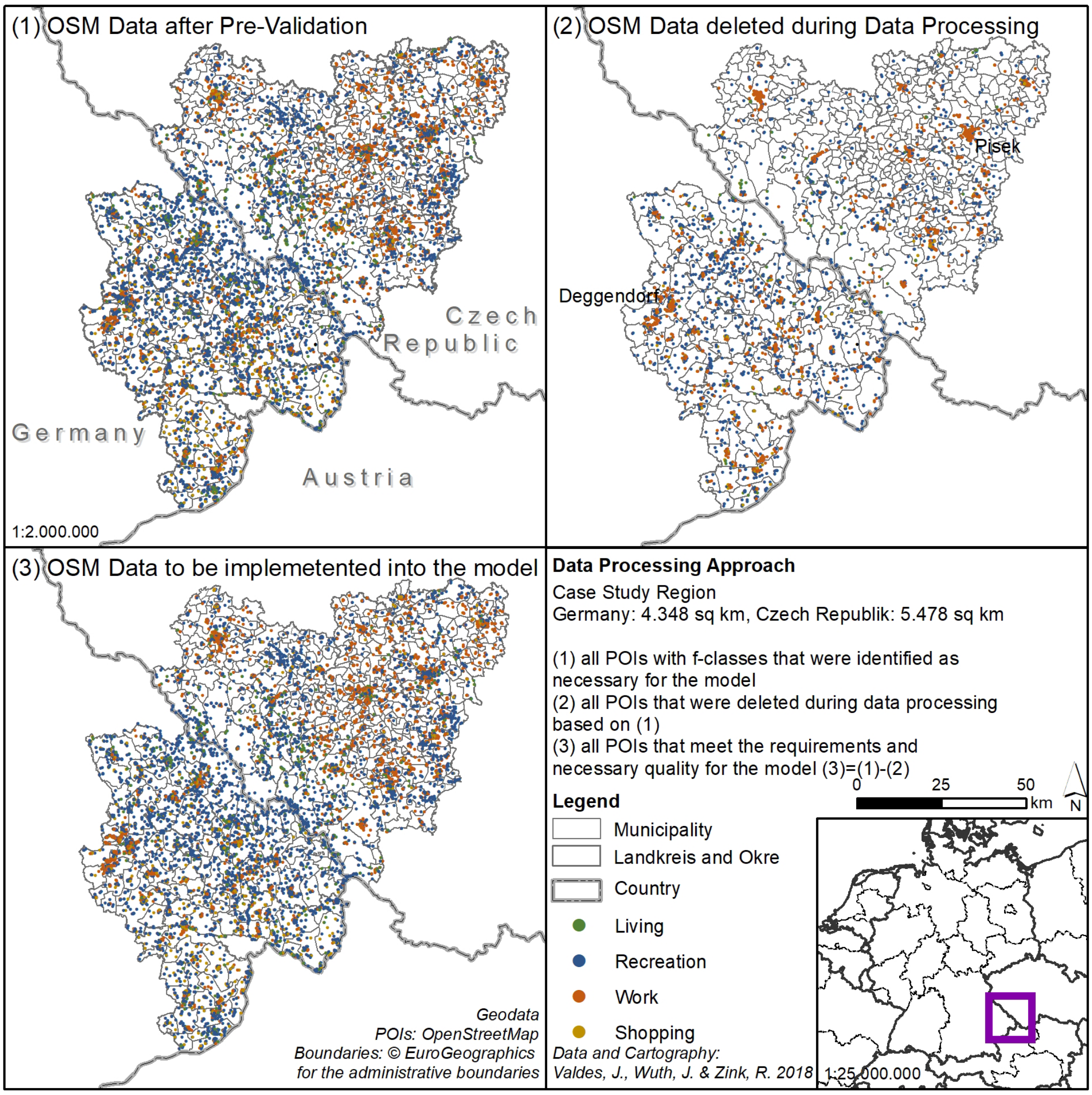

Figure 5. eRoad project region and POIs from OSM data

The full OSM dataset was downloaded from Geofabrik GmbH (https://www.geofabrik.de/) covering Lower Bavaria, and the Czech Republic in June 2018 and in August 2018, respectively. Following the first quality criterion, POIs were selected based on their proximity to roads and parking spaces. For the regions of the study, OSM data are mainly composed by polygon layers and f-classes associated with buildings and land use, which account for almost 80% of the whole data set followed by data on transport infrastructure, mainly roads and railways (12%) and points signaling very different classes of locations, from natural parks to cafés and bus stations (8%).

In the pre-validation phase, the georeferenced f-classes were evaluated in relation to the explained criteria: relevance, differentiability and classifiability. Using a scale from 1 to 3, each f-class received a rating on how well they covered the queried need for the model. For instance, a bus station is relevant for the e-mobility model as some users may drive to the station by car and then continue their journey by bus, and therefore may score a 3 in relevance. It is, however, not differentiable, as the f-class contains small bus stops that cannot be considered to have a car transport demand but also central bus stations which may raise a large demand. It thus would also be difficult to classify and therefore would score a 2 in the classifiability and a 1 in the differentiability criterion. On the other hand, a waterfall may also be relevant as it could generate interest to visit it, but not as relevant as a supermarket that would score a 3. Moreover, a waterfall is highly differentiable and may score a 3 there, unlike a building with no information on its use, which scores a 1 or 2. Finally, all f-classes containing a 1 were discarded as they were not at all considered to be relevant, differentiable or classifiable. In this process, the number of f-classes was reduced from 313 to 130 in the case of Germany, and from 270 to 113 in the case of the Czech Republic.

Based on the model classifications of Zink et al. [9], the f-classes were organized into the four different time categories “work”, “home”, “recreation” and “shopping” in order to introduce them to the model (figure 6). The f-class categorization was done equally for both countries. The results of the remaining points per f-class are demonstrated in figure 7. It shows that the category “recreation” is the largest one in Germany, including 4,407 points, directly followed by the category “shopping” with 2,126 points. In the Czech Republic, the category “shopping” is the largest with 3,126 points, followed by “recreation” with 2,982 points. The different order of time categories between the countries may indicate that users mapping the Czech Republic have concentrated their efforts on different f-classes compared to users mapping Germany, or that the structures of the two countries are differently specified, even though the regions observed are directly neighboring each other.

In figure 7, an overview of the points eliminated by demand category in each methodology step is presented. After allocating every f-class to a time category, the data processing started with the point in polygon comparison. 677 of the 10,620 locations in the German case, respectively 101 of the 9,613 locations in the Czech region observed show a problematic entanglement. Several points were found in one single polygon. For example, 18 attraction points were located in one polygon belonging to the f-class zoo. One OSM user named each attraction according to the animal that could be seen from that exact spot in the zoo. Simultaneously, several large and broader classified f-classes like, for instance, industrial contained more specified points like car wash, hairdresser or butcher. As a result, the f-classes industrial and commercial of the German data set were removed as more than 50% of the points and polygons in these f-classes were erroneous. The other point-in-polygon incidents were deleted depending on the more precise explanation of the f-class.

After cleaning the data set according to the findings, all remaining polygons were transformed into points and merged with the shapefile including all locations that were marked as points from the beginning. Step 2 in the analysis deleted 958 German and 520 Czech points of the datasets, as they were duplicates by OSM ID. In both regions, these points were mainly recreation places related to religious activities. Due to the proximity of churches, cemeteries, chapels and locations with the reference Christian, which obviously in many cases made reference to the same location, many of these points had to be deleted in order to avoid a non-existing demand for CS infrastructure. Moreover, in the Czech regions, a high number of camping sites were referenced in the OSM data as different locations, even if they made reference to buildings and land areas belonging to the same camping area. On the other hand, in the German regions many duplicates were locations belonging to the categories chalet, gift shop and car wash. These differences give a further idea of the dependence of OSM data to regional and cultural characteristics and preferences.

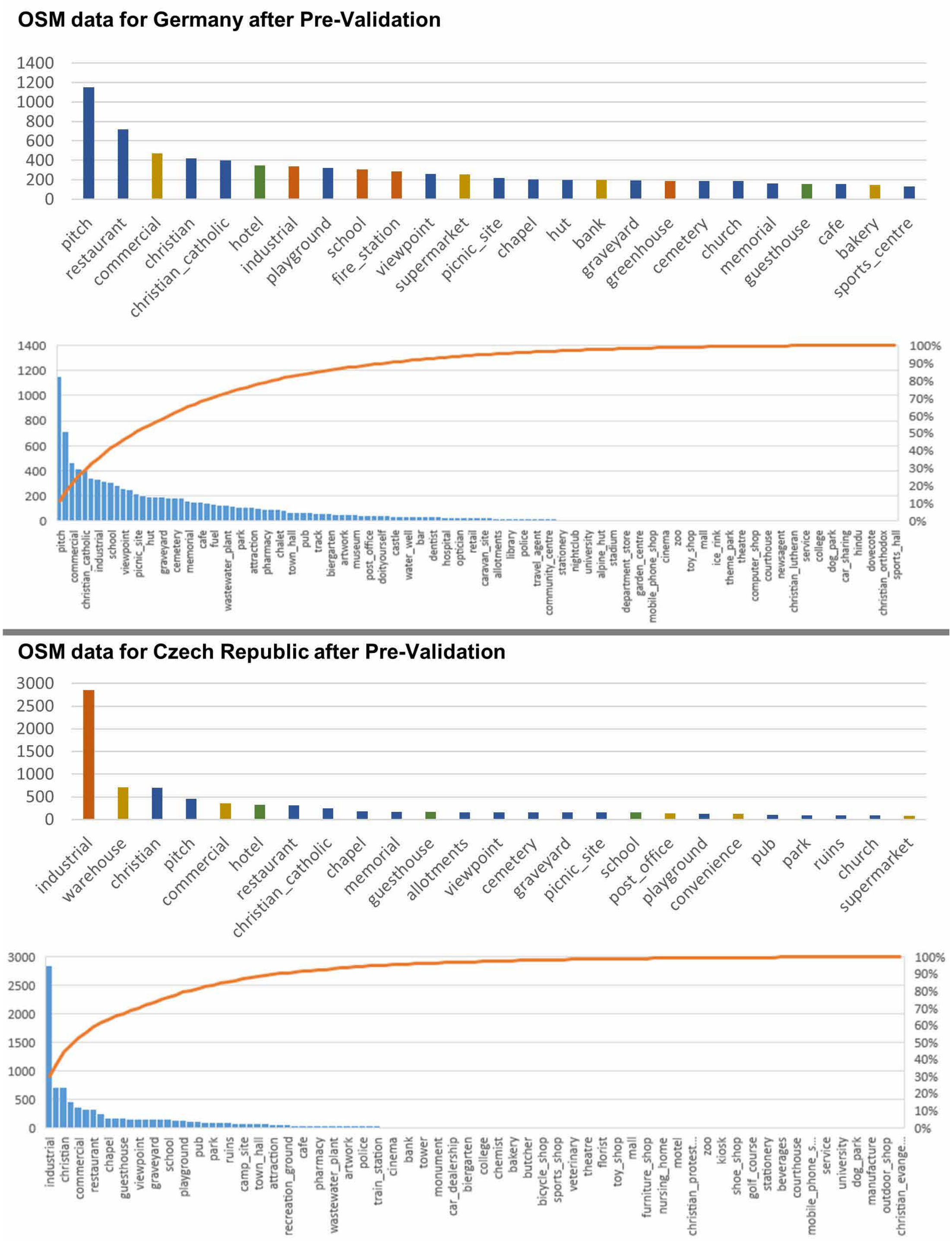

Figure 6: Number of POIs by f-class after Pre-validation (top 25 f-classes)

The last step of the methodology presented herein is responsible for most of the discarded data. This step is to a strong degree regionally dependent as it has to do with the way OSM users insert their data. A large number of locations were eliminated in the Czech Republic (1,907), of which the most were industrial locations (1,212 out of 1,625), schools (51 out of 93) and pitches (130 out of 329). In Germany, 1,275 locations were eliminated including a large number of chapels (52 out of 146), huts (64 out of 134) and also pitches (367 out of 782). This last step reduced the dataset to the final 8,010 locations in the German regions and 7,085 individual locations in the Czech Republic. 5,438 points were eliminated during the process (Figure 7). In both countries, around 73% of the pre-validated data are left after data are left to be implemented into the model after data processing.

Figure 7: Number of POIs by demand category by data pre-validation and data processing step

5. Discussion and outlook

This study focused on the potential of OSM data for locating demand for modeling EV energy demand, presenting a novel approach for OSM data quality validation. Instead of conventional statistical approaches, the performed analysis is based on qualitative criteria which are related both to the content and the structure of the data. The results of the analysis performed show that OSM data cannot be included in e-mobility models as they are because of the way in which they are generated. In particular, the OSM data analyzed in this project show that the features in many cases lack adequate descriptions that allow to identify basic characteristics of the locations as, for instance, their names. This particularly applies to the f-classes “industrial”, “commercial” and “buildings”, which in many cases do not contain any description of the industrial and commercial activities they made reference to. In the case of buildings, the purpose of those buildings and their typology is mostly missing.

The results show that the high degree of subjectivity of the users and the administration of the platform are other issues related to data quality. There is a lack of quality assessments by the platform administrators of common errors like duplications of POIs. These errors can occur in different situations, like when mapping an already existing site or adding an already existing POI by allocating it to a different POI f-class with a slightly different definition. A common mistake, for example, is to allocate one church to the f-class Catholic, Catholic church or church. What's more, the mapping of data is very user and POI-specific. Some users might map "swimming pools" not only as publicly available swimming pools, but define every private pool as a swimming pool. It would therefore be interesting if the tag for public and private locations was better controlled. Moreover, another common mistake related to classification stems from confusing different classes, for example not all participants may know the differences between the f-classes graveyard and cemetery.

Adding these feature class errors to a model may not have an impact at the aggregated level, but it can heavily distort the outcomes for some specific location to an even greater extent than if the erroneous feature class were left out completely. Taking once more the example of the swimming pools, defining one POI as several ones can be another area for errors, because the institution "swimming pool" consists of more than one pool. Thus, a swimming pool with 3 different pools would be marked in the map as 3 different POIs, which falsifies the data set and triples the calculated energy demand when using three POIs instead of the single one existing. An avenue of future research will be the evaluation of these biases through case studies in different regions.

As the f-classes function as tags for POIs, different POI categories sometimes contain very similar f-classes. This may lead to further POI duplicates as some users may map the viewpoint as a "watchtower", some as an "observation point" and then again, others may just use the category "viewpoint". In this example, one POI would turn out to be three on the map with different names but referring to the same spot. Moreover, all f-classes consist of point and polygon data sets. As a result, many, however not all of the points are additionally represented as polygons, inducing more duplications.

In order to cope with these problems, one of the potential possibilities is to complement OSM data with data from other sources. For example, in the case of Germany and the Czech Republic, the data can be enriched by firm-level data obtained through the Czech Statistical Office (CZSO) and the German Chambers of Industry and Commerce (IHK) company registers in order to locate industries. Both institutions collect data on firm locations and the numbers of workers which allow to differentiate and calibrate the model in function of the affluence to work places based on the numbers of workers. Nevertheless, in order to include such data sets, it would be necessary to ensure that there are no duplicates between the different data sources as the official registers may contain enterprises that are already included in the OSM dataset. Moreover, such data sets are often very costly and the large advantage of OSM data, besides its richness, is that it is free of charge.

The methodology presented in this paper shows the relevance of conducting studies to increase the use of OSM data for geographic modeling. Nevertheless, the current classification methodology based on tags should be improved in order to make OSM more user-friendly. To this end, one option would be to re-define the tag classification methodology in order to simplify the complexity of the data. This option, although possible, would probably impact one of the main advantages of OSM data: its richness. Another option would be to generate a parallel or multiscale tag classification that allows to identify which data is susceptible to be used in different contexts.

The analyzed OSM data in the scope of a model for CS placement show that most of the selected POIs are not suitable for the model. Nevertheless, it is necessary to note that OSM is not complete and therefore there may be locations that have not been included in the model. This bias is normal, taking into account the relative novelty of the OSM project and the constant nature of OSM data. For this reason, the major part of the methodology presented herein is based on automatic processes and algorithms specifically designed to reduce human supervision of the results. Moreover, the data processing also includes a validation step in order to acknowledge for any bias associated to the f-class classification during the validation process itself.

Finally, it should however be noted that many research projects could not have been carried out in the way they are currently done if OSM data were not available. The availability of such a rich and diverse data set can despite large error fields provide insights that would normally have not been possible without considering costly datasets. Therefore, there is a need to continue the research in OSM data quality control in order to increase the range of applications of such a rich source of information. For that, it may be necessary to create specific classification methods. These classifications would allow to identify which data are susceptible to be used within different contexts. This would make it possible for a region. or city interested in, for instance, applications of OSM data for tourism to just download a set of data already validated. Further work should focus on approaches to quality assurance of such data for accuracy assessment and to extend the analyses to other regions. This may impact the quality and accuracy of the overall model and reduce biases, especially in rural areas with lower overall numbers of POIs.

6. Acknowledgement

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Usage Profiling in Electric Vehicles

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ABSTRACT

In the overall effort of reducing CO_2 emissions, the significance of alternative drive engines is growing. The transition from combustion engine vehicles to electric vehicles is high on the political agendas, with governments providing extensive funding to promote electric mobility. However, there are still challenges that hamper the dissemination of electric vehicles. One of those challenges is the limited range and the resulting range anxiety. Displayed vehicle range data contribute to this, as they are relatively inaccurate and might vary quite strongly during individual trips. This problem could be addressed by personalizing the range display according to the driving style of the current driver. Driver assistance services, like distance control, are becoming increasingly personalized nowadays, however, they are predominantly designed for internal combustion engine vehicles. In this paper, relevant input parameters for classifying the driving styles of electric vehicle users are identified. Furthermore, a system based on real-life driving data is developed to determine the driving style. Real-life driving data were collected in experiments and used to profile the driving style by means of fuzzy logic. Based on the results, an approach for a realistic classification of driving styles of electric vehicle users is discussed.

Die Wichtigkeit alternativer Fahrantriebe zur Reduktion von CO_2-Emissionen wird immer stärker. Der Umstieg von Verbrenner- auf Elektrofahrzeuge wird auch immer nachdrücklicher von der Politik gewünscht und gefördert. Jedoch gibt es immer noch Aspekte, die das Wachstum der Elektromobilität einbremsen. Einer dieser Aspekte ist die begrenzte Reichweite und die daraus resultierende Reichweitenangst. Auch die Reichweitenanzeigen in den Fahrzeugen tragen hierzu bei, da diese relativ ungenau sind und während einer Fahrt stark schwanken. Dies könnte durch die Personalisierung der Reichweitenanzeigen auf der Grundlage des Fahrstils des aktuellen Fahrers verbessert werden. Fahrerassistenzsysteme wie Abstandhalter werden heutzutage immer mehr personalisiert, jedoch sind diese meist für Verbrennerfahrzeuge ausgelegt. In dieser Arbeit werden die wichtigsten Parameter zur Bestimmung des Fahrstils bei Elektrofahrzeugen identifiziert und ein System entwickelt, welches auf Basis realer Fahrdaten den Fahrstil bestimmt. In Experimenten wurden reale Fahrdaten aufgezeichnet, welche zur Bestimmung des Fahrstils mit Hilfe von Fuzzy Logic genutzt wurden. Darauf aufbauend wird ein Ansatz diskutiert, der eine realistische Klassifikation des Fahrstils in Elektrofahrzeugen ermöglicht.

KEYWORDS

Electromobility, range, driving style classification, fuzzy logic

Elektromobilität, Reichweite, Fahrstilklassifikation, Fuzzy Logic

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1. Introduction

Electric vehicle (EV) technology, especially EV battery technology, is constantly improving. Thus, the potential of EVs to reduce CO_2 emissions [1] increases under the premise that the charged energy originates from regenerative sources. EVs can therefore reduce our ecological footprint and bring a real environmental benefit. Introducing more EVs may also mitigate health risks like fine dust pollution or slow down global warming [2]. There are, however, still issues concerning the attractiveness of EVs which need to be tackled in order to increase the number of EVs in our daily life. One issue is the lower range in comparison to combustion engine vehicles (CEV). Therefore, one of the biggest anxieties of EV drivers is not being able to reach their destination due to the low range and the imprecise remaining range calculation of the EV.

To address this issue, the calculation of the remaining range has to be improved in order to turn range prediction more precise. To this end, EV characteristics like battery type and age, as well as topological information like the elevation difference along the route are important. However, the driver himself is another relevant factor for determining a precise model. His/her driving style and behavior can have a huge impact on the driving range of an EV [3]. A sportive and very fast driver will have a significantly higher energy consumption than a very slow and foreseeing driver. Here, the differences in driving behaviors between EV and CEV users are relevant, as shown in [4]. The constant torque produced by EVs brings the benefit of maximum acceleration at any time. In a CEV, acceleration depends on the engine's rpm value (revolutions per minute). Another difference lies in braking behavior, as the EV regenerates energy when there is no acceleration and while braking. This process is called regenerative braking or recuperation. It affects the braking behavior of the driver quite strongly as the energy recovery mechanism already slows down the vehicle and less braking activity from the driver is necessary. Taking this into account, integrating the driving behavior could bring a real benefit in terms of improving the accuracy of range calculation for EVs. Besides, EV drivers' behavioral profile data may also be used for other driver assistance services, ultimately increasing user acceptance.

In a first step, a method for improving range prediction by usage profiling is discussed. EV drivers' usage profiles are directly derived from driving data originating from the EV's CAN bus. The Controller Area Network (CAN) bus is the EV's internal communication system. The proposed system is based on real driving data and is capable of identifying the driving style whilst driving, which may serve as an input for a range model that is constantly being updated during a trip. To this end, we analyze the existing related work of usage profiling methods in Section 2. We present our approach and discuss first results in the sections 3 to 5. Section 6 provides a conclusion.

2. Related work

A broad range of literature discusses the problem of range anxiety as a barrier to going electric. To tackle the problem of range anxiety, trust in range estimation needs to be increased [5], which may be achieved by enhancing range calculation accuracy. Different factors influence an EV's range, particularly route properties like the elevation profile, but also weather conditions, e.g. the outside temperature, as well as the individual driving style. The aspects of route properties and weather conditions were already addressed in an earlier publication [6]. We argue that taking the driving style into account and combining it with these indicators may substantially increase the accuracy of range estimations. Driving style profiling might contribute to a more accurate prediction of battery range and increase the trust in EVs and is therefore the focus of this paper.

One way to categorize existing studies on driving style classification is by the area in which the driving style is employed as a factor. Some researchers focus on driving safety. Their aim is thus to group drivers into different risk categories [7, 8]. Other research focuses on vehicle dynamics control [9] and the adoption of assistance services such as lane change or cruise assistance services [10]. Finally, the economic and ecological efficiency of driving behaviors is an additional area of focus [11], and the present paper belongs to that category.

In the above-mentioned research areas, user profiling is usually based on driving behavioral data generated from CEVs. Mostly data on gas pedal operation, brake pedal operation and the distance kept to the vehicle ahead are used to classify driving behaviors. These data can be grouped into three different categories [10]:

- Driving behavior signals
  e.g. gas pedal operation, brake pedal operation and steering angle
- Vehicle status signals
  e.g. velocity, acceleration and engine speed
- Vehicle position signals
  e.g. distance to the vehicle ahead, relative lane position and yaw angle

Different approaches are used to determine the driving style [12]. Some less common methods include correlation analysis [13], different clustering methods [7, 14] or data-dependent pointer models [12]. However, the majority of studies uses fuzzy logic as the common method for usage profiling in vehicles [8, 12, 15, 16].

Fuzzy logic depends on prior knowledge of the groups where the data can be divided into. However, fuzzy rules have no exact boundaries; they rather are descriptive rules by which arithmetic operations can be carried out. Fuzzy rules can describe behavior, for example the aggressiveness of a driver.

If gap time is	If accelerator pedal rate is	If brake pedal rate is	Then driver index is
Low	Low	Low	**Less aggressive**
High	Low	Low	**Cautious**
Low	High	Low	**Aggressive**
Low	Low	High	**Aggressive**
Low	High	High	**Aggressive**
High	High	High	**Less aggressive**
High	Low	High	**Cautious**
High	High	Low	**Less aggressive**

Table 1: Fuzzy rules of aggressiveness of a driver [17]

Table 1 presents a common example for fuzzy rules that allow to distinguish between aggressive or cautious driving behaviors. It is apparent that a user who is pressing the accelerator and brake pedals only gently while delaying the subsequent pedal pressing (gap) is most likely less aggressive than others. On the contrary, aggressive users tend to use both pedals with nearly no delay, while either or both pedals are pressed at a high rate. In this way, different user classes can be described and modelled according to these fuzzy rules.

Dörr et al. proposed an online system for driving behavior profiling in CEVs [18]. This profiling is done on the basis of data from the CAN bus of the vehicle and is calculated whilst driving. They propose three levels of driving styles: sporty, normal and comfortable. Parameters that are taken into account include speed, longitudinal acceleration, the time gap between two vehicles or the street type. Different driving parameters for different street types were also used for profiling. The driving behavior was determined by fuzzy logic and was tested through simulation only.

In this paper, we adhere to the basic concept of Dörr et al. The approach is adapted to EVs and their corresponding requirements. Furthermore, real-life driving data are used. The proposed system receives data directly from the EV in real time, processes and calculates the driving style and thus builds the basis for analyzing the driving behavior after or even during a trip.

3. Data Basis and Experiments

Driving behavioral profiling in this work is based on real-life driving data from EVs. Driving data therefore need to be transferred from EVs. The used data collection consists of multiple components, as it can be seen in Figure 1.

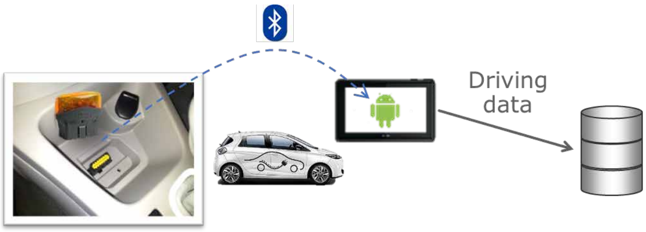

Figure 1: Data acquisition system

Data are acquired via additional hardware located in the EV and a software component, the so-called *InCarApp,* which also displays a range estimation based on altitudinal differences along the route and the current temperature. At first, an OBD (on-board diagnostics) module allows the acquisition of driving data from the EV's CAN bus. In a second stage, a tablet computer with the installed *InCarApp* receives the CAN data via Bluetooth. It filters, decodes and transmits them over a secured cellular internet connection to a server. This system allows collecting a range of different parameters from the EV that are relevant to the driving behavior.

As to driving behavior analysis in the context of EVs, the relevant data differ from those of CEVs. The constant torque and the regenerative braking, known as recuperation, entail a very different pedal usage pattern compared to CEVs. Furthermore, there is an eco-mode or eco button in most EVs. Using this functionality does not only affect the intensity of acceleration, as it does in CEVs, but also brake pedal operation. On the one hand, acceleration will be decreased, however on the other hand, recuperation will be increased. This results in a higher impact of the eco-mode on pedal usage in EVs, as compared to CEVs. Therefore, the approach of analyzing EV usage has to be adjusted with respect to several new dimensions, like the influence of recuperation on the brake pedal. To demonstrate the feasibility of this new method of usage profiling described in this paper, it is currently designed for and tested on Renault ZOEs. Moreover, driving behavior profiling is only done for single trips, because the way an EV is driven by an individual person may differ from trip to trip, depending on various influencing factors like the current mood or traffic conditions.

Initial experiments served to identify the relevant data for usage profiling. For these experiments, a 9 km test route consisting of 50% city and 50% rural streets and minimal altitudinal differences was used. The test route was driven three times each for the chosen driving behavior-related classes "careful", "normal" and "sportive". For this experiment, drivers were instructed to stick to the prespecified driving behavior as long as traffic and safety allowed it. One driver employed all three investigated driving behaviors. The experiments were conducted in a row in order to minimize temperature differences and traffic-related influences.

After these initial experiments, the driving data were analyzed. The results of this analysis are described in the following section.

The intensity of accelerator pedal input differs significantly between the different driving behaviors. This is shown in Figure 2.

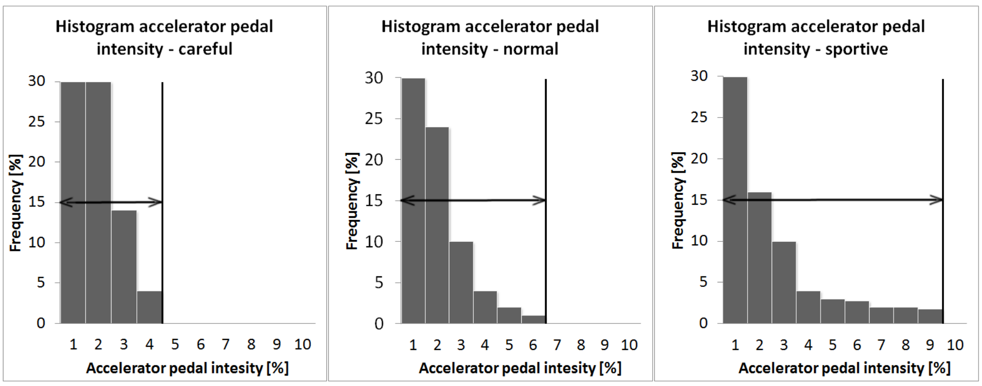

Figure 2: Histograms of acceleration pedal data for driving styles: careful - normal - sportive

This figure shows the different driving styles and their corresponding histograms: careful – normal – sportive (from left to right). The x-axis represents the intensities of accelerator pedal inputs shown as percentages, and the y-axis displays the frequency of the different intensities. To better identify the driving styles, frequencies of above 30 are not shown in this figure, however, they are later used for the analysis. This provides the possibility of gaining a better insight into higher intensities of accelerator pedal input as they demonstrate the key differences in driving styles. It is clearly shown that the range of intensities differs strongly in connection with the various driving styles as is marked with arrows. Careful drivers show a maximum intensity of accelerator pedal input of 40 %, normal drivers display intensities of up to 60 % and sportive drivers show intensities of up to 90 %. Consequently, the average values differ, too: for the careful driving style the average amounts to 9.6195 %, for the normal driving style it is 10.6723 % and for the sportive driving style it is 12.2748 %. These average values may also serve to identify the different driving styles.

The intensity of brake pedal operation is identified as the second indicator for usage profiling. Here too, it becomes obvious that there are differences in brake pedal intensity patterns, however, not in all driving styles. The frequencies of different intensities of brake pedal operation are shown in Figure 3.

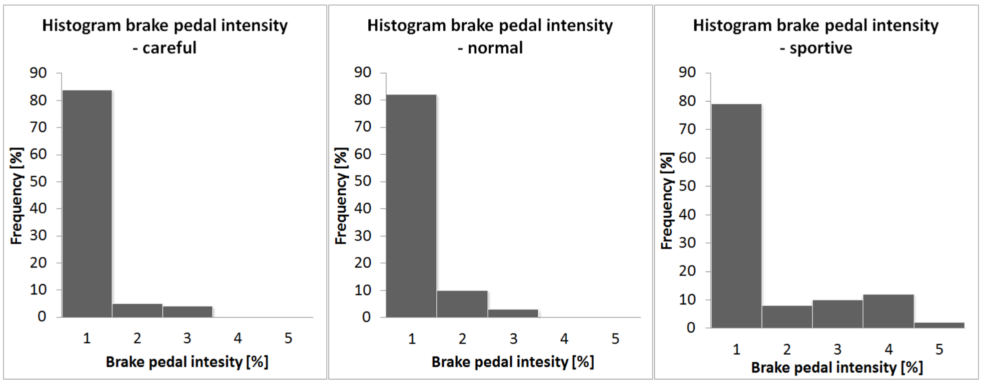

Figure 3: Histograms of brake pedal data for driving styles: careful - normal - sportive

As in the histograms of the accelerator pedal data, the order from left to right is careful, normal and sportive. The x-axis shows brake pedal intensity as percentages, and the y-axis displays the frequency of the different intensities. It is obvious that the differences between the various driving styles are not as striking as the differences in connection with the accelerator pedal. This constitutes one important difference between EVs and CEVs. As EVs recover energy when the accelerator pedal is not hit, the brake pedal is much less used and there is also less need for strong braking action. Thus, differences that seem small at first sight are also of relevance to driving behavior. It was shown that in comparison to the careful driving behavior, there is a higher frequency of the 10–20 % brake pedal intensity in normal driving behavior. For the sportive style, the frequency of between 10–20 % is less often documented, however, a high frequency of the 20–30 % brake intensity is registered. Furthermore, there are brake pedal intensities of above 30 %, unlike in normal or careful driving styles. These differences also become apparent when looking at the average values of brake pedal intensities. The average of brake pedal intensity for the careful driving style amounts to 2.3349 %, for the normal driving style it is 2.6178 % and for the sportive driving style it is 4.5536 %.

The eco-mode button is another influencing factor. When the driver activates the eco-mode button it will decrease the intensity of the accelerator pedal and increase energy recovery. Accelerator pedal and brake pedal patterns will therefore be different when the eco-mode button is switched on. A normal driver is more likely to activate the eco-mode button than a sportive driver. However, when the eco-mode button is activated, the accelerator pedal needs to be pushed stronger in order to achieve a certain degree of acceleration and thus this specific accelerator pedal pattern could be classified as sportive, too. Hence the ratio of eco-button usage during a trip is a crucial parameter for usage profiling in electric vehicles.

We therefore identify the following parameters as relevant data:

- Intensity of accelerator pedal operation
- Intensity of brake pedal operation
- Use of eco-mode button

4. Design of Usage Profiling

In the following section, the general processes of fuzzification and defuzzification are explained. Furthermore, the specific design of usage profiling for EVs is described.

The fuzzy logic is an extension of the classical propositional or Boolean logic. While propositional logic is only capable of differentiating between true and false (an element is part of a set or not), fuzzy logic also allows statements to be partly true or false. Differentiating subsets provides more room for interpretation. Membership functions, the so-called fuzzy sets, are established to represent the degree of affiliation of an element to a group. The degree of membership of an element in a given set is then represented as a number from 0 to 1. 0, if the element is not part of the set (false) and 1, if it is completely part of the set (true). Every number in between shows how strongly an element belongs to a set. The accelerator pedal intensity can be considered as an example, for it can vary between "weak", "middle" or "strong", as can be seen in Figure 4. For our first approach, the fuzzy set was modelled with triangle and trapezoid functions.

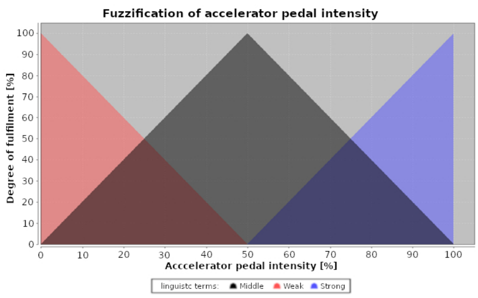

Figure 4:
Fuzzification example of the accelerator pedal intensity

The x-axis represents the accelerator pedal intensity as a percentage and the y-axis indicates the degree of fulfilment with respect to the 3 different linguistic terms. Weak is thus 0%, middle is 50% and strong would be 100%. These are called linguistic terms and the boundaries between these categories are fluid. Hence a distribution will be defined for each term that describes the degree of fulfilment. Here it can be seen that one input value can correlate to more than one linguistic term. An accelerator pedal intensity of 45 % would fulfil the term "weak" by 10 %, however, the term "middle" would be fulfilled by 90 %. This is called fuzzification. Different membership functions can be used for fuzzification. In Figure 4, the very common triangular membership function is used. The trapezoid function, which is also frequently employed, will be mentioned in a later section of this paper.

Rules can be employed to connect the fuzzifications of the different input parameters. One rule consisting of the input parameters "average of accelerator pedal intensity" and "average of brake pedal intensity" and the corresponding linguistic terms "low", "medium" and "high" can be described as follows:

IF acceleratorpedalAverage IS high AND brakepedalAverage IS high THEN drivingStyle IS sportive

In fuzzy logic, as many rules as needed can be described with linguistic terms. Each rule may consist of several linguistic terms that are connected with "and", "or" and "not". One or more linguistic output terms are derived from each rule to define the driving styles "careful", "normal" and "sportive". This is called inference process. Hence the rules are linked by logic as geometric functions. Many different rules need to be applied for a functioning system and it needs to be ensured that an output value can be generated for every possible combination.

In a last step, the generated output values will be converted into a numerical value. This is called defuzzification. Defuzzification also uses distributions that can be the same membership functions as for the fuzzification. In the following section, we describe the design of our approach for a fuzzy logic for EVs. We have identified the relevant data for EV usage profiling in the chapter above. In a first validation of our usage profiling approach, the following parameters were chosen as input aggregation for calculating the driving style:

- Average of accelerator pedal intensity [%]
- Average of brake pedal intensity [%]
- Ratio of eco-mode button activation [%]

The input value range is adjusted according to the experimental average values so that during fuzzification, different linguistic terms are created for the different driving styles. This may also be seen in connection with the fuzzification of the average brake pedal intensity.

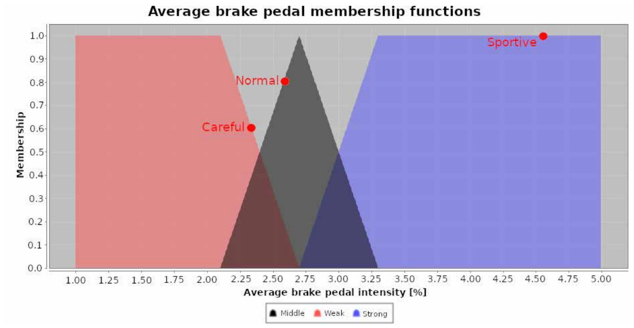

Figure 5: Fuzzification of the average brake pedal intensity

In Figure 5, the distribution of the fuzzification of the average brake pedal intensity and the identified driving style are shown. The x-axis represents the average brake pedal intensity as a percentage and the y-axis displays the degree of fulfilment with respect to the 3 different linguistic terms. The value range of brake pedal intensity is limited from 1 % to 5 % as the averages from the experiments are in this range. A trapezoid membership function was chosen for the terms “weak” and “strong” and a triangular membership function was chosen for the term “middle”, because these functions provided the best results for our limited test data. However, further experiments are planned in the future, so that the membership functions can be adjusted accordingly, for instance with machine learning techniques. For our experiment, however, the average brake pedal intensities for the different driving styles are depicted with red markings in Figure 5. It can be seen that the range of the different brake pedal averages is very close as the total range is only from 1 to 5. Furthermore, there is only a small difference between the careful and the normal brake pedal intensity. This is due to the fact that the braking behavior of EVs is very different from CEVs. Therefore, brake pedal intensity alone is not sufficient for classifying the driving style.

The accelerator pedal is a clearer indicator for the driving style, as is shown in the respective membership functions in the figure below.

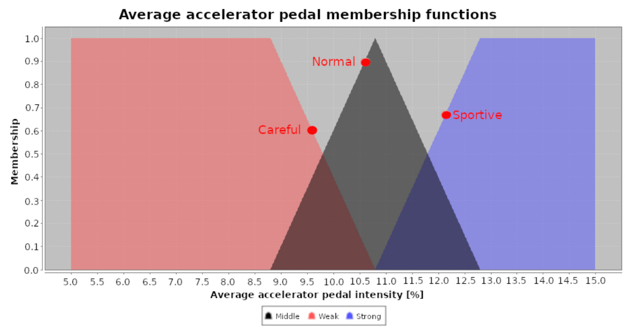

Figure 6: Fuzzification of the average accelerator pedal intensity

Figure 6 shows the distribution of the fuzzification of the average accelerator pedal intensity and the identified driving style. The x-axis depicts the average accelerator pedal intensity as a percentage and the y-axis displays the membership to the 3 different linguistic terms. For the linguistic terms “weak” and “strong”, a trapezoid membership function was used and for the linguistic term “middle”, a triangular membership function was used to best fit the driving styles. It can be seen that the average acceleration is a good indicator for the driving style and it can be very well distinguished. Moreover, with a range from 5 to 15, the value range is broader than the one for the brake pedal intensity. The driving styles lie further apart from each other and are thus better distinguishable.

The eco-mode button ratio was identified as a last input. Comparable to Figure 4, it was fuzzified with triangular membership functions for all three driving styles.

A set of rules was created for calculating the output values from the fuzzified input values, as depicted in Table 2.

Rule block					
Rule	accelerationAverage	brakeAverage	ecoAverage	drivingStyle	weight
01.	weak	weak	weak	careful	1.0
02.	weak	weak	middle	careful	1.0
03.	weak	weak	strong	careful	1.0
04.	weak	middle	weak	careful	1.0
05.	weak	middle	middle	careful	0.8
06.	weak	middle	strong	careful	1.0
07.	weak	strong	weak	normal	0.4
08.	weak	strong	middle	careful	0.5
09.	weak	strong	strong	careful	0.6
10.	middle	weak	weak	normal	0.7
11.	middle	weak	middle	careful	0.2
12.	middle	weak	strong	careful	0.4
13.	middle	middle	weak	normal	1.0
14.	middle	middle	middle	normal	0.6
15.	middle	middle	strong	careful	0.2
16.	middle	strong	weak	normal	0.8
17.	middle	strong	middle	normal	0.6
18.	middle	strong	strong	careful	0.1
19.	strong	weak	weak	sportive	0.6
20.	strong	weak	middle	sportive	0.4
21.	strong	weak	strong	normal	0.3
22.	strong	middle	weak	sportive	1.0
23.	strong	middle	middle	sportive	1.0
24.	strong	middle	strong	sportive	0.8
25.	strong	strong	weak	sportive	1.0
26.	strong	strong	middle	sportive	1.0
27.	strong	strong	strong	sportive	1.0

Table 2: Fuzzy logic rule block

The table provides an overview on the different rules. In the left column, all 27 rules are listed. The columns “accelerationAverage”,” brakeAverage” and “ecoAverage” represent the three parameters. The three linguistic terms “weak”, “normal” and “strong” were assigned to each parameter. Each row is a permutation of the three linguistic terms pertaining to the parameters. The right column “drivingStyle” is the result of the rule. It had been assigned the three linguistic terms “careful”, “normal” and “sportive”. Hence this table can be transformed into the Fuzzy Control Language (FCL). The Fuzzy Control Language is a programming language especially designed for the evaluation of fuzzy statements. It is a domain-specific programming language. Therefore, it is only capable of interpreting statements to the fuzzy logic. One rule (Rule 22) transformed into FCL is shown below as an example:

*“**IF** accelerationAverage* **IS** *strong **AND** brakeAverage **IS** middle **AND** ecoAverage **IS** weak **THEN** drivingStyle **IS** sportive **WITH** 1.0”*

The rules cover all possible combinations to ensure a working system. The design of these rules depends on prior knowledge to judge a certain behavior. The keyword “WITH” at the end of every rule represents a factor for the strength of a rule. Rule 22 with a factor of 1.0 is therefore stronger than rule 21 with a factor of 0.3. These factors are used to adjust the system and are chosen according to the experiments so that the system calculates the driving styles correctly. Despite the limited amount of test data, however, the first draft of these rules seems promising. With more test data available, the results may be refined in the future.

5. Results

After the calculation via the fuzzy system the output value is retrieved. This value represents the driver's driving behavior during an individual trip. However, the developed system does not only classify a driver into one driving style category, but provides a percentage value incorporating two driving styles for the profile of an individual trip. This means that a driver can be 75 % sportive and 25 % normal, which allows a better insight into the driving profile of a driver.

Thus, the system calculates a numerical number that correlates with the driving styles as output. This is done with a scale of between -10 and 10 that is used for defuzzification by the system. The distributions of the defuzzification of the driving style are shown in Figure 7.

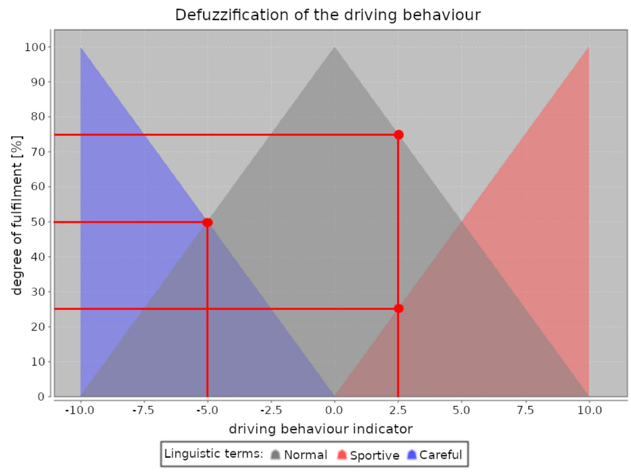

Figure 7: Defuzzification of the driving style on the defined scale between -10 and +10

The x-axis shows the described scale of between -10 and 10 for the driving style outputs and the y-axis displays the degree of fulfilment of the linguistic terms. The linguistic terms are divided into "careful", "normal" and "sportive" and refer to the driving styles. The value of -10 characterizes a 100 % careful driver, the value of 0 characterizes a 100 % normal driver and the value of 10 characterizes a 100 % sportive driver. As the transitions between these values are fluid, a classification and a percentage mix of two driving styles is possible. Marked in red on the left-hand side is the value of -5 which would refer to a "careful" as well as a "normal" driving style at 50 % each. The value of 2.5, which refers to a 25 % sportive and a 75 % normal driving style, is also marked in red.

As this classification is based on the gathered test data, it may lack accuracy for different trips or drivers. However, this may be improved by larger-scale experiments. Nevertheless, our experiment demonstrates that it is possible to generate real-time and real-life usage profiling for EVs with the system we have established.

6. Conclusion

In this paper, the suitability of fuzzy logic for driving style classification with real-life driving data was demonstrated. Moreover, the differences between EVs and CEVs with respect to driving style classification were evaluated. Furthermore, a lack of driving style classification methods for EVs was shown as the majority of related work refers to CEVs.

To address this issue, a system was developed that is able to classify the driving behaviors of EV drivers using fuzzy logic. This system is based on real-life driving data from EV users and is specifically designed for EVs. Important EV-specific input parameters were evaluated and the differences as compared to CEVs were described. The basic driving behavior indicators accelerator pedal, brake pedal and eco-mode button usage were used as inputs for the classification. This shows that EV users' driving styles are correctly classified by means of the developed system and by using basic driving data only.

Another important aspect of this work is the real-life experiment, which was conducted in an EV with an integrated data collection system. Thus, the developed system is based on real-life driving data. Further experiments using the developed system therefore can easily be conducted. By gathering more test data, the accuracy of the system is expected to be markedly improved. The fuzzy sets may be refined, e.g. by machine learning techniques. In addition, the accuracy of the FCL results can be improved.

Our classification system provides a percentage value for the degree of fulfilment of all driving styles. Thus, by classifying the driving style during an individual trip e.g. as 40 % careful, 60 % normal and 0 % sportive, a better assessment of driving behavior can be provided. In consequence, not only a dominant driving behavior would be evaluated, but also tendencies toward other driving behaviors. This allows for better adjustment of different assistance services, such as range prediction or adaptive cruise control.

In future work, additional parameters like speed in relation to the speed limit or street type will be evaluated. Further experiments that will be combined with a psychological questionnaire are planned in order to improve the developed system.

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Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

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A Simulation-Based System for Calculating Optimal Numbers of Forklift Drivers in Industrial Plants

Mohammed Alnahhal* **Diane Ahrens***

ABSTRACT

This article describes an optimization method for the material handling system of forklifts using queueing theory and simulation. The objective is to reduce several types of wastes such as waiting time, capacity costs, delayed job orders, and transportation costs. A certain IT infrastructure is assumed, such as monitors for forklift drivers to check on the current job orders at different work stations. Mathematical equations are used to find initial upper and lower limits for the needed capacity levels over the day. Subsequently, a simulation for different levels of capacity within the range of theoretical results is performed in order to find the exact man hour needed for different jobs sequencing strategies. On the basis of the statistical software R, a tool is devised to provide companies with the results for the different parameters they determine. These results show the effects of using batching, considering limitation of line-side space, and the empty drives reduction strategy on performance measures. The strategy of reducing empty drives by identifying the nearest workstation needing a job order was found to be not efficient since it increases the needed capacity. This is due to the fact that the variability of waiting time and hence the late orders percentage are increased.

Dieser Artikel beschreibt eine Optimierungsmethode für ein Materialtransportsystem von Gabelstaplern mittels Warteschlangentheorie und Simulation. Ziel ist es, verschiedene Arten von Verschwendung bei den Kapazitätskosten, verspäteten Arbeitsaufträgen und Transportkosten zu reduzieren. Es wird eine gewisse IT-Infrastruktur angenommen, wie etwa die Verwendung von Monitoren, um die aktuellen Arbeitsaufträge von verschiedenen Arbeitsplätzen anzuzeigen. Mathematische Gleichungen werden benutzt, um anfängliche obere und untere Grenzen für die benötigten Kapazitätsniveaus zu finden. Danach wird eine Simulation für verschiedene Kapazitätsniveaus innerhalb des Bereichs der theoretischen Ergebnisse durchgeführt, um die genau benötigte Mannzeit für verschiedene Jobsequenzierungsstrategien zu finden. Mit Hilfe der Statistiksoftware R wird ein Tool erstellt, welches Unternehmen für verschiedene Parameter Ergebnisse liefert. Diese Ergebnisse zeigen die Auswirkungen der Verwendung von Batching, unter Berücksichtigung der Begrenzung des Zeilenseitenraums und der Reduzierung der Leerfahrtstrategie für Leistungsmessungen. Die Strategie, das Leerfahren zu reduzieren, indem nach dem nächsten Arbeitsplatz gesucht wird, der einen Auftrag benötigt, ist nicht so effizient, da es die benötigte Kapazität erhöht. Dies liegt daran, dass es die Variabilität der Wartezeit vergrößert und somit den Prozentsatz der verspäteten Bestellungen steigert.

KEYWORDS

Forklifts, material handling, simulation, queueing theory

Gabelstapler, Fördertechnik, Simulation, Warteschlangentheorie

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1. Introduction

Material handling is one of the most important factors affecting costs and performance in manufacturing companies [1]. Any delay in moving the needed materials can cause production delay that, in turn, affects productivity. Moreover, the space for line-side inventory can be very scarce and insufficient for much material to be stacked. On the other hand, increasing the needed capacity can lead to major costs and an unorganized allocation of workload. Therefore, material handling is one of the most important activities that need to be optimized. Capacity in this paper means the total needed man hours for forklifts, which affect the maximum number of needed forklifts. Using forklifts is the traditional way in most material handling activities. *Loading units* and *pallets* will be used interchangeably in this paper. In small and medium-sized companies, it is common to see that forklift activities and the needed capacity are manually planned. This paper presents a tool for optimizing a forklift system assuming the availability of data about job orders. The number of drivers needed throughout the day and different performance measures can be obtained by using analytical equations and simulation. Different possibilities of job sequencing by using different priority rules can be done. We present the results of a case study for a company operating in Germany. The tool has been developed at Technology Campus Grafenau (TCG), which is an applied research center affiliated to Deggendorf Institute of Technology. This tool is part of efforts in a project called *Industrie 4.0 Werkstatt Bayerischer Wald* (Industry 4.0 Workshop Bavarian Forest) which is funded by the EU program EFRE (*Europäischer Fonds für Regionale Entwicklung*; European Fund for Regional Development). The tool performs with R Software, a free software that can be used by companies. More information about this software can be found in an article by Ihaka & Gentleman [2].

After this brief introduction about the importance of optimizing material handling systems and the tool developed, a literature review about using queueing theory and simulation in logistics and forklifts systems is presented. Moreover, some previous studies that investigated characteristics of forklifts systems such as batching and time-dependent arrival rates are discussed. After that, a problem definition and the objectives of the study are presented. The methodology, which depends on analytical equations and simulation, is explained. Analytical equations define boundaries of the needed capacity of drivers. Subsequently, simulation of forklift operation with different options and priority rules is done. Finally, results and conclusion are presented.

2. Literature review

2.1. Forklift system as a queueing system

The range of applications of queueing theory includes telecommunications and computer science, manufacturing, air traffic control, military logistics, design of theme parks, and many other areas that involve service systems whose demands are random [3]. Forklift system can be considered as a queueing system. Driving time of forklifts plus loading and unloading activities can be considered as service time. Forklifts and drivers are considered as servers. Pallets are the customers. More details about queueing theory can be found in Shortle et al. [4]. Little was published about using queueing theory to analyze forklift system. An example of applying queueing theory in logistics is the study by Masek et al. [5], where queueing theory was applied in warehouse optimization. Another paper by Munisamy [6] presents a port planning and operations model for capacity planning at a timber terminal. The analytical model was the closed queueing network model. The model evaluated the efficiency of the timber terminal in relation to the cargo handling system and its impact on terminal throughput capacity.

Simulation was used in logistics activities including forklifts. For example, simulation was used in a study by Takakuwa et al. [7], where a procedure to build simulation models for move-store activities of complicated and non-automated distribution warehouses was proposed. Vonolfen et al. [8] developed an optimization model for assembly line supply by integrating warehouse picking and forklift routing using simulation. Their research was motivated by an industrial application where multiple production lines were supplied from various warehouses at the production plant. Material was stored in high rack storage areas and picked by employees utilizing forklifts. Tarczyński [9] analyzed the impact of storage parameters and the size of orders on the choice of the method for routing order picking where the forklift truck's manoeuvers such as turns back and turns aside were considered.

2.2. Characteristics of the forklift queueing system

When there are several jobs served together, the system is called *bulk* service queueing model [10]. An example is the study by Parimala & Senniappan [3] who investigated the queueing model with single server. The service starts only when *batches* of 'a' customers are present. When the queue length is 'a', but less than or equal to 'b', then the entire queue is taken up for service. If there are more than 'b' customers in the queue, then the server accepts the first 'b' customers. Sometimes the arrivals are coming in batches. In a study by Chakravarthy et al. [11], they consider a multiple server queueing model in which customers arrive according to a batch Markovian arrival process (BMAP). Moreover, Haridass & Arumuganathan [12] concentrated on a bulk arrival and bulk service queueing system with variant threshold policies for vacations.

In this paper, the service time and the inter-arrival times have been assumed to be exponentially distributed, where multiple servers have been assumed. Some studies considered the M/M (a, b)/c queueing system such as Medhi [13], Neuts & Nadarajan [14], and Sim & Templeton [15]. See more details about Kendall's notation in Kendall [16]. Medhi [13] obtained an analytical expression for the customer waiting time distribution in terms of the steady-state probability P(0, 0) that there are no idle servers and no waiting customers. Neuts & Nadarajan [14] estimated the joint distribution of customer waiting time and service group size, and also the distributions of the number of waiting customers and the number of free servers. Sim & Templeton [15] derived an exact recursive algorithm to study the steady-state probability that there are m idle servers and j waiting customers in the queue. They also derived analytical expressions for steady-state system performance measures, in terms of P(0, 0), which can be computed using a recursive algorithm. Adan et al. [17] relaxed the assumption of exponential service time. In the previously mentioned studies, each customer takes the same size from the server's capacity. In this paper, however, the batch size depends on the size of pallets (customers) where different pallets have different sizes. An analytical expression is obtained for the number of servers (forklifts) needed for guaranteeing a certain limit of late percentage. This is only part of the methodology, which depends on analytical investigation and simulation.

The arrival rate of job orders is not only stochastic but also with *time-dependent rates*. Sometimes the jobs arrival rate in the middle of the day is much higher than the rate of jobs arrival in the evening. Therefore, the needed workers capacity must vary from time to time. The study by Massey [18], who analyzed queues with time-varying rates for telecommunication models, is an example of a study employing a time-varying rate. Queueing theory as discussed in that paper was organized and presented from a communications perspective. More details and a survey about time-dependent rates can be found in a study by Schwarz et al. [19], where there are several approaches for the performance analysis of queueing systems with deterministic parameter changes over time.

In queueing theory, it is common to use the First Come First Served (FCFS) rule for sequencing the waiting job orders. However, other *service disciplines* are found in practice. Iyer & Jain [20] modeled the impact of merging capacity in production-inventory systems where there are two warehouses. They presented a priority system in which orders from the lower-variability warehouse are given non-preemptive priority. They prove conditions under which the FCFS operating rule failed to achieve a Pareto improvement over the separate systems because it increases inventory cost at the lower-variability warehouse. Moreover, Silva & Serra [21] studied locating emergency services with different priorities. In urban medical emergency services, calls that involve danger to human life deserve higher priority over calls for more routine incidents. The performance of an emergency center may be judged by the number of persons in queue or by the length of time that a person must wait. These indicators are strongly correlated with the number of centers available and with their locations. In this paper, some job orders have higher priority over others based on some priority rules such as decreasing empty driving.

For a queue to be in steady state, the possibility of service rate must be higher than the arrival rate. However, in real-life peak periods, the number of arriving job orders is sometimes higher than the capacity of forklifts. Therefore, a queueing system with *blocking* is used for investigating this case. This means that the waiting line must not be longer than a certain limit. An example of blocking in queueing theory is the study by Roy et al. [22], in which an autonomous vehicle-based storage and retrieval system (AVS/RS) was investigated. In that study, protocols were developed to address vehicle blocking, and a semi-open queueing network model was proposed to analyze system performance and evaluate design trade-offs. Another example is the study by Koizumi et al. [23]. In their study, “blocking” denotes situations where patients are turned away from accommodations to which they are referred, and are thus forced to remain in their present facilities until space becomes available. Both mathematical and simulation results were presented and compared.

Numerous studies used very simple assumptions to simplify the system, hence it can be very difficult to represent the real situation on the ground. The majority of queueing theory studies assumes very simple situations that cannot be suitable for the forklift-planning problem. The mathematical derivation in this paper has special characteristics due to grouping pallets with different sizes. Little was published about employing queueing theory to study forklifts systems, especially when it comes to using IT infrastructure to send job orders, not using traditional kanbans, but electronic signals. Moreover, the system is not a normal *pull* system with electronic kanbans, but there is the possibility to use priority rules for sequencing job orders according to different criteria. This study combines queueing theory mathematical equations with simulation using R Software with very wide possibilities of combinations of parameters and options to be a tool for optimizing the forklifts systems in terms of capacity planning and job sequencing rules.

3. Problem statement

Usually, forklift system planning in terms of capacity planning and sequencing rules of job orders is performed manually. Especially small and medium-sized companies do so, even if there is an IT infrastructure immediately providing data about job orders. However, an optimized forklifts system may decrease work force costs, waiting times, line-side inventory costs, and congestions problems. The forklifts system contains the following complications, hence it is very difficult to be analyzed without simulation:

- Different demand rates from time to time
- Different used labor capacities during the day
- Working pauses
- Batching (bulking)
- Different sizes of load units
- Different possibilities of batching according to the area in which jobs are waiting
- Blocking in some peak periods
- Different priority rules used

Using simulation, however, can be time consuming and expensive for small and medium-sized companies. Sometimes, companies have no license for expensive simulation software, yet they will need to use simulation in every shift to estimate the needed capacities. Besides the fact that R Software is free, another advantage lies in its capabilities to calculate the results about capacity upper and lower limits from the mathematical equations and then using the results as input in simulation.

A simple way is to upload the Excel file containing the needed data prepared in a certain way using the internet browser. The model exists in the cloud and companies get their results immediately without seeing the code. One of the tool’s most important advantages is that it was developed to be very flexible for different layouts and parameters.

By using this tool, the following objectives can be achieved:

- Minimize total needed capacity (workforce and maximum number of forklifts)
- Minimize empty driving (lower transportation costs)
- Better utilization (driving with the highest possible forklift capacity by grouping small pallets into one route)
- Enhancing other performance measures such as delay delivery, average waiting time per order, average number of orders waiting in the queue, etc.

4. Methodology

The methodology can be divided into three major steps:

1. First theoretical estimation of the upper and lower limits of the possibly needed number of drivers by using analytical mathematical equations.
2. Simulation

3. Final estimation of the needed capacity of forklift drivers using simulation and trying all the values of capacity between upper and lower limits found in the first step, and taking into consideration the different options selected by the user such as the assumed priority rules.

To handle the problem of different drivers' capacity during the day, the following two points are considered:

- Working time was divided by small time periods (hours). Each hour has the same arrival rate of job orders and the same workforce capacity.
- The system performance during the day will almost be the same. If arrival rate is increased, workforce capacity is also increased to keep almost the same performance. Small deviations in performance are ignored. In this case, the effect of time-dependent rates can be alleviated. In some peak periods, however, the needed demand can be higher than the forklifts available. In this case, more workforce capacity must be used directly after peak periods.

The two boundaries of the needed capacity (number of drivers and forklifts) found by equations are as follows:

- The upper limit assumes no batching, the same size of loading unit, and no breaks.
- The lower limit assumes full possibilities of batching, all waiting batches to be in the same area, loading time to be independent from batch size, and pallets that can be grouped together to have the highest priority to be loaded first. That means the FCFS rule is not applied.

4.1. Case study and study assumptions

This study was motivated by a case study where a company based in Germany uses forklifts to move materials among 12 departments distributed on four floors. Lifts are used to move forklifts among different departments. Each department has its own inventory locations. However, the tool developed in this study is flexible to handle several different layouts without the need for any adjustments. The company uses six forklifts. Demand is different from one hour to another and from one day to another. Therefore, a flexible capacity plan is necessary. Some drivers perform only driving and loading activities. Others are working on other activities besides using forklifts. Job orders are sent to a central system, which is connected to monitors fixed on forklifts displaying the needed jobs and their origins and destinations. Three different sizes of pallets are available: small, medium, and large. A forklift can load a maximum of 4 small pallets, 2 medium pallets, or only one large pallet. It is also possible, for instance, to load one medium pallet and two small pallets together. Each driver usually clicks on the monitor to choose the next job he wants to work on. His choice is based on his experience for the best route. Whenever he finishes a job order, he clicks on the monitor to save the time point of ending the job. Sometimes individual job orders are overlooked for a very long time. The task was to estimate the needed capacity during the day so that job lead time is not longer than 2 hours. Five percent of job orders exceeded this time limit. Another objective was to check the effect of using different strategies for prioritizing the different job orders and the effect on performance measures. Besides this forklifts system, there is another system using small trucks for small bins. For example, a truck can load up to 25 small bins at the same time. This second system was not considered in this study.

The main assumptions in the tool are:

- Forklift drivers are informed about the currently needed job orders.
- All forklifts have the same capacity.
- Workers can do driving, or can also perform other tasks such as order picking.
- One forklift can load one or several loading units if there is enough capacity and if all the pallets are on the same route.
- If the planned working time of a driver finishes while he is still working on an order, he finishes the order before he leaves.
- The forklift can stay at a central station if there are no new orders, or just wait at the last destination.

4.2. Upper and lower limits of workforce needs

Assuming that forklifts can carry only one pallet with exponentially distributed time of loading, unloading, driving, and empty driving, and assuming that the inter-arrival time of job orders is also exponentially distributed, then we have the queueing system M/M/C. In this case, the probability that waiting time in queue (T_q) for more than a certain time t can be found using the following equation (cf. Shortle et al., [4]):

$$Pr\{T_q > t\} = \frac{r^c P0}{c!\,(1-\rho)} e^{-(c\mu-\lambda)t}$$

(1)

Where,

- λ is the number of job orders within a time unit (e.g. an hour)
- μ is the number of job orders that can be fulfilled by one forklift within the time unit
- c is the number of available forklifts/ drivers
- $r = \lambda/\ \mu$
- $\rho = \lambda/\ \mu c$
- P0 is the probability that there are 0 customers (job orders) in the system and can be found by:

$$P0 = 1/\left[\sum_{m=0}^{c-1} \frac{(c\rho)^m}{m!} + \frac{(c\rho)^c}{c!\,(1-\rho)}\right]$$

(2)

If the objective is that the waiting time of an order is not to exceed 2 hours minus average service time (e.g. 5 minutes) with a probability of 95%, then t is set to be 1.92 and $\Pr\{T_q>t\}$ is set to be 0.05. Then c, which represents the number of needed forklifts drivers, is simply found by trying all the possible values for c in equation (1). The lowest c value that yields 0.05 or less for the left hand side is used. The result is then rounded up. Note that variability in service time, which is usually small, has been assumed to be ignored if the objective is to concentrate on lead time. To try all the possible values of c, upper and lower limits are needed. The value $\lceil r \rceil$, which equals $\lceil \lambda/\mu \rceil$, can be used to find the lower limit where $\lceil x \rceil$ is the upper bound of x. This simple initial solution ignores several characteristics that can increase or decrease the needed capacity. For example, the following points decrease the needed capacity:

- Batching of job orders
- Production pause

On the other hand, the following points can increase the needed capacity:

- Forklifts drivers pause
- Forklifts breakdown
- Maximum limitation on the numbers of available forklifts at the same time. The effect of this point is for the period after the peak period, where it is sometimes necessary to increase the workforce capacity after the peak period in order to compensate for not using the optimal theoretical value of c because of a limitation on the number of used forklifts in the peak period.
- The line-side inventory limit. Some areas have small space for inventory so they might have a higher priority than the other areas. That might increase the needed capacity.
- Rules other than FCFS

It is important to consider forklift drivers' pauses in the calculations of upper and lower limits. For example, suppose that all drivers are leaving for a 30-minute break at 11:30 o'clock, then if the theoretical needed capacity is three drivers, the actual number should be six because drivers are not working half the time during this hour. Moreover, if it is expected that the needed capacity is even larger than the calculated upper limit – due to limitation on line-side space – then a higher level of capacity can also be tried by simulation. This option was activated by the tool.

One of the main features of the forklift system is batching more than one pallet on the forklift. Sometimes these pallets come in different sizes. In this paper, the pallet size is measured based on its percentage to the whole capacity of forklifts. For example, a certain pallet can take 50% of the whole loading capacity of a forklift. Sometimes, a pallet is not big, however, it is unstackable. In this case, only one pallet is loaded, and therefore the size of this pallet is considered to be 100%. A complicating feature is that there are different sizes of different pallets in the same facility. A parameter that is very important in the analysis of the system is the average pallet size, which can be found using equation (3):

$$Average\ pallet\ size = \sum_{i=1}^{X} s_i f_i \leq 1$$

(3)

Where,

- X: number of different sizes of pallets
- s_i: size of pallet i (as percentage of loading capacity of forklifts)
- f_i: percentage of demand on pallet i. It can be found by dividing the daily demand on i pallets by the daily demand on all pallets.

Batching should reduce the needed capacity. Assuming for simplicity that the time needed for a batch exactly corresponds to the time needed for only one pallet, the system has the same service time µ, however, with a different arrival rate, which is λ' indicating the arrival of batches. Service time here means driving and loading/unloading times. In λ', any arrival of jobs will be ignored until a complete batch is available or when a server (forklift) is available to start a new job. This system is similar to the lift system in which serving one or a group of people will take almost the same amount of time. The lift starts moving when there is only one person or a group of people without exceeding the capacity of the lift. Later a range for λ' is estimated.

Because pallets come in different sizes, forklifts sometimes drive without full capacity. For example, a forklift can leave with two pallets of which one is 50% and the other one 25% of the capacity of forklift. Therefore, the total loaded material corresponds to 75% of the capacity of forklift. It is important to consider the average percentage of loading material without full capacity (P_l) (underutilization percentage). For simplicity, assume that the average size of unutilized capacity is $0.5P_l$. If, for example, all drives of forklifts are with some unused capacity then, on average 50% of forklifts capacity will not be utilized. If, however, sizes of pallets are for example 50%, 75%, and 100%, then it is possible to consider the 75% size as the 100% size, because it is impossible to combine the 75% pallet with the 50% pallet.

Assuming for simplicity that batching will not affect the service time and assuming that whenever there is any number of jobs in the queue that do not exceed the capacity of forklift they will be batched together, then in order to find the number of batches in the queue it is possible to write

$$L_{q\_batch} = 0.5P_l + L_q{}' \sum_{i=1}^{X} s_i f_i$$

(4)

Where L_{q_batch} is the number of batches in the queue, L_q' is the number of jobs in the queue, and P_l is the probability of driving without utilizing the full loading capacity of forklifts. This equation shows the relationship between the number of job orders (pallets) in the queue and the number of batches in the queue. If the driver finds pallets that need part of forklift capacity then he will take the currently available pallets. Therefore, the system behaves as if there was an upper bounding effect for the number of batches. The value $0.5P_l$ was added to compensate for this upper bounding. For example, if the waiting orders in the queue amount to 3 pallets and they form 1.5 of the capacity of the forklift (average pallet size is 50% of forklift loading capacity), it is assumed that there are 2 batches. Moreover, if the number of batches in the queue is always greater than one batch, then $P_l = 0$, which means that forklift loading capacity is fully utilized.

Number of arriving batches within a unit of time (λ')

The same previous method for finding the average number of waiting batches in the queue can be applied for λ':

$$\lambda' = 0.5P_l + \lambda \sum_{i=1}^{X} s_i f_i$$

(5)

For example, if λ = 2 and average pallet size = 30%, and if the number of batches in the queue is always greater than 1, then λ' = 0.6. This means that the forklift will not only take the two pallets, but will also add the rest of loading capacity from the waiting pallets in the queue.

Because $0<P_l<1$, then

$$\lambda \sum_{i=1}^{X} s_i f_i < \lambda' < 0.5 + \lambda \sum_{i=1}^{X} s_i f_i$$

(6)

Since we want to find the lower limit of the number of drivers, the lower limit of λ' is considered. Equation (1) can be rewritten to find the needed *c* value (number of forklifts drivers):

$$Pr\{T_q > t\} = \frac{(\lambda'/\mu)^c P0'}{c!\,(1-(\lambda'/\mu c))} e^{-(c\mu-\lambda')t}$$

(7)

where

$$P0' = \left(\frac{(\lambda'/\mu)^c}{c!\,(1-(\lambda'/\mu c))} + \sum_{n=0}^{c-1}\frac{(\lambda'/\mu)^n}{n!}\right)^{-1}$$

(8)

The effect of omitting $0.5P_l$ is not great. Using simulation on data in which λ' is from 1 to 60 and μ is from 1 to 30 it was found that the biggest difference that can arise is only an increase of one server. Furthermore, it was found that an increase of 0.5 on λ' can make a difference of less than 6% of possible values of λ' if, for example, μ = 8. The higher the value of μ, the lower this percentage. It is unlikely for the needed capacity to equal the result in equation (7) because of the following reasons:

- Loading a batch will take more time than loading only one pallet.
- In the case of several areas with waiting pallets, it is almost impossible to perform batching every time because the waiting pallets are going to different places and are following different routes. The higher the number of inventory areas and the more complex the layout, the higher the chance of not utilizing batching at its maximum possibility.

Thus, equation (1) and equation (7) provide initial estimations for the upper and lower limits of the number of needed workers. Simulation can be used to find the results for all scenarios between these two limits. For example, assume that service time is exponentially distributed with an average of 12 minutes, and inter-arrival time is exponentially distributed with an average of 5 minutes, then 4 drivers are needed in the case of no batching at all,. Moreover, assuming that batching is possible where all the waiting job orders are in the same area and time for loading a batch is exactly as for loading a pallet, then two drivers are needed. In this case, simulation is required to try scenarios in which the *c* value is 2, 3, and 4.

4.3. Priority rules for different orders (jobs)

A driver starts to serve a certain job order based on the following rules: (Rules are sorted starting from the highest priority to the lowest one)

1. A job order waiting for longer than a threshold time value.
2. Job orders coming from departments with small areas for line-side inventory.
3. Bulking: If there are several waiting pallets and they can be grouped, they have the priority where:
    1. there is the possibility of loading bigger loading units at first.
    2. the time needed for loading and delivering the whole group is affected by *bulking effect*. For example, if it amounts to 10 %, then grouping two pallets will make the average service time to equal the average time multiplied by 110%.
4. Reducing empty driving time: whenever possible, the forklift should start with the closest place to the previous forklift destination.
5. FCFS

The decision-maker can deactivate any of rules 1 to 4 in the tool.

Line-side inventory

Factors affecting the response time for a job order, i.e. available man hour capacity, available forklifts, forklift loading capacity, empty transportation time, other job orders, and traffic jam of forklifts may increase line-side inventory.

The workplace priority index is used. It can be dynamic and may change from one hour to another. Therefore, it is possible to write:

$$PI_{ph} = \frac{d_h O_{ph} \sum_{i=1}^{X} s_i f_i}{LSIC_p}$$

(9)

Where:

- PI_{ph}: priority index for workplace p in hour h
- dh: average hourly demand in hour h. In other words, the average arrival rate of job orders in hour h.
- O_{ph}: percentage of job orders for workplace p in hour h
- $LSIC_p$: capacity of line-side space for workplace p measured in units of capacity of forklifts. For example, if the maximum area capacity is two pallets of a certain size and forklift can load these two pallets together, and it cannot take more than them, then $LSIC_p$ =1.

In the case of the percentage of demand for different workplaces being stable over the day, O_p is used instead of O_{ph}. In this case, the priority index for each workplace will be the same over the day. The term "$d_h\ O_{ph}$" represents the workplace's hourly demand in terms of pallets. If it is available, d_{ph} can be used instead. The nominator represents the hourly demand or arrival rates for the workplace p in hour h in units of forklifts. If the index equals one, then, on average, the line-side area will be filled with pallets within one hour if there are not any forklifts to take these pallets during that hour. Whenever the priority index for a certain workplace is more than for example 0.5, any order coming from that workplace must have a higher priority.

4.4. Simulation with R

Apart from simulation purposes, R is also used to perform the theoretical calculations about the initial limits of capacity needs. It is easy to find these limits for the c value using R, where all the possible values are tried until the appropriate value is found. Therefore, R was used to perform the whole tool. Performing simulation with R renders the model independent from the facility layout as in traditional simulation software. That saves a considerable amount of time of simulation development. The data must be entered into an Excel file in a predefined way and uploaded via a specific link on the internet, and then the user can obtain the results.

The package "queueing" can be used to get exact results for some types of queues. Moreover, the package "queuecomputer" may be used to perform simulation of some basic types of queues. There is the possibility to set variable server capacity to be used by the package. Because forklift systems have so many unique characteristics that make it impossible to directly use such a package to simulate the system, a new code has been written to be suitable for such a system. Some parts of the package code may also be used. The starting capacity of servers (drivers) can be set employing the two limits found in mathematical equations. Because the arrival rate of job orders is different over the day, the model must take into consideration changeable workforce capacity over the day. For the waiting job orders, the priority rules in section 4.3 are considered, and performance measures are calculated. All the parameters and data can be set by the user him/herself. The user can for example employ the tool for simulation instead of optimization. In this case, he/she must determine a capacity plan. Any one of the priority rules can be activated or deactivated. Moreover, bigger pallets can be loaded at first in the case of batching.

It is important to know that for any system to be in steady state, ρ that equals $\lambda/\mu c$ must be less than one. Therefore, if λ/μ = integer, then c must be at least $\lambda/\mu+1$. In this case, the performance of the system is usually good and most of the jobs wait for a short time only. Figure 1 shows the probability that waiting in the queue takes longer than a certain time t if $\lambda = \mu$ and if $c = 2$. Figure 2 shows the case when λ/μ is an integer which can be greater than 1, and waiting in queue is 2 hours. The two figures show the fact that when λ/μ is an integer and c is set in a way to turn the system into steady state, then waiting time in the queue is not very long. For example if $\lambda=\mu=1$ and $2<=c<=$any value greater than 2, and if t = 2 hours, then there will be no way that $\Pr\{T_q>t\}$ is >0.05. Therefore, $c=\lambda/\mu+1$ can immediately be chosen.

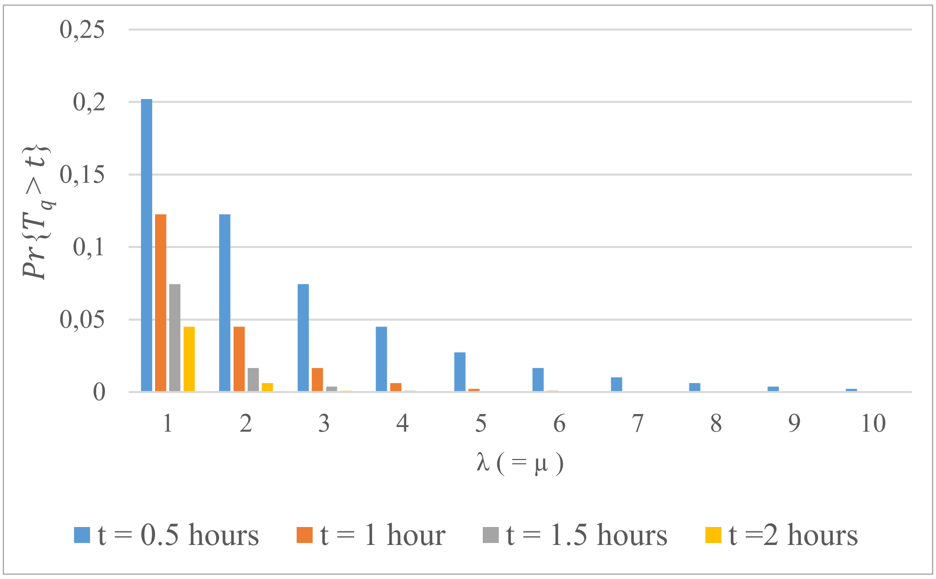


Figure 1: Probability that waiting in the queue is more than *t* hours when c=2

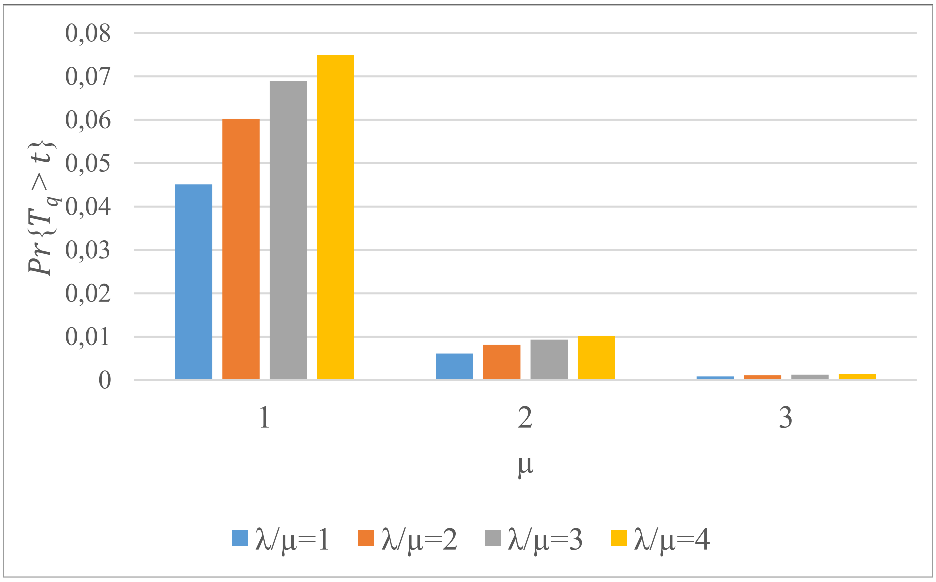


Figure 2: Probability that waiting in the queue is more than *t*=2 hours when c= λ/μ+1

Because the size of capacity is different during the day, a possible solution to go through the range between the two limits found by mathematical equations is to start from the highest one and then reduce the capacity for example 5% in each iteration until getting the lowest possible one. Because capacity must be integers, upper bounding of the needed capacity must be done. Because of this upper bounding, the system performance will not be the same over the day. There must be some differences from time to time.

For the case study, data about driving time and the percentage of different loading packages was drawn from historical data of more than one year. The arriving rates, however, are different from one day to another. Service time was sometimes found to be exponentially distributed, and sometimes it follows different types of distributions. The theoretical equations were found based on the assumption of exponential distribution. However, the simulation itself for values within the range found by theoretical equations provides the decision-maker with the possibility to define the appropriate distribution such as exponential, uniform, normal, etc. for each different driving time. For example, in some places where there is a lot of traffic, the variability in driving time can be high. However, the variability in other places where there is not much traffic can be low. For instance, driving time can be exponentially distributed from workstation 1 to workstation 2, and normally distributed from workstation 2 to workstation 3. There is transportation with forklifts within the same workstation, especially when it is relatively large. For example, figure 3 shows the histogram for the full load driving time within workstation 5. KolmogorovSmirnov test was also done and the p-value was found to be 0.112 when testing the exponential distribution hypothesis. That means that the available historical data about this driving time show that it follows exponential distribution.

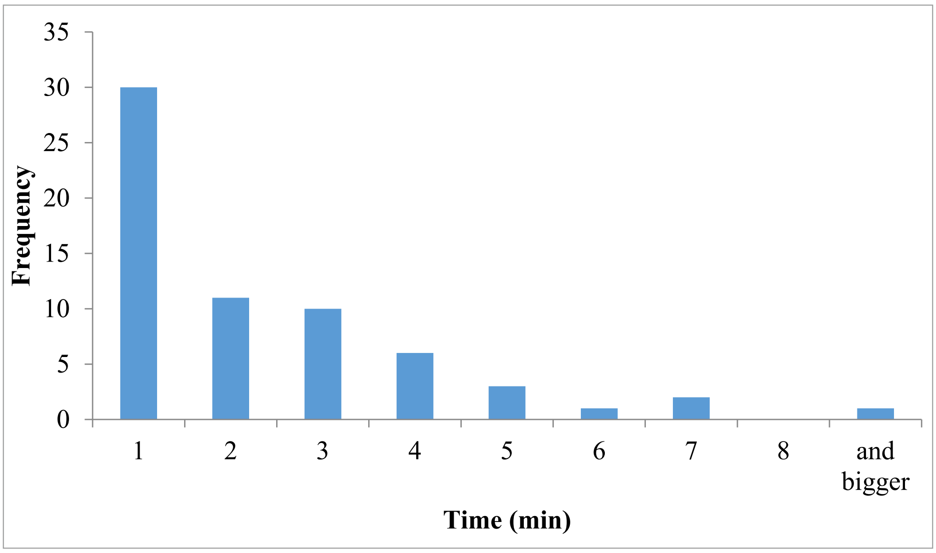


Figure 3: Histogram for full load driving within workstation 5

5. Results and analysis

In this section, input data are presented and then the results and their analysis are shown. The pallets data was as in table 1. Table 2 displays arrival rates of job orders. For the 12 workplaces, demand percentages were variable and can be 0, 5%, 10%, 20%, 30%, 40%, and 50% from the total hourly demand. A matrix of driving times from each workspace to another based on their origins and destinations was used. Another matrix was used for empty driving time. The empty driving time showed a slightly lower average. Driving time here also includes the loading and unloading time of pallets.

Pallet types	Percentage of demand	Size (compared to forklift loading capacity)
Small	36.4%	25 %
Medium	57.3%	50 %
Large	6.3%	100 %

Table 1: Pallets types in case study

Time	**from**	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
	to	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Inter-arrival time (min)		4.3	2.7	4	2.7	2.7	2	1.6	1	1.3	5	12	15	15	15	15	15	15

Table 2: Job arrival rate

The following scenarios were tried out by the tool:

Scenario 1: All priority rules are activated.
Scenario 2: Only batching was deactivated.
Scenario 3: Only reducing empty driving was deactivated.
Scenario 4: Five places have capacity for line-side inventory of 4 forklifts capacities.

Batching effect on time was set to be 10%. The number of iterations was set to be 20 and no break was considered. Maximum allowable lead time was set to be 60 min. Only 5% of job orders were allowed to be late (take more than 60 minutes). No limitation was selected on the maximum number of used forklifts in any hour. Moreover, work ends in the middle of the night.

For the case study containing 12 workstations, the calculation time using R Software took about 1 minute on a normal personal computer. Results about order fulfillment time (lead time) are shown in figure 4. Working hours mean the starting of an hour. For example, the working hour 6:00 means the time period 6:00-7:00 h. The average values of order fulfillment time can be found in table 3. The average values are almost the same for scenario 1 and scenario 2. As expected, the performance of the system is not stable over the day, even if the number of drivers is variable to alleviate the changes in demand. This is due to the aforementioned upper bounding effect for the capacity determined.

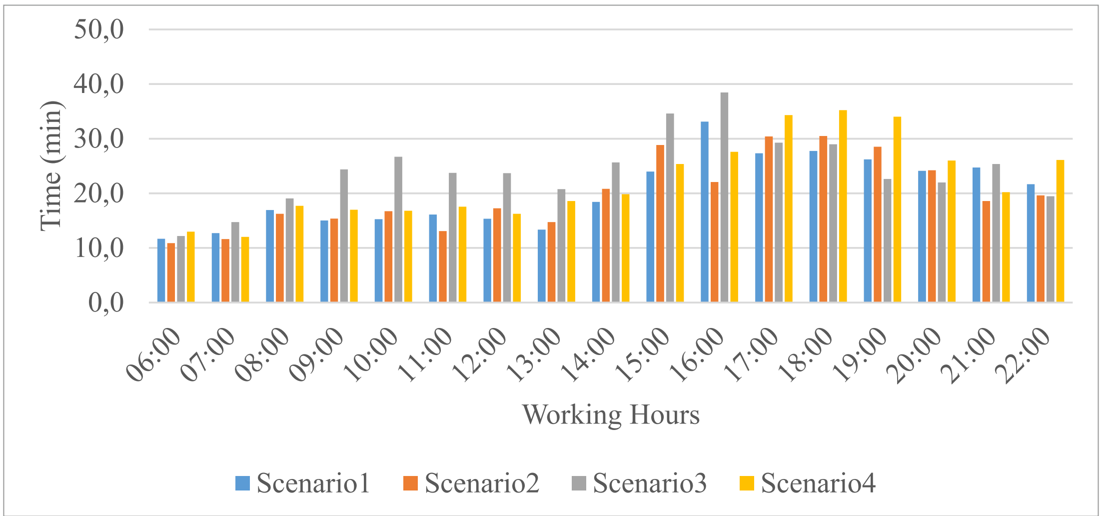
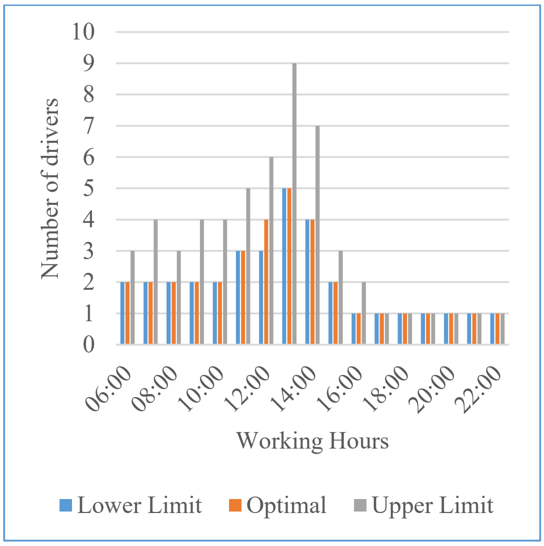


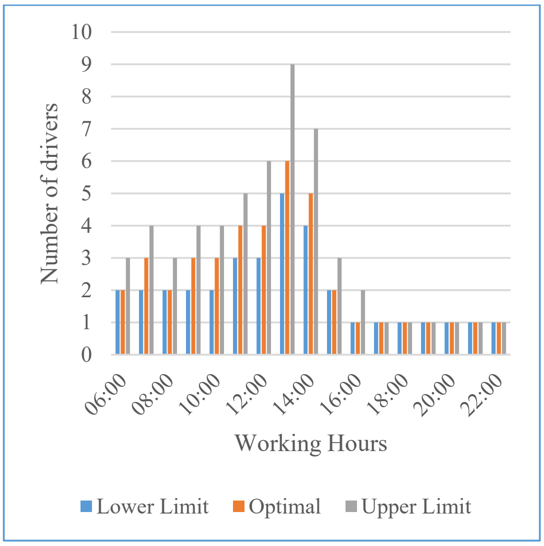
Figure 4: Average hourly order fulfillment time over the day for different scenarios

a. Scenario 1

b. Scenario 2



c. Scenario 3



d. Scenario 4

Figure 5: Optimal number of forklift drivers versus theoretical upper and lower limits

Figure 5 shows capacity variable levels. The optimal level of capacity is the lowest level of capacity that does not cause a lead time to be longer than the maximum allowed one with a probability of 95%. That means only 5% of orders can take an order fulfilment time which is longer than the maximum allowed one. It is clear that in all the different scenarios, the capacity level is within the expected theoretical range. The level of capacity in scenario 2 was the highest. An interesting point in table 3 is that the number of needed forklift drivers was found to be the lowest in scenario 3. To explain that, table 4 shows a comparison between the optimal iteration in scenario 1 and a previous iteration in which the man hour is 41 for scenario 3. One new performance measure was added, which is the standard deviation of waiting time. It is higher for scenario 1, when the option for reducing empty driving was activated. This is due to the simulation model trying to find the closest workstation for the forklift on the expense of the job orders waiting for longer times, but being for farther workstations. Therefore, the late orders percentage is higher in scenario 1. Thus, the decision-maker may want to deactivate this option to get the lowest man hour and that may reduce the maximum needed forklifts. This is especially useful when there are maintenance tasks for forklifts.

Performance Measures	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Percentage of late orders (%)	1.92	2.97	2.97	3.14
Average order fulfillment time (min)	17.32	17.07	23.04	19.14
Mean waiting time in queue (min)	13.12	13.03	18.68	14.99
Man hour	41	44	35	41
Utilization (%)	83.65	86.9	86.86	84.59
Total empty driving time (min)	951.17	1051.45	873.8	988.63
Average number of orders in the queue	4	3.99	5.71	4.54
Maximum number of forklifts	6	7	5	6

Table 3: performance measures for different scenarios

Performance Measures	Scenario 1 Optimal Iteration	Scenario 3 Previous Iteration
Percentage of late orders (%)	1.92	0.33
Average order fulfillment time (min)	17.32	16.96
Mean waiting time in queue (min)	13.12	12.75
Standard deviation of waiting time (min)	12.28	9.66
Man hour	41	41
Utilization (%)	83.65	83.64
Total empty driving time (min)	951.17	1054.35
Average number of orders in the queue	4	3.85
Maximum number of forklifts	6	6

Table 4: Performance measures comparison for scenario 1 and scenario 3 for the same man hour value

Conclusion

In this paper, a forklift material handling system was analyzed to find the optimal capacity levels over the day and the best priority rule for sequencing the job orders. The analysis depends on performance measures such as man hour, waiting time, lead time, and percentage of delayed orders. Queueing theory and simulation were used to find the best parameters of the system. Even though the study considered a case study for obtaining results, its methodology can be applied to other environments in which forklifts are used. It has been assumed in this study that workers work on driving, or might also do driving from time to time as well as other tasks such as order picking. Another limitation lies in the theoretical mathematical equations where service times and inter-arrival times are assumed to be exponentially distributed. However, the tool provides the decision-maker with the possibility to choose other types of distributions in simulation, such as normal, uniform, and triangular distributions. Results showed that batching orders has a significant effect on enhancing performance measures. Results also showed that trying to decrease the needed empty driving times might not be the optimal decision because it increases the variability in waiting times. It is therefore recommended for future research to find other priority rules that consider waiting times. That is possible when the IT infrastructure allows that by informing drivers about the optimal sequence of job orders via monitors attached to forklifts.

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Mobiles Eye-Tracking in den angewandten Wissenschaften

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ABSTRACT

Mobiles Eye-Tracking ist als Forschungsmethode beliebter denn je und gewinnt in unterschiedlichen Feldern der angewandten Wissenschaften mehr und mehr an Bedeutung. Dieser Beitrag diskutiert, wie die Aufzeichnung und Analyse von Blickbewegungen in der Mobilität, im Usability Engineering, den Sportwissenschaften, der Augmented Reality/Mixed Reality/Virtual Reality und der Medizin bzw. medizinischen Weiterbildung eingesetzt wird. Der Beitrag gliedert sich dabei in drei Teile: in einem ersten Teil werden Grundzüge des Eye-Trackings erläutert; in einem zweiten Teil wird der Einsatz mobilen Eye-Trackings in ausgewählten Feldern der angewandten Wissenschaften veranschaulicht; und in einem abschließenden dritten Teil werden Potentiale und Risiken sowie zukünftige Forschungslinien skizziert, um die Anwendung mobilen Eye-Trackings als digitale Forschungsmethode weiter zu etablieren.

Mobile eye tracking is gaining more and more in popularity as a method of research and is becoming ever more significant in various areas of applied research. The present article discusses how eye movement recordings and analyses are applied in mobility research, usability engineering, sports sciences, Augmented Reality/Mixed Reality/Virtual Reality, medicine and healthcare professional education. It consists of three parts: in the first part, the fundamentals of eye tracking are outlined; in the second part, the application of mobile eye tracking in selected areas of applied research is exemplified; and the third and final part discusses the potentials, risks and future research lines to further establish mobile eye tracking as a digital research method.

KEYWORDS

Eye-Tracking, Mobilität, Usability Engineering, Sportwissenschaften, Augmented Reality/Mixed Reality/Virtual Reality, Medizin, Weiterbildung

Eye tracking, mobility, usability engineering, sports sciences, augmented reality, mixed reality, virtual reality, medicine, further education

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1. Das Messen von Augenbewegungen

Eye-Tracking als Forschungsmethode ist beliebter denn je und gewinnt mehr und mehr an Bedeutung – in so unterschiedlichen Disziplinen wie Mobilität, Verkehr und Luftfahrt, *Usability Engineering*, *Augmented* und *Virtual Reality*, Sport- und Trainingswissenschaften, Medizin und Pflege, sowie der Pädagogik und (pädagogischen) Psychologie. All diese angewandten Wissenschaften haben ein berechtigtes Interesse an den Möglichkeiten und Potentialen, die Eye-Tracking bietet. Einer der Gründe für die stark zunehmende Aufmerksamkeit, die Eye-Tracking als Forschungsmethode genießt, ist die technologische Weiterentwicklung auf dem Gebiet der Blickbewegungsmessungen: Die Geräte und die technische Ausstattung, die für Eye-Tracking notwendig sind, werden günstiger. Gleichzeitig zum sinkenden Anschaffungspreis steigt die Benutzerfreundlichkeit der Geräte, so dass Prozesse der Datenerhebung und -auswertung schneller erlernbar sind. Auch deshalb wächst das Interesse an Eye-Tracking-basierten Forschungsarbeiten.

Abbildung 1 zeigt, wie die Zahl wissenschaftlicher Publikationen zu Eye-Tracking gewachsen ist. Die Daten stammen aus einer Suche vom 01. September 2018 in „Scopus“, der größten und umfassendsten interdisziplinären Datenbank für Fachartikel, Bücher und Konferenz-Proceedings. Gesucht wurde nach Beiträgen, die den Suchbegriff „Eye Tracking“ in Titel, Abstract oder Keywords enthielten. Die Zahlen in Abbildung 1 verdeutlichen einen exponentiellen Anstieg an Publikationen startend mit der ersten Publikation im Jahr 1962 hin zu 1765 Publikationen allein im Jahr 2017.

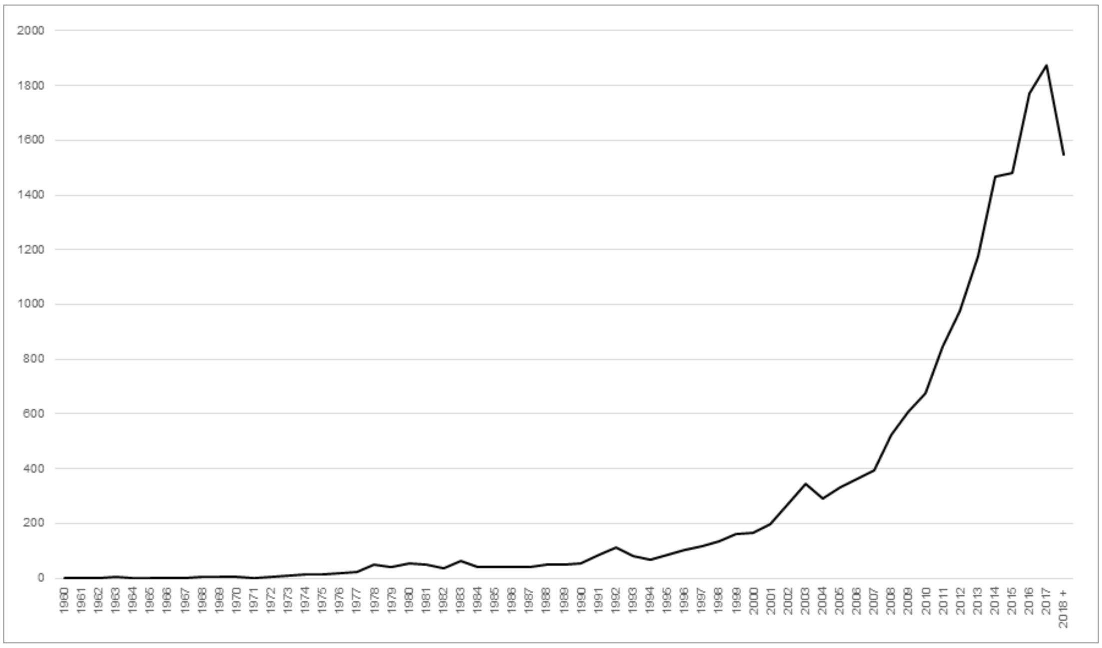

Abbildung 1. Zahl der Publikationen nach Jahr zu „Eye-Tracking“ in der Datenbank Scopus.

Warum ist Eye-Tracking als Methode so beliebt? Holmqvist und Andersson [1, S. 3] schreiben hierzu: “There is no doubt that it is useful to record eye movements, it advances science and leads to technological innovations” (Übersetzung: Es gibt keinen Zweifel daran, dass es nützlich ist, Augenbewegungen aufzuzeichnen, es bringt die Wissenschaft voran und führt zu technischen Innovationen). Und Duchowsky [2, S. 3] hält fest: “Why is eye tracking important? Simply put, we move our eye to bring a particular portion of the visible field of view into high resolution so that we may see in fine detail whatever is at the central direction of gaze” (Übersetzung: Warum ist Eye-Tracking so bedeutsam? Einfach ausgedrückt bewegen wir unsere Augen, um einen bestimmten Teil des visuellen Feldes hochauflösend zu betrachten, damit wir detailliert sehen können, was immer wir direkt in den Blick nehmen). Durch Eye-Tracking gelingt es, den Blick von Personen und deren Aufmerksamkeitsallokation auf bestimmte Objekte oder Interessensbereiche aufzuzeichnen und für Forschung zugänglich zu machen. Aus diesem Grund installieren immer mehr Hochschulen, Universitäten und die

Industrie angewandte Eye-Tracking-Labore und gründen Forschergruppen für die Analyse von Augenbewegungen.

Dieser Beitrag widmet sich verschiedenen Anwendungen und Beispielen der Eye-Tracking-Forschung. Das Ziel ist dabei, einen Überblick über die Möglichkeiten von Eye-Tracking als Forschungsansatz zu geben. Gleichzeitig soll dabei aber auch der Blick auf die Risiken und Beschränkungen der Blickbewegungsanalyse gerichtet werden; dazu wird in der Diskussion an späterer Stelle dieses Beitrags auch auf das Problemfeld *Privacy* und Datensicherheit eingegangen. Ein besonderes Augenmerk liegt in diesem Beitrag in der Betrachtung des mobilen Eye-Trackings in Form von Brillen, die im Gegensatz zu festinstallierten Geräten im Labor ganz neue Räume für angewandte Eye-Tracking-Forschung im Feld eröffnen.

Der Beitrag gliedert sich in drei Teile: in einem ersten Teil werden Grundzüge des Eye-Trackings erläutert; in einem zweiten Teil wird der Einsatz von Eye-Tracking in ausgewählten Feldern der angewandten Wissenschaften diskutiert; in einem abschließenden dritten Teil werden Potentiale und Risiken, sowie zukünftige Forschungslinien skizziert.

1.1. Mobiles Eye-Tracking

Seit den Anfängen des Eye-Trackings [3] entwickelten sich verschiedene Verfahren zur Aufzeichnung von Blickbewegungen. Im Wesentlichen haben sich zwei Verfahren etabliert. Zum einen die Elektrookulographie (EOG), bei der Elektroden in verschiedener Konstellation um das Auge angebracht werden [4], um Unterschiede im elektrischen Potential zwischen dem corneo-retinalen Potential des Augapfels und der Haut aufzunehmen. Über digitale Signalanalyse kann anhand von Frequenzen, Signalstärke und Magnitude auf die Auslenkung der Augäpfel und damit auf Blickwinkel geschlossen werden [2]. Zum anderen die Cornea-Reflex-Methode, die auch als kamera-basierte oder video-basierte Methode bezeichnet wird. Hier wird mittels Infrarotdioden eine Reflexion auf der Hornhaut erzeugt. Kameras zeichnen sowohl die Augen und deren Infrarotreflexion als auch den Sichtbereich des Benutzers[1] auf. Bildverarbeitende Software extrahiert dann die Pupillen und setzt deren Bewegungen in das Verhältnis zum Gesehenen. Als Ergebnis liegen hauptsächlich Koordinaten zur Zeitachse vor, sowie darüber hinaus meist auch Informationen zur Pupillenweitung, Blinzelfrequenz und Vergenz.

Einen neuen Ansatz des mobilen Eye-Trackings verfolgen Dietrich et al. [5]. Sie nutzen okulare Artefakte im Elektroenzephalogramm (EEG) zur Detektion der Augenpositionen. Diese Methode basiert wie das EOG auf dem cornea-retinalen Potential der Augäpfel, allerdings lässt sich ihre Lösung technisch flexibler in *Head-Mounted Devices* (*HMD*s) integrieren, da sich die notwendigen Messpunkte nicht auf die Region um das Auge beschränken. Darüber hinaus eröffnen sich neue Möglichkeiten der Interpretation von Augenbewegungen im Zusammenhang mit aktiven Gehirnarealen.

Augenbewegungen lassen sich mittels mobiler und externer Aufnahmegeräte registrieren [1]. Zu den externen Systemen zählen *Remote*-Geräte, die häufig an Laptops und Desktop-Computern integriert sind und nach erfolgreicher Kalibrierung die Blickbewegungen berührungsfrei via Infrarot messen, sowie Geräte der experimentellen Grundlagenforschung, in denen der Kopf von Versuchsteilnehmenden fixiert wird, um präzisere Aufnahmen der Augenbewegungen mit hoher externer Validität zu generieren [2]. Externe Systeme finden sich häufig in Szenarien der Laborforschung unter Bedingungen strenger experimenteller Kontrolle.

Mobile Aufnahmegeräte sind häufig in ein Brillengestell integriert, das nur wenige Gramm wiegt und wie eine normale Brille getragen werden kann. Diese mobilen Systeme werden auch als *head-mounted* oder *wearable* Eye-Tracker bezeichnet. In der Regel wird bei mobilen Geräten mit der Cornea-Reflex-Methode via Infrarot eine Reflexion auf der Hornhaut erzeugt. Kameras zeichnen simultan die erzeugte Infrarotreflexion und das Blickfeld der Teilnehmenden auf.

Mobile Eye-Tracker eignen sich besonders für die angewandten Wissenschaften, weil sie nicht auf Laborräume beschränkt sind, sondern Menschen in angewandten Lebenssituationen begleiten können – etwa im Auto [6], im Cockpit eines Flugzeugs [7], beim Sporttraining [8], bei komplexen sozialen Konstellationen in der Notaufnahme [9] oder im Klassenzimmer

[1] Aus Gründen der besseren Lesbarkeit wird im weiteren Verlauf des Textes alleinig das generische Maskulinum verwendet. Im Verständnis werden hierbei jedoch stets alle Geschlechter impliziert.

[10]. Als Methode der Blickbewegungsmessung limitieren sie die Bewegungsfreiheit nur wenig. Dadurch haben entsprechende Versuche im Vergleich zu Laborstudien mit externen Systemen oft eine höhere ökologische und externe Validität.

Eine weitere Möglichkeit, mobile Eye-Tracking-Aufnahmen zu nutzen, sind die sogenannten *Eye Movement Modeling Examples* [11, 12]. Dabei werden Blickbewegungen von erfahrenen Personen (zum Beispiel Profis, unfallfreien Autofahrern, Lehrpersonen o.ä.) auf Video aufgezeichnet und diese Videoaufzeichnung dann unerfahrenen Personen (zum Beispiel Anfängern, Fahrschülern, Studierenden) zur Vorlage gezeigt. Durch das Betrachten der Blickbewegungen von erfahrenen Personen lernen unerfahrene Personen beispielsweise, welche Informationen im Blickfeld potentiell relevant sind und welche perzeptuell ignoriert werden können [11–14].

1.2. Analyse von Blickbewegungen

Die Rohdaten aus der Erhebung von Blickbewegungsmessungen werden typischerweise nach bestimmten Parametern in Fixationen und Sakkaden ausgegeben. Gleichzeitig existiert eine hohe Zahl unterschiedlicher Parameter, die aus den Rohdaten von Blickbewegungsmessungen errechnet werden können, etwa auch Mikrosakkaden und *Smooth Pursuits* (wenn die Augen der Bewegung eines Objekts folgen). Eine umfassende Darstellung unterschiedlichster Parameter ist bei Holmqvist und Andersson [1] nachzulesen. Fixationen sind definiert als Zustand „when the eye remains still over a period of time“ [1, S. 21]. Häufig wird dabei theoretisch angenommen, dass mit einer Fixation – zum Beispiel auf einen Gegenstand oder eine Person – auch Aufmerksamkeit einhergeht, das heißt, wir schauen auf etwas, weil es unsere Aufmerksamkeit erregt hat. Diese Annahme wird auch die *Eye-Mind Hypothesis* genannt [15]. Fixationen lassen sich nach ihrer Häufigkeit und ihrer Dauer charakterisieren.

Neben Fixationen sind Sakkaden gängige Parameter in der Analyse von Eye-Tracking-Daten. Eine Sakkade ist definiert als „rapid motion of the eye from one fixation to another“ [1, S. 23]. Sakkaden sind also Sprünge zwischen zwei Fixationen. Sakkaden können nach ihrer Länge und ihrer Geschwindigkeit beschrieben werden. Wenn wir annehmen, dass Sakkaden die Verschiebung von Aufmerksamkeit auf neue Informationen im Blickfeld implizieren [15], kann die Sakkadenlänge – dabei insbesondere die langer Sakkaden – Aufschluss über das periphere Sehen bzw. die parafoveale Verarbeitung von Informationen am Rande des Blickfelds geben [2, 16].

Die Region im Blickfeld, auf die wir schauen (z. B. eine Person oder ein Gegenstand), wird als *Area of Interest* bezeichnet. Eine *Area of Interest (AOI)* kann – abhängig von der Wahl der Aggregationsebene – ein einzelner Gegenstand (z. B. ein Drehzahlmesser im Auto), der Teil eines Gegenstands (z. B. der Bereich hoher Drehzahlen) oder eine Gruppe an Gegenständen (z. B. das gesamte Cockpit im Auto) sein. Analog dazu kann eine *AOI* eine Person (z. B. eine Patientin), ein Teil einer Person (z. B. eine Wunde) oder eine Gruppe von Personen (z. B. alle am Boden liegenden Personen am Unfallort) sein. Auf diese Weise werden Rückschlüsse über die Zuweisung von Aufmerksamkeitsressourcen auf bestimmte, im Sichtfeld befindliche Informationen gezogen [1, 15–17]. *AOI*-Sakkaden werden als Transitionen bezeichnet.

Als grafische Visualisierungen von Fixationen sind in der angewandten Forschung häufig Blickpfade (eng. *scanpaths*) und *Heatmaps* im Einsatz. *Scanpaths* zeigen das Blickfeld der Teilnehmenden inklusive deren Fixationen, symbolisch dargestellt durch Kreise. Kreise mit kleinem Radius signalisieren kurze Fixationsdauern; Kreise mit großem Radius signalisieren lange Fixationsdauern. In *Scanpaths* lässt sich auch die Reihenfolge von Fixationen darstellen, woraus ein Rückschluss über den Ablauf der Aufmerksamkeitsverteilung gezogen werden kann. Abbildung 2 zeigt ein Beispiel eines *Scanpaths*.

Abbildung 2. Beispiel eines Scanpaths. Darstellung von Tschneidr (2017); Quelle: https://de.wikipedia.org/wiki/Eye-Tracking#/media/File:Gaze_plot_eye_tracking_on_Wikipedia_with_3_participants.png

Heatmaps färben das Blickfeld der Teilnehmenden zur Auswertung der Blickhäufigkeiten ein. Nach gängiger Konvention wurden rote Bereiche häufiger fixiert (und waren dadurch heißer) als kältere Bereiche in blauer Färbung, die weniger häufig fixiert worden sind. *Heatmaps* lassen auch eine grafische Aggregation der Daten mehrerer Probanden zu, um etwa das Blickverhalten einer Personengruppe zu untersuchen. Die Interpretation der farblichen Unterschiede im Blickfeld lassen einen Schluss zu über die Verteilung von Aufmerksamkeit auf verschiedene *AOI*s, um etwa die Frage zu beantworten: Was wurde häufiger angeschaut und was weniger häufig. Abbildung 3 zeigt ein Beispiel einer *Heatmap*. An dieser Stelle soll darauf hingewiesen werden, dass neben *Scanpaths* und *Heatmaps* noch weitere Visualisierungen existieren (siehe dazu [18]).

Abbildung 3. Beispiel einer Heatmap. Darstellung von Tschneidr (2017); Quelle: https://commons.wikimedia.org/wiki/File:Eye-Tracking_heat_map_Wikipedia.jpg

2. Beispiele aus den angewandten Wissenschaften

Im folgenden Abschnitt werden einige ausgewählte Felder der angewandten Wissenschaften vorgestellt, in denen Eye-Tracking eingesetzt wird. Diese Auswahl ist selektiv und eklektisch; sie erhebt auch aufgrund der enormen Heterogenität in der Gesamtheit aller Anwendungsfelder, in denen mobile Eye-Tracker zum Einsatz kommen, keinen Anspruch auf Vollständigkeit. Die in dieser Übersichtsarbeit vorgestellten und berücksichtigten Disziplinen reflektieren die Schwerpunktthemen Mobilität, Digitalisierung und Gesundheit. Mit Blick auf das in Abbildung 1 dargestellte starke Wachstum der Eye-Tracking-Forschung gerade in den letzten Jahren ist es wahrscheinlich, dass Anwendungen von Blickbewegungsanalysen in zahlreichen weiteren Disziplinen etabliert werden. Die nachfolgend präsentierten Anwendungsbeispiele sind aufgrund ihrer Vielfalt gut in der Lage, die Breite möglicher Einsatzgebiete von mobiler Eye-Tracking-basierter Forschung abzudecken. Die Beispiele stammen aus den Bereichen Mobilität, Usability Engineering, Sportwissenschaften, *Augmented Reality/Mixed Reality/Virtual Reality* und Medizin bzw. medizinische Weiterbildung.

2.1. Mobilität

Mobile Eye-Tracker werden mehr und mehr in der Mobilitätsforschung eingesetzt [19]. Bei Studien zum Blickverhalten von Autofahrerinnen und Autofahrern wird dabei beispielsweise untersucht, wie sich Augenbewegungen bei nächtlichen von Fahrten tagsüber unterscheiden, wie sich Fixationen und Sakkaden von erfahrenen und unerfahrenen Autofahrern unterscheiden und wie die Sicherheit beim autonomen Fahren von Eye-Tracking profitieren kann.

Lebensbedrohliche Unfälle sind bei Nacht häufiger als bei Tag [20], auch aufgrund der geringen Helligkeit bei Nacht. Lichtquellen beim nächtlichen Fahren stammen überwiegend von Verkehrsbeleuchtung wie Straßenlaternen. Brimley und Kollegen [21] haben gezeigt, dass Autofahrer häufig die Lichtkegel von Laternen fixieren und dort nur geringe Sakkadenlängen aufweisen. Tagsüber sind Fixationen und Sakkaden stärker gestreut und weniger auf Lichtquellen bezogen. Dadurch werden Objekte am Straßenrand, etwa Fußgänger oder Wild, schneller wahrgenommen. Nachts hingegen werden sie eher nur dann fixiert, wenn sie in geographischer Nähe zu Lichtquellen sind. Auch beim Abbiegen an Kreuzungen ändert sich das Blickverhalten bei Nacht. Während tagsüber Fixationen auf beiden Seiten des Fahrzeugs bzw. der Kreuzung auftreten, wird nachts nur die Seite fixiert, in deren Richtung abgebogen wird [22]. Diese Informationen aus Eye-Tracking-Daten können Autobauer und Straßenbauämter dazu nutzen, die nächtliche Illumination durch Straßenbeleuchtung und Scheinwerfersysteme am Auto zu optimieren, um Unfallzahlen zu senken [20–22].

Erfahrene Autofahrer haben im Laufe der Jahre durch die Fahrpraxis ein anderes Blickverhalten erlernt als unerfahrene Autofahrer [23]. In einer Meta-Analyse von elf Studien mit insgesamt 455 Autofahrern konnten Gegenfurtner et al. [11] zeigen, dass erfahrene Autofahrer kürzere Fixationsdauern haben als unerfahrene Autofahrer. Dieser Befund deutet daraufhin, dass erfahrene Autofahrer dank erworbener Gedächtnisstrukturen weniger lang brauchen, um Verkehrssituationen visuell zu verarbeiten. Erfahrene Autofahrer sind in ihrer visuellen Aufmerksamkeit darüber hinaus stärker selektiv als Fahranfänger, was ihnen beim Erkennen von Gefahrensituationen und in der generellen Wachsamkeit in komplexen Verkehrssituationen zu Gute kommt [11, 24, 25].

Eye-Tracking kann auch beim autonomen Fahren eingesetzt werden. Hier übergibt der Autofahrer die Kontrolle an das Fahrzeug und kann dadurch sekundäre Tätigkeiten ausüben oder entspannen. In manchen Situationen kann es jedoch notwendig sein, dass das autonome Fahrsystem die Kontrolle an den Autofahrer zurückgibt, um die Fahrsicherheit zu gewährleisten – etwa dann, wenn das Ende einer Straße erreicht wird oder Fahrbahnmarkierungen verloren werden [26]. In solchen Situationen kann Eye-Tracking dazu dienen, die sogenannte *Take-Over Readiness* des Autofahrers zu bestimmen – also ob der Autofahrer tatsächlich bereit und in der Lage ist, das Fahrzeug wieder eigenständig zu führen oder ob der Autofahrer unaufmerksam ist und das Fahrzeug alternativ selbst anhält. Oft sind die Situationen einer Übergabe der Fahrzeugkontrolle zeitlich dringend; in solchen Fällen kann die Augenbewegungsmessung einen Beitrag zur Sicherheit beim autonomen Fahren leisten [26].

Auch hinsichtlich der Effektivität als Leistungsdimension des Usability Engineering in der Mobilitätsforschung bietet Eye-Tracking Untersuchungspotential. Hier sind es insbesondere Leistungsaspekte, die die Display-vermittelte Interaktion mit dynamischen Systemen betreffen. Das umfasst im Bereich der Mobilität beispielsweise die Interaktion des Fahrers mit Anzeigen von Assistenzsystemen im PKW [27], des Fluglotsen mit Anzeigen der Flugüberwachung [28] oder des Piloten mit dem *Primary Flight Display* [29]. Einen umfassenden Überblick über die Einsatzmöglichkeiten von Eye-Tracking im Flugumfeld liefert Glaholt [30].

Mobilität wird auch in den Sportwissenschaften thematisiert. Erkenntnisse aus dem Motorsport werden von Automobilherstellern und ihren Zulieferern routinemäßig auf verschiedene Aspekte der Alltagsmobilität übertragen: Sicherheit bei Unfällen (z. B. Verbesserung von Aufprallschutz und Helmen), Sicherheit im Straßenverkehr sowie Verletzungsprävention und -rehabilitation in Motorsport und urbaner Mobilität [31–33]. Generell werden alle möglichen modifizierten oder neuen Materialien im Motorsport unter Extrembedingungen getestet und bei entsprechender Eignung auf die Anforderungen der Alltagsmobilität angepasst und eingesetzt [31, 32, 34].

Während der Fahrt mit einem Automobil müssen vom Fahrer viele Sinneseindrücke verarbeitet und die gewonnenen Informationen in entsprechende motorische Aktionen umgesetzt werden. Darrelmann et al. [35] untersuchten Blickbewegungsmuster von Profirennfahrern und Fahranfängern mittels eines auf dem Helm des Fahrers montierten mobilen Eye-Tracking-Systems. Dabei fanden sie heraus, dass die Profirennfahrer im Vergleich zu den unerfahrenen Fahrern längere Fixationszeiten aufwiesen und in Kurven schneller, präziser, und häufiger die relevanten Punkte fixierten. Allerdings konnte bei den unerfahrenen Fahrern ein Lerneffekt dahingehend gefunden werden, dass sie ihren *Scanpath* (Aufeinanderfolgen von Fixationen und Sakkaden) mit zunehmender Rundenzahl dem der erfahrenen Fahrer mehr und mehr anglichen [35].

Van Leeuwen et al. [36] untersuchten ebenfalls Profirennfahrer und verglichen diese mit Fahrern ohne Rennerfahrung. Ihre Probanden sollten Runden einer Rennstrecke auf einem Fahrsimulator so schnell wie möglich absolvieren, während ihre Augenbewegungen verfolgt wurden. Während die Fahrer ohne Rennerfahrung ihre Blickbewegungsmuster am Scheitelpunkt der Kurven orientierten, fixierten die Profirennfahrer Referenzpunkte hinter den Scheitelpunkten, wobei Entfernung und Richtung dieser Referenzpunkte zum Scheitelpunkt je nach Kurve variierten. Zudem wiesen die Profirennfahrer mehr und markantere Kopfbewegungen auf.

2.2. Usability Engineering

Usability Engineering liefert einen sowohl konzeptuellen als auch operativen Rahmen, um Aspekte der Leistung sowie der Zufriedenstellung bei der Interaktion mit technologischen Produkten zu untersuchen. Um die Rolle des Eye-Tracking in diesem Zusammenhang zu diskutieren, stellt die Definition von *Usability* aus der Normenreihe DIN ISO 9241 einen geeigneten Ausgangspunkt dar. Demnach ist *Usability* das „(…) Ausmaß, in dem ein Produkt durch bestimmte Benutzer in einem bestimmten Nutzungskontext genutzt werden kann, um bestimmte Ziele effektiv, effizient und zufriedenstellend zu erreichen" (DIN ISO 9241-11 [37, S. 4]). Eine Evaluation der *Usability*-Dimensionen setzt damit voraus, dass die Perspektive der Benutzer eingenommen und der situative Kontext berücksichtigt wird. Beide Anforderungen können potentiell gut durch mobile Eye-Tracker erfüllt werden. Da diese Systeme örtlich nicht gebunden sind, kann die Datenaufnahme in realistischen Settings erfolgen. Das Problem mangelnder Generalisierbarkeit von Untersuchungsergebnissen durch zu rigide Versuchsbedingungen im Labor kann damit umgangen werden. Den Blickwinkel der Benutzer nehmen mobile Eye-Tracker quasi definitionsgemäß ein.

Es ist aber insbesondere die Operationalisierung der *Usability*-Kriterien, bei der Methoden der Blickuntersuchung Mehrwert liefern. Effizienzmaße im Allgemeinen betreffen den Aufwand an Ressourcen, insbesondere die „psychische oder physische Beanspruchung, Zeit, Material oder monetäre Kosten" (DIN ISO 9241-11 [37], S. 7). So wird üblicherweise die Effizienz bei der Interaktion mit Produkten über die erforderliche Zeit zur Bearbeitung definierter Szenarien erhoben (DIN ISO 9241-11 [37]). Für die Untersuchung der Interaktion speziell in dynamischen Umgebungen werden häufig mehrere Aufgaben gleichzeitig durchgeführt; es ist also hier die Ressource *Aufmerksamkeit*, die im Fokus einer Effizienzbetrachtung liegt. Im motorisierten Individualverkehr beispielsweise konkurrieren Primär- (Fahraufgabe), Sekundär- (z. B. Bedienung eines Navigationssystems) und Tertiäraufgaben (z. B. Bedienung eines Infotainmentsystems) um die Aufmerksamkeit der Fahrer. Hier verspricht Eye-Tracking einen geeigneten methodischen Zugang, Aufmerksamkeitszuwendungen zu quantifizieren. Beispielsweise können relevante Blickbereiche für die unterschiedlichen Sekundärsysteme definiert werden. Selbst wenn ein Leistungsmaß der Primäraufgabe, beispielsweise die Güte der Spurhaltung, eine Differenzierung der Sekundärsysteme nicht zulässt, liefert die durchschnittliche Blickzuwendung bzw. Verweildauer auf den *AOI*s ein indirektes Effizienzmaß. Je höher die visuelle Verweildauer bei den Sekundärsystemen, desto weniger effizient erfolgt die Interaktion mit diesen.

Mit zunehmender Auflösungsfähigkeit und Aufzeichnungsfrequenz mobiler Eye-Tracker kann ein weiteres Maß der Interaktionseffizienz erhoben werden. Steigen die Ansprüche an die Informationsverarbeitung der Operateure (z. B. Pilot, Fahrer, Manager) und damit deren kognitive Belastung in herausfordernden Situationen, steigt damit zumeist auch die subjektiv empfundene Beanspruchung (vgl. das Belastungs-Beanspruchungs-Konzept von Bornemann [38], das Eingang in deutsches und internationales Normenwerk gefunden hat; DIN EN ISO 10075-1 [39]). Diese erhöhte *Workload* hat verschiedene körperliche und physiologische Folgen, die auch über Blickbewegungsmessung registriert werden können. Das sind zum einen diverse Maße in Zusammenhang mit Sakkaden (z B. Dauer, Geschwindigkeit) bzw. Fixationen (z. B. Dauer, Häufigkeit), zum anderen aber auch Maße der Pupillometrie. So liefert die Pupillendilatation, also der Grad der Pupillenweitung, Informationen zum aktuellen Beanspruchungsniveau [40]. Diesen Zusammenhang zwischen Anstrengung und Pupillendurchmesser konnte Daniel Kahneman schon 1973 feststellen und hinsichtlich seiner Relevanz für das Aufmerksamkeitsmanagement diskutieren [41, 42]. Es existieren diverse Auswertealgorithmen, die die Messungen des Pupillendurchmessers von lichtabhängigen und emotionalen Einflüssen bereinigen und damit einen leicht interpretierbaren Indikator für die kognitive *Workload* anbieten ([9] vgl. für eine grundlegende Untersuchung zum Thema Schwalm [43]). Gleichzeitig findet Pupillometrie derzeit noch überwiegend in standardisierten Umgebungen im Labor statt, um einen Nullwert bzw. einen Ausgangswert als Baseline zur Messung möglicher Veränderungen zu generieren.

Ein wichtiger Bestandteil einer entsprechenden Leistungsbeobachtung vergleichbarer Tätigkeiten umfasst das Ausmaß, in dem Operateure in der Lage sind, die Situation nachhaltig *wahrzunehmen*, zu *verstehen* und ihre unmittelbare Entwicklung *vorwegzunehmen*. Zusammengefasst werden diese drei Leistungsaspekte einer Interaktion unter dem Begriff „Situationsbewusstsein“ (vgl. Endsley [44, 45]). Für alle drei Ebenen des Situationsbewusstseins – Wahrnehmung, Verständnis, Antizipation – kann Eye-Tracking wertvolle Informationen und Leistungsindikatoren liefern. So *können* Operateure wichtige Elemente einer Situation nicht verstehen, wenn sie sie nicht wahrgenommen haben; das betrifft beispielsweise auch das weite Feld der Gestaltung von Warnmeldungen [46, 47]. Bestimmte Blickmuster können anzeigen, ob Operateure eine Situation verstanden und interpretiert haben. Ändert sich das Blickmuster trotz objektiv veränderter Bedeutung für die Situation nicht, kann auf Verständnisdefizite geschlossen werden.

Für eine Leistungseinschätzung ist es häufig nicht ganz einfach, Kriterien der Effektivität und der Effizienz gegeneinander abzuwägen. Wenn Operateure im Schnitt nur kurz auf eine relevante *AOI* blicken, ist diese kurze Zuwendungszeit Zeichen für effiziente Informationsaufnahme oder für mangelnde Registrierung einer wichtigen Informationsquelle? Vor einer Untersuchung müssen daher konkrete Kriterien definiert werden, die zudem auf einer soliden theoretischen Basis stehen sollten, um damit die Interpretation von Ergebnissen erst zu ermöglichen oder zu erleichtern.

2.3. Sportwissenschaften

In den Sportwissenschaften sind vor allem zwei verschiedene Systeme für das Eye-Tracking verbreitet (vgl. hierzu die Ausführungen in Abschnitt 1.1), mit unterschiedlichen Stärken und Schwächen: Stationäre Systeme haben den Vorteil, dass sie meist mit einer höheren Auflösung messen können. Teilweise kann zudem der Kopf des Probanden fixiert werden, so dass eine isolierte, exakte Bestimmung der Augenbewegungen erfolgen kann [48]. Allerdings ist die externe Validität der Forschungsergebnisse, die mit Hilfe von stationären Eye-Trackern gewonnen wurden, im Sport wohl kaum gegeben [48]. Mobile Eye-Tracking Systeme haben den offensichtlichen Vorteil, dass sie – zumindest theoretisch – *in situ* messen können. Es offenbaren sich allerdings gerade im Sport die Besonderheiten und Limitationen wissenschaftlicher Datenerhebung: Die häufig deutlich komplexeren, meist kaum standardisierbaren Umweltinteraktionen stellen gerade am Körper getragene Messsysteme vor große Herausforderungen [48–50]. Bezogen auf das Eye-Tracking gilt dies in vielerlei Hinsicht: *Usability* (Limitationen durch Einschränkung des Sichtfeldes; erhöhte Verletzungsgefahr gerade bei Kontakt mit Gegner und/oder Sportgerät etc.); erschwerte Messung auf Grund dynamischer, veränderlicher Bedingungen (freie Bewegung im Raum; Verrutschen der Eye-Tracker bei schnellen, ruckartigen Kopfbewegungen etc.); interne vs. externe Validität (je standardisierter die Datenerhebung, desto vorsichtiger müssen die Daten im Hinblick auf die Sportpraxis interpretiert werden; je freier die Datenerhebung im Feld, desto schwieriger gestaltet sie sich hinsichtlich ihrer Qualität) [48, 49, 51, 52]. Obgleich im Zuge des allgemeinen technischen Fortschritts der Anwendungsbereich des Eye-Tracking stark erweitert werden konnte, werden wahrscheinlich vorerst nicht alle methodischen Limitationen des mobilen Einsatzes dieser Technologie gelöst werden können [48, 49]. Kredel et al. [48] beziehen sich hierbei vor allem auf die Problematik, dass bei allen derzeit verfügbaren mobilen Eye Trackern eine oder mehrere Kameras und Spiegel unmittelbar vor dem Auge des Probanden angebracht werden müssen (meist integriert in eine Brille), um die Bewegungen der Pupillen verfolgen zu können. Die Lösung könnte darin liegen, winzige Kameras und/ oder Bewegungstracker auf einer Kontaktlinse anzubringen, die zudem den Fokus der Augen übernehmen können. Auch wenn dies mit den derzeit verfügbaren technischen Mitteln nicht möglich ist, wäre es durchaus vorstellbar, dass in der Zukunft eine derartige Lösung entwickelt wird.

Eye-Tracking wird in der Sportwissenschaft bisher vor allem in der Erforschung des Erlernens und Meisterns von Bewegungen und in der Expertiseforschung eingesetzt [53]. Bisher stehen vor allem Zielsportarten (Golf, Bogenschießen etc.) und Zielwurf-, -schuss-, und -schlagbewegungen aus den Spielsportarten (Aufschlag im Volleyball, Elfmeter im Fußball, Korbwurf im Basketball etc.) im Kern des Forschungsinteresses [50, 54–59]. Aber auch in der Erforschung des Entscheidungsverhaltens von Schiedsrichtern und der sporttaktischen Expertise wird Eye-Tracking eingesetzt [60–62]. Überdies findet es sogar in Randsportarten wie Tischtennis, Klettern, Sprungreiten, und Fechten vereinzelt Anwendung [52, 63–65].

Auf Grund der Herausforderungen der Datenerhebung fokussieren sich die meisten Studien dabei auf einfache, relativ leicht kontrollierbare sportartspezifische Bewegungen (*closed skills*) [49]. Entscheidend für die Expertise *in* und den Erfolg *von* Zielbewegungen im Sport scheint die Dauer und Qualität der letzten Fixierung der Augen auf den optimalen Zielpunkt zu sein (*Quiet Eye*) [53, 58, 59], wobei über fast alle Sportarten hinweg die Experten oder höherklassigen Athleten längere Sakkaden und kürzere Fixationszeiten aufzeigen und häufiger relevante Gegenden im Blickfeld fixieren [16, 56, 58]. Die Entdeckerin des *Quiet Eye*, Joan N. Vickers, sieht in dieser perzeptiv-neurokognitiven Fähigkeit gar die Wurzel des *Flow* im Sport [58]. Letzteres Phänomen beschreibt den häufig beobachteten, jedoch bisher von der Wissenschaft nicht eindeutig erklärbaren Zustand eines Athleten, dem für eine begrenzte zeitliche Dauer innerhalb der Ausübung seiner Sportart unabhängig von Zeit-, Gegner-, und Umweltdruck alles zu gelingen scheint [58].

Ein weiteres zukünftiges Anwendungsfeld des Eye-Trackings könnte in der Diagnostik von Sport-induzierten Gehirnerschütterungen liegen. Allerdings ist die derzeitige Forschungslage hierzu noch zu dünn [66].

Trotz methodischer Herausforderungen öffnen mobile Eye-Tracker der Sportwissenschaft interessante neue Forschungsfelder. Inwiefern die Forschungsergebnisse unter Einsatz mobiler Eye-Tracker im Training zur Verbesserung sportartspezifischer Technik und Taktik umgesetzt werden können, muss sich erst noch zeigen – es erscheint aber durchaus nicht unrealistisch [52, 58, 67].

Mit Hilfe von Eye-Trackern konnte darüber hinaus gezeigt werden, dass Profirennfahrer aus dem Motorsport während der Fahrt andere Blickbewegungsmuster als Nicht-Rennfahrer und unerfahrene Fahrer aufweisen. Diese Erkenntnisse könnten jedoch in den unterschiedlichen Zielen von motorsportlicher und urbaner Mobilität liegen [36].

Mobile Eye-Tracker sind in der angewandten Sportwissenschaft hinsichtlich der externen Validität von Studien den stationären Systemen deutlich überlegen [48, 49, 52]. In zukünftigen Forschungsvorhaben sollten daher vermehrt mobile Eye-Tracking-Systeme zum Einsatz kommen, auch wenn die derzeit verfügbaren Systeme mit methodischen Herausforderungen verbunden sind und (noch) nicht in allen sportartspezifischen Situationen angewendet werden können.

2.4. Augmented Reality, Mixed Reality und Virtual Reality

Augmented Reality (AR), *Mixed Reality (MR)* und *Virtual Reality (VR)* haben in den letzten Jahren einen enormen technischen Fortschritt erlebt. Sie bilden die vierte Welle disruptiver Digitaltechnik und haben einen zunehmenden Einfluss auf unser tägliches Leben. Sie verbessern die Arbeitsleistung in Industrie und Medizin. Außerdem profitieren Bildung, Gaming und Entertainment von diesen Innovationen. *Smart Glasses* (z. B. Google Glass, Epson Moverio BT), *Mixed-Reality-Devices* (z. B. Microsoft Hololens) und *Virtual-Reality*-Brillen (z. B. Oculus Rift, HTC Vive) sind kopfgetragene Geräte (*Head-Mounted-Devices*) und erlauben dem Träger eine räumliche Mobilität, solange das notwendige *Computing-Device* verbunden oder integriert ist.

Eye-Tracking in Verbindung mit *HMD*s bietet neue Möglichkeiten der Untersuchung: Einerseits lassen sich Situationen im freien Feld erforschen, bei dem der Benutzer nicht an räumliche Gegebenheiten gebunden ist. Andererseits erhält man Erkenntnisse über Aufmerksamkeit und Reaktion des *Users* in erweiterten oder immersiven Realitäten. Darüber hinaus lassen sich Informationen über Augenstellungen und ihre Bewegungen für technische Optimierungen von *HMD*s und deren Applikationen, sowie innovativer Interaktionskonzepte nutzen.

Man hat schon früh begonnen, Eye-Tracking-Anwendungen aus dem 2D-Bereich [68] in den 3D-Bereich zu überführen [69]. Ein besonderer Aspekt von Eye-Tracking in *HMD* liegt in der Möglichkeit, durch binokulares Eye-Tracking und Beobachtung der Vergenz die Entfernung zum Betrachter zu bestimmen. Das erfordert zumeist eine vorhergehende Kalibrierung des Systems, d. h. die Position der Augen in Relation zum Sichtfeld (in der Regel das Display).

In technischer Hinsicht lässt sich der Fokus des menschlichen Betrachters dazu nutzen, Rechenleistung und somit die Energie in mobilen *HMD*s zu reduzieren bei gleichbleibender wahrgenommener *Performance* und Bildqualität. Beim *Foveated Rendering* [70] respektive *Foveated Ray Tracing* [71, 72] wird lediglich der Bildausschnitt gerendert, den der Mensch in seinem Fokus scharf sieht. Der Bildschirminhalt außerhalb des Fokus wird nur teilweise gerendert oder mit einem *Blur*-Effekt versehen [73]. Hillaire et al. gehen noch einen Schritt weiter und verwenden den Fokus zur dynamischen Optimierung der individuellen Kamerafahrten einer virtuellen Szene.

Pfeiffer et al. [74] wenden die Kenntnisse des Eye-Trackings aus dem zweidimensionalen auf den virtuellen dreidimensionalen Bereich an, um Inhalte und Objekte effizienter zu platzieren. Basierend auf Blickinformationen des Auges und der Bestimmung des Bildsegmentes nach Aufmerksamkeit und Interesse können dann Objektinformationen sowie Trigger zur Interaktion und Objektmanipulation eingeblendet und berücksichtigt werden [75]. Aufgrund des eingeschränkten Sichtfeldes der Geräte verwenden Renner und Pfeiffer [76] den peripheren Sehbereich des Nutzers zur Führung von Aufmerksamkeit und Orientierung. Zank und Kunz [77] zeigen darüber hinaus eine Technik, bei der man anhand von Augenbewegungen die (virtuelle) Laufrichtung des Betrachters vorhersagt, um damit die räumlichen Einschränkungen der Realität gegenüber der virtuellen Welt zu umgehen.

Zur aktiven Interaktion und Manipulation von 3D-Inhalten müssen auch neue Interaktionskonzepte erforscht werden, da herkömmliche Eingabegeräte wie Tastaturen, Controller und Touchscreens nicht zweckmäßig sind und andere Formen wie Sprach- und Gestensteuerung ablenkend oder störend wirken. Eye-Tracking bietet eine Aussicht zur natürlichen, non-intrusiven Art der Interaktion. Chun et al. [78] nutzen z. B. die Blickrichtung zur Auswahl von Objekten, die der Benutzer dann mittels *Brain-Computing-Interfaces* manipulieren kann. Sidorakis et al. [79] zeigen gleich sechs Anwendungsmöglichkeiten des binokularen Eye-Trackings zur Steuerung von Multimedia-Inhalten im virtuellen Raum. Darunter das Verfassen von Emails, das Abspielen von Audio- und Bilddateien, sowie das Interagieren in Games.

Die Erkennung von Augenbewegungen in Verbindung mit Position zur Anzeigefläche kann auch zur automatisierten Interaktion verwendet werden, wie zum Scrollen von Inhalten [80] oder zur Navigation in Kartenmaterial [81]. Das Detektieren bestimmter Bewegungsmuster, wie z. B. Lesen, in Verbindung mit der Aufmerksamkeitsspanne des Benutzers, kann zur Anzeige von Übersetzungen oder Weiterleitung zu anderen Dokumenten und Textpassagen eingesetzt werden [82].

Derzeit werden fast ausschließlich kamera-basierte Lösungen verbaut (z. B. VR-Brille FOVE) oder als Erweiterung von Drittanbietern angeboten (z. B. *Pupil Labs*). Die Kameras können jedoch nur unterhalb oder seitlich der Augen platziert werden, was die Integration in *HMD*s erschwert. Die Elektrookulographie (EOG) bietet in ihrer Messgenauigkeit eine Alternative, ist aber aufgrund der Platzierung der Elektroden (vergleiche López et al. [4]) um das Auge für *HMD*s in der kommerziellen Anwendung unpraktisch.

Auch ohne Kalibrierung der Eye-Tracking-Systeme können die Informationen von Augen und ihren Bewegungen in *HMD*s verwendet werden. Gleichmäßige Augenbewegungen (*smooth pursuits*) etwa, sind nützlich zum Einstellen einer kontinuierlichen Variable, wie beispielsweise der Lautstärke einer Audioquelle oder der Intensität eines Lichts [83]. Extreme Augenauslenkungen (45° horizontal, 30° vertikal) hingegen eignen sich zum schalten binärer Zustände (z. B. Menü ein- und ausblenden), wobei die zentrierte Augenstellung als neutraler Zustand gilt. Dietrich et al. [5] zeigen, dass sich diese extremen Augenstellungen schon durch vier EEG-Elektroden mit hinreichend guter Wahrscheinlichkeit detektieren lassen.

In kommerziellen Anwendungen bietet der EEG-basierte Ansatz [5] zudem den Vorteil, weder Kameras noch Elektroden an exakten EOG-Positionen platzieren zu müssen. Mit VR-Brillen von LooxidLabs oder Neurable, die bereits EEG-Elektroden integrieren, könnte man dann technisch gesehen auf Eye-Tracking-Kameras verzichten. Unabhängig davon ergeben sich aus der Kombination von Eye-Tracking und EEG weitere neue Untersuchungsfelder. Interessant sind u. a. die Reaktionszeit vom empfangenen Lichtreiz bis zur kognitiven Wahrnehmung, aktive Gehirnareale bei der Verarbeitung des Gesehenen oder etwa das Auftreten von Emotionen in Abhängigkeit von visuellen Stimuli.

Künftige Anwendungsgebiete des Eye-Trackings in *HMD*s, bei denen EEG-Signale wesentlichen Aufschluss geben können, sind z. B. Mensch-Mensch-Kommunikation, nahtlose Interaktion sowie medizinische Diagnostik und Therapie. Roberts et al. [84] und Steptoe et al. [85] zeigen in virtuellen Umgebungen, dass der natürliche Blickkontakt ebenso wichtig für zwischenmenschliche Kommunikation ist, wie Augengesten unerlässlich für eine Übermittlung und Interpretation von Anweisungen sind. Markante Muster von Augenbewegungen, wie etwa bestimmte Formen von Sakkaden, lassen Rückschlüsse auf die gerade ausgeführte Tätigkeit zu, wie z. B. das Suchen oder Lesen von Inhalten. Die psychische Belastung hingegen ergibt sich aus der Pupillenweitung, die in Abhängigkeit von Inhalt und Stimulus unterschiedlich zu interpretieren ist [86].

Kombinationen aus einzelnen Eye-Tracking-Informationen werden mittlerweile auch zu medizinischen Zwecken genutzt. Lahiri et al. [87, 88] analysieren Bereiche der Aufmerksamkeit (*AOI*s) zusammen mit Blinzelfrequenz, Fokus, Pupillendurchmesser und Fixationen für die Entwicklung eines dynamischen und individuellen Feedbacksystems für soziale Interaktion in virtuellen Räumen für Kinder mit Autismus. VR und Eye-Tracking kann künftig auch bei der Bewertung und Diagnose von neurodegenerativen Erkrankungen und Prüfung ihrer Verwendung in einem klinischen Umfeld unterstützend beitragen [89].

Die Verfolgung der Augenbewegung lässt sich auch in der Optimierung des Anzeigekomforts in VR- und AR-Anwendungen einsetzen. Derzeitige Implementierungen verwenden meist eine Projektionsfläche (Display) pro Auge in einem festen Abstand und erzeugen den binokularen Tiefeneffekt durch relativen Versatz korrespondierender Bildpunkte auf beiden Displays. Hierbei entsteht der sogenannte Akkommodations-Vergenz-Konflikt [90, 91], da die Scharfstellung auf die Position des Displays erfolgen muss, während die Vergenz der Augen sich nach den korrespondierenden Punktpositionen der visualisierten Objekte ausrichtet. Bei der Betrachtung realer Objekte tritt diese Diskrepanz nicht auf. Der Betrachter reagiert auf starke vorübergehende Diskrepanzen mit kurzfristigem Unwohlsein (*Visual Discomfort*), längere Betrachtung auch bei geringen Diskrepanzen führen zu dauerhaften Ermüdungserscheinungen (*Visual Fatigue*; [92]).

Eye-Tracking ermöglicht die Detektion unangenehmer Bildinhalte, zum Beispiel durch kontinuierliche Korrelation der Disparität der dargestellten Sequenzen mit der Blickrichtung des Betrachters. Darüber hinaus konnte gezeigt werden, dass sich über die Frequenz des Blinzelns auf die wahrgenommene Bewegung und das empfundene akute Unwohlsein in einer Videosequenz schließen lässt [93]. Ein weiterer Ansatzpunkt liegt in der dynamischen Anpassung des Bildinhalts. Durch selektives Hinzufügen von Unschärfe in Tiefenregionen nicht-fokussierter Objekte lässt sich der Akkommodations-Vergenz-Konflikt verringern und der Tiefeneffekt verstärken [94]. Falls Blickrichtung und Vergenz des Betrachters, beispielsweise durch EEG-basiertes Eye-Tracking, zur Verfügung stehen, können Bildbereiche, die weiter entfernt oder näher am Betrachter liegen, unscharf dargestellt werden. Zusätzlich kann die Disparität des betrachteten Objekts in Richtung des Disparitäts-Nullpunkts verschoben werden, um den Akkommodations-Vergenz-Konflikt zu minimieren.

2.5. Medizin und medizinische Weiterbildung

Eye-Tracking hat in der Medizin eine lange Geschichte, nicht nur zur Bestimmung von Krankheitsbildern, sondern insbesondere auch in der Analyse von Blickbewegungsmustern erfahrener Ärzte und Therapeuten [95–97]. Diese Analyse findet häufig in zwei Bereichen ihre Anwendung: bei der Interpretation bildgebender Verfahren der menschlichen Anatomie und ihrer Funktionen (wie etwa Röntgenbilder, Positronenemissionstomographien oder Ultraschallaufnahmen) und bei der Schulung von Blickbewegungen bei Medizinstudierenden durch die eingangs erwähnten *Eye Movement Modeling Examples*.

Bei der Interpretation bildgebender Verfahren lassen sich mittels Eye-Tracking klare Unterschiede zwischen Experten und Nicht-Experten identifizieren. Beispielsweise untersuchten Gegenfurtner und Seppänen [98], wie sich Nuklearmediziner und Radiologen in der Diagnose dreidimensionaler, dynamischer Modelle des menschlichen Körpers und ihrer Funktionen, die durch die Fusion von Positronenemissionstomographie und Computertomographie generiert wurden, hinsichtlich der Zahl und Dauer ihrer Fixationen auf diagnoserelevante und diagnoseredundante Informationen unterschieden. Replizierbare Expertiseunterschiede finden sich auch in der mikroskopischen Pathologie [99, 100], der Kardiologie [101], der Laparoskopie [102], der Chirurgie [103], der Nuklearmedizin [104] und der Notfallmedizin [105, 106]. Übersichtsarbeiten über diese Belege visueller Expertiseunterschiede – die systematische Vorteile von Experten in der Detektion von Auffälligkeiten und in der Diagnose von Symptomen dank herausragender visueller Informationsverarbeitungsprozesse belegen – finden sich beispielsweise bei Kundel [97], Gegenfurtner et al. [95], sowie Gegenfurtner und Van Merriënboer [107].

Der Einsatz mobiler Eye-Tracker bietet mittlerweile die Möglichkeit, das Blickverhalten von Ärzten und klinischem Pflegepersonal in ihrer gewohnten Arbeitsumgebung aufzuzeichnen. So können ganz neue Aufnahmen von Augenbewegungen generiert werden, in denen die Komplexität und Dynamik alltäglicher Arbeitssituationen etwa in Notfallaufnahmen oder im Operationssaal abgebildet werden kann [108]. Auch in Simulationen, in denen die klinische Kompetenz unter realistischen

Bedingungen nachgestellt und trainiert werden kann, lassen sich mobile Eye-Tracker einsetzen. So konnten Szulewski und Kollegen [105] im Kontext der Notfallmedizin zeigen, dass das Blickverhalten von Personen, die in einer Facharztausbildung sind, signifikant mit der diagnostischen Leistung in simulierten Notaufnahmen korreliert. Solche komplexen und wirklichkeitsnahen Szenarien, wie sie Simulationslabors ermöglichen, bieten neue und vielfältige Chancen, Blickverhalten von klinischem Fachpersonal zu analysieren.

Neben der Analyse von Augenbewegungen können Eye-Tracking-Daten aber auch für die Weiterbildung und Schulung genutzt werden und auf diese Weise die (visuelle) Expertiseentwicklung begünstigen. Ein didaktisches Modell, das vielfach eingesetzt und auf seine Wirksamkeit hin erprobt worden ist, bietet die Weiterbildung durch *Eye Movement Modeling Examples*. Dahinter steckt das Lernen durch Beispiele bzw. die Annahme, dass Personen mit geringem Vorwissen bzw. Expertise durch das Beobachten von Personen mit hoher Expertise lernen können, wie domänenspezifische Lösungsschritte aussehen [11] (vgl. hierzu auch die Ausführungen in Abschnitt 1.1). Oft ist es nur schwer möglich, Experten bei der Lösung komplexer Probleme zu beobachten, insbesondere dann, wenn die Lösungsschritte internal („im Kopf") ablaufen und nur schwer von außen beobachtbar sind [109]. Augenbewegungen sind ein Beispiel für solche internalen Prozesse. Eye-Tracking bietet hier die Möglichkeit, die Augenbewegungen von Experten während der Lösung eines Problems – etwa der Diagnose eines Röntgenbildes – aufzuzeichnen und die internalen Prozesse der Informationsverarbeitung zu externalisieren.

Diese videobasierte Externalisierung von Augenbewegungen kann auf zwei Arten für Zwecke der Weiterbildung genutzt werden. Einerseits kann das Video des Blickverhaltens eines Experten Personen mit noch geringer Erfahrung (etwa Studierende) vorgespielt werden. Auf diese Weise erhalten Studierende wertvolle Einblicke in die Mechanismen und Strategien, die von Experten bei Problemlösungen genutzt werden. Konkret können Studierende dabei lernen, in welcher Reihenfolge Experten bestimmte Bereiche fixieren, welche Bereiche bzw. Informationen häufig und stark fokussiert werden und welche Bereiche redundant sind und potentiell ignoriert werden können [12]. Andererseits kann das Video des Blickverhaltens eines Experten dem Experten selbst vorgespielt werden. Dadurch erhalten Experten die Möglichkeit einer Rückmeldung der eigenen Augenbewegungen, die ohne Eye-Tracking nicht zur Verfügung stünde [106]. Es ergeben sich hier unmittelbar Chancen des Feedbacks und der Reflexion der eigenen beruflichen Praxis, die für die Fortbildung und Weiterentwicklung der eigenen Expertise genutzt werden können.

Diese Szenarien werden national und international bereits eingesetzt und erprobt, in Bereichen wie etwa der Notfallmedizin [108], der Nuklearmedizin [13] und der Radiologie [12]. Insbesondere der Kontext simulationsbasierter Lern- und Trainingsumgebungen scheint sich für den Einsatz von *Eye Movement Modeling Examples* zur Optimierung des Blickverhaltens und der *Agency* in komplexen medizinischen Situationen zu geben [106, 108, 110–112]. Weitere Anwendungsfelder in Medizin und Pflege müssen in weiterführenden Forschungsarbeiten prüfen, inwieweit die Wirksamkeit von *Eye Movement Modeling Examples* unter veränderten Bedingungen und mit unterschiedlichen klinischen Diagnoseszenarien besteht und wie Feedbackmechanismen und das Beobachten von Experten didaktisch am besten in Curricula der beruflichen Aus- und Weiterbildung implementiert werden können.

3. Chancen und Risiken mobilen Eye-Trackings

Das Ziel dieses Beitrags war, einen Überblick über die Möglichkeiten von Eye-Tracking als Forschungsansatz zu geben. Dabei wurden verschiedene Beispiele aus den angewandten Wissenschaften präsentiert, in denen mobiles Eye-Tracking eingesetzt werden kann oder auch bereits intensiv genutzt wird. Diese konkreten Anwendungsbeispiele aus der Automobilität, des *Usability Engineerings*, der Sportwissenschaften, der *Augmented Reality/Mixed Reality/Virtual Reality* und der Medizin bzw. medizinischen Weiterbildung dokumentieren die vielfältigen Einsatzmöglichkeiten, die eine Analyse von Blickbewegungen bietet. In diesem Abschnitt sollen zusammenfassend die Chancen und Risiken abgewogen werden; ein Ausblick auf zukünftige Forschung rundet den Beitrag ab.

Die Chancen des mobilen Eye-Trackings liegen in mehreren Bereichen, die sich wie folgt zusammenfassen lassen:

- Externalisierung internaler Prozesse der Informationsverarbeitung, auch in komplexen und dynamischen Arbeitsfeldern
- Präzise Analyse von Blickbewegungen und *AOI*s
- Einschätzung des Situationsbewusstseins in komplexen Szenarien
- Eingehenderes Verständnis der Verarbeitungsprozesse des Gehirns in Zusammenhang mit visuellen Reizen
- Training zur Verbesserung sportartspezifischer Technik und Taktik
- Kontaktlose Steuerung von Endgeräten und technologischen Innovationen durch Fokus und Blickbewegung
- Warnsysteme bei Unaufmerksamkeit etwa in der Automobilität und im Verkehr
- Video von Augenbewegungen in Form von *Eye Movement Modeling Examples* für Zwecke von Reflexion, Feedback sowie Aus- und Weiterbildung
- Im Falle von Studien mit mobilen Eye-Tracking-Systemen hohe externe Validität
- Langzeitbeobachtungen zur neurologischen und medizinischen Diagnostik und Therapie
- Augenbewegungen sind intuitiv und müssen im Gegensatz zu anderen Interaktionsmodellen nicht erlernt werden
- Augenbewegungen sind bei motorisch eingeschränkten Personen oft die einzige Möglichkeit der Kommunikation

Neben diesen Chancen bestehen aber auch einige Grenzen und Herausforderungen, die beim Einsatz von Blickbewegungsanalysen nicht außer Acht gelassen werden sollten. Dazu zählen etwa:

- Finanzielle Ressourcen für Anschaffung und Instandhaltung der Geräte
- Aufwendige und unflexible Integration kamera-basierter Systeme in *HMD*s
- Stark schwankende Unterschiede in Qualität (Genauigkeit, Latenz) und Verlässlichkeit der Hardware
- Notwendiges Knowhow für die Erhebung, Auswertung und Interpretation von Augenpositions- und Blickbewegungsdaten
- Schwierigkeit des intrapersonellen Vergleichs von Daten und Mustern aufgrund individueller Sehleistung (Visus, Vergenz, Akkommodation) und physischer Gegebenheiten (Augenabstand, Motorik, Krankheit)
- Problematische interne Validität und experimentelle Kontrolle in Studien mit mobilen Eye-Trackern
- Probleme der Fixierung der Eye-Tracking-Brille in Situationen hoher körperlicher Agilität
- Individuelle Langzeit-Kalibrierung des Messsystems
- Notwendige Formulierung von Kriterien der Effektivität und der Effizienz als Analyserahmen der aufgezeichneten Daten
- Herausforderungen des Datenschutzes bei der Aufnahme von (möglicherweise unbeteiligten) Personen über die Eye-Tracking-Kameras in realistischen Szenarien
- Mögliche Verletzung des individuellen Persönlichkeitsrechts durch (permanente/wiederholte) Iris- und Retinascans
- Didaktische Implementierung von *Eye Movement Modeling Examples* in existierende Curricula
- Vernachlässigung anderer kognitiver Indikatoren, die jedoch zur Triangulation der Dateninterpretation hilfreich (und vielleicht notwendig) sind
- *Midas-Touch*-Problem (Die Nutzung von Augenbewegungen zur Interaktion im Mensch-Maschine-Kontext führt zu ständigen, auch ungewollten Aktionen)

Die hier aufgelisteten Risiken mobilen Eye-Trackings können in zukünftigen Forschungsarbeiten adressiert werden. Dabei scheint vor allem eine interdisziplinäre Zusammenarbeit hilfreich, in denen die Kompetenzen und die Expertise unterschiedlicher Fachbereiche und Praxispartner der Industrie gebündelt werden können. Gerade die angewandten Wissenschaften haben hier eine besondere Stärke, weil sie in einem Zusammenspiel hoher Praxisorientierung unter gleichzeitiger Berücksichtigung hoher wissenschaftlicher Standards neues, anwendbares Wissen generieren. Dabei lassen sich mobile Eye-Tracker auch hervorragend in Strategien der Digitalisierung integrieren, weil die digital genutzten Daten für digitale Situationen in Alltag, Beruf und Weiterbildung neue Horizonte eröffnen können, wenn die internalen Prozesse der visuellen Informationsverarbeitung dank Eye-Tracking sichtbar und damit auch für neue Anwendungen nutzbar gemacht werden.

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Armin Eichinger studied psychology and computer science in Regensburg. In 2011, he received his doctorate on the subject of human-machine interaction in aviation. He was appointed professor at DIT in 2014. He teaches and researches in the fields of usability engineering, business informatics as well as organizational and economic psychology.

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Richard Latzel, who studied to become a teacher of Physical Education and English in Würzburg, has for many years worked as a sport scientist, head coach, and strength and athletics coach in high-performance sports (basketball). Cognitive and perceptual abilities play a major role in sports performance, especially in game sports, and on many levels, particularly in technique and tactics. Hence, eye-tracking is receiving increasing attention in applied sports sciences research.

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Wolfgang Stern studied Telecommunications Engineering at the University of Applied Sciences in Regensburg. In addition, he earned a Bachelor's degree in Information Systems and Management as well as a Master's degree in Business Administration at DIT while working full-time. He was engaged in IT projects at Deutsche Telekom AG from 1998 until 2001. Ever since 2001, he has been employed at DIT where he runs the Further Education Center IQW. As head of department he is responsible for several areas, including further training and development, quality management, E-learning, and multiple projects dedicated to teaching. Furthermore, he is a lecturer in operating systems and business informatics. Since 2013, he has been representing DIT's non-scientific staff in the senate and the council.

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Heft 5 (2019): Standards und Messbarkeit nachhaltiger Entwicklung

Inhaltliche Redaktion: Prof. Dr. Roland Zink, Prof. Dr. Bernhard Bleyer (THD)

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Guest Editors: Prof. Dr. Roland Zink, Prof. Dr. Bernhard Bleyer (DIT)

Call for scientific contributions
With the enactment of the Sustainable Development Goals (SDGs) by the UN General Assembly as part of UN Resolution 70/1 „Transforming our world: the 2030 Agenda for Sustainable Development“, the subject of sustainable development has entered a new phase. The United Nations Member States have agreed on 17 basic goals for sustainable development which have been subdivided into 169 associated intermediary targets. Breaking down the goals into specific targets should help countries to better monitor progress across all goals and targets. Several initiatives have been trying to make sustainable development measurable: the SDG Index and the Global SDG Indicators Database on a global and a national level, the Global Reporting Initiative and the SDG Compass on a business level, and organic certifications and Life Cycle Assessments on the product level.

Questions of measurability of sustainable development touch upon a plethora of academic disciplines. The 2019 5th issue of the Bavarian Journal of Applied Sciences will be dedicated to standards, criteria, measuring methods and the respective processes in sustainable development. Thus we would like to invite scientific contributions related to this topic.

Please submit contributions in line with our style guidelines and citation procedures via the journal's website http://jas.bayern **until July 31st 2019**. Contributions will be selected by the editorial team for double-blind reviewing. We will notify the authors of articles accepted for review until August 31st 2019. Contributions may be in either German or English.

Call for contributions to the BJAS Spotlight section
The BJAS Spotlight section will provide a space for specific concepts of practical implementation. We therefore invite you to submit contributions (of a maximum of 1.500 words) portraying practicable ideas on how sustainable development may be standardized and measured. Deadline of submission: **July 31st 2019**.

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