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REVIEW

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Smart lighting systems: state-of-the-art and potential applications in warehouse order picking

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ABSTRACT
Artificial lighting is a constant companion in everyday private and working life, influencing visibility in interior spaces as well as outdoors. In recent years, new technical solutions have extended traditional lighting systems to become 'smart'. Different types of smart lighting systems are available on the market today, and researchers have concentrated on analysing their usability and efficiency, especially for private households, office buildings and public streets. This paper presents a systematic literature review to analyse the state-of-knowledge of technologies and applications for smart lighting systems. The results of the review show that smart lighting systems have been frequently discussed in the literature, but that their potentials in industrial environments, such as production and logistics, has rarely been addressed in the literature so far. Lighting systems for industrial environments often have very different requirements depending on the working environment and operating conditions. Based on the results of the literature review, this paper contributes to closing this research gap by discussing the usage potential of smart lighting systems to improve the efficiency of warehouse order picking, which is an application that may benefit from various functions smart lighting systems provide. Several propositions are developed that emphasise research opportunities and managerial implications in this context.

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KEYWORDS
Intelligent lighting; light; systematic literature review; order picking; warehousing

1. Introduction

Global carbon dioxide emissions have continuously increased in recent years. These emissions are considered a crucial contributor to the greenhouse effect and the subsequent environmental damage (Xie, Fang, and Liu 2017; Ohlan 2015). With both electricity production and consumption increasing worldwide, companies around the world have been forced to reduce energy consumption due to scarce resources, rising energy prices, and an increasing awareness of companies' environmental responsibility. Industrial energy efficiency measures, in general, attempt to reduce the amount of energy required for providing products and services. A large share of the total greenhouse gas emissions generated in production and logistics facilities emanate from heating, cooling, air conditioning, and lighting (Pérez-Lombard, Oritz, and Pout 2007). In warehouses, for example, lighting is responsible for up to 65% of the total energy consumption, significantly contributing to operating energy costs and the facility's carbon footprint (UKWA 2010; Dhoorna and Baker 2012; Richards 2014; Fichtinger et al. 2015). In the last few years, general improvements in energy efficiency and the use of renewable energy sources have been supported by innovative solutions that extend from individual smart homes to smart grids as well as to the future of smart cities and factories (Cimini et al. 2015). In this context, new lighting technologies have emerged, such as light emitting diodes (LEDs), which have already become a popular lighting source (Maurer 2015). The energy-saving potential of LEDs is enormous (Tähkämö, Räsänen, and Halonen 2016; Kıyak, Oral, and Topuz 2017; Gentile et al. 2018). In case LEDs are combined with an intelligent light control system (that may use advanced motion and occupancy sensors, for example), energy consumption can be reduced even further (Cimini et al. 2015).

The potentials of so-called smart lighting systems (SLS) are, however, not limited to the reduction of energy requirements. They may, for example, complement communication networks and serve as data transmitters, provide indoor positioning functionalities, and improve

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human well-being (we refer the reader to a more detailed discussion of SLS in Section 2.1).

Typical SLS application fields include street lighting in the context of smart cities, interior lighting in office buildings and lighting in smart homes (Shahzad et al. 2018; Xu et al. 2017; Byun et al. 2013). These areas have seen a strong increase in publications recently, with the majority of the published works focusing on light quality and energy efficiency. The benefits of SLS discussed in the literature for different application areas indicate that production and logistics facilities may profit from SLS as well (see Bartolini, Bottani, and Grosse 2019). Because each production and logistics facility needs artificial lighting, and considering the potentials of SLS for improving both energy and process efficiency, one would expect an active academic debate in this area. However, SLS research has, as we will show, focused mainly on private households, office buildings and public streets.

Our paper has two main objectives. First, we intend to give a broad overview of the state-of-knowledge of SLS. For this purpose, we conduct a systematic literature review and investigate alternative technologies and application areas of SLS and provide a comprehensive classification of the identified literature (see the supplemental data provided as an online appendix). Second, we highlight the potential of SLS in warehouse order picking as a specific industrial environment that has not attracted attention in this research stream so far. We first define a generic typical process of manual order picking and then, based on the evidence obtained in the literature review, discuss for each process step how SLS could support order picking operations and improve the indicators energy savings, operational performance and worker well-being. The propositions on the influence of SLS on warehouse operations we develop in this paper are based on the results of the literature review and the authors' practical and theoretical knowledge of warehouse processes and order picking. In addition, workshops with warehouse managers from industry and professionals from leading companies of the lighting industry were conducted to validate and enrich the identified potentials. The methodology used for extracting information from the workshops is presented in more detail in Section 4.2. To outline the structure of the paper and to highlight how the methodologies used in the different sections are connected, a process diagram is presented in Appendix 1.

The remainder of this paper is structured as follows: Section 2 describes the basic attributes of SLS, outlines the methodology of the literature review and descriptively evaluates the literature sample. Section 3 presents the results of the literature review by discussing the state-of-knowledge of technical characteristics and application fields of SLS. Section 4 develops propositions to support the integration of SLS into order picking warehouses. In addition, research opportunities are outlined. The paper concludes and presents managerial implications in Section 5.

2. Background and literature review methodology

This section specifies the basic characteristics of SLS, briefly discusses insights from earlier literature reviews in this research field and then outlines the review's methodology.

2.1. Basic characteristics of smart lighting systems

Lighting describes the use of natural and artificial light to illuminate areas in general, for specific tasks, or for accent lighting (Boyce 2014). This paper focuses on artificial lighting, more precisely on artificial lighting from electric light sources and related technologies. Traditional lighting systems often consist of one or more switches and lighting fixtures. SLS use additional components, such as motion or occupancy sensors (hereafter referred to only as motion sensors) or daylight sensors, to adjust the light intensity to the environment and/or the user's needs. In all application areas where light is required, SLS provide possibly useful solutions. Typical use cases are interior lighting, in offices and residential buildings for example, and outdoor lighting, such as in public streets (Füchtenhans, Grosse, and Glock 2019a).

A main characteristic of SLS is an improved light quality and energy efficiency. Due to the application of efficient technologies such as LEDs, the energy consumption of lighting can be reduced significantly, with the additional advantages of improved light quality. Flexible light control can provide light depending on the user's requirements by adjusting the colour and intensity of light. Integrating sensors enables automatic light control with the possibility of closed-loop feedback, which provides enhanced services in addition to reducing energy consumption (Karlicek 2012). With recent developments in lighting technologies and light sources, such as LEDs and digital light control, SLS are also part of the Internet of Things (IoT) concept with positive impacts from technology, economy, information, and end-user perspectives (Van de Werff, Van Essen, and Eggen 2018). In general, SLS provide functionalities that extend beyond lighting, and they consequently influence warehouse performance in more than just energy efficiency. Applied in the industrial environment, SLS allow communication between lighting devices with benefits, for example, in quality management, contributing to more predictable, more failsafe and efficient work processes, resulting in reduced cost. SLS are sustainable and environmentally friendly due to longer-life components, and flexible light control helps reduce light pollution. Light pollution is responsible for wasted energy due to excessive or obtrusive artificial light caused by bad lighting design with, for example, negative affects to wildlife or health (Gallaway, Olsen, and Mitchell 2010). Failsafe and self-commissioning systems enable reduced maintenance and lower associated costs, while improving functional safety (Füchtenhans, Grosse, and Glock 2019a). Comfortable handling, easy usability, and individual adaption as well as the opportunity for integration into existing systems are important for high user acceptance. Lighting functionalities, like visible light communication (VLC) enabled by light modulation, provide network access and interlink the environment by integration into novel platforms of SLS (see Section 3.1.4). Furthermore, SLS enable more accurate positioning in indoor environments to provide location-based services (see Section 3.1.5). Another SLS benefit is the potential to stimulate humans by circadian rhythm regulation according to the human-centric lighting (HCL) approach, which can improve well-being (see Section 3.1.6).

Our understanding of SLS, in conformance with the literature (e.g. Chew et al. 2017; Sharma et al. 2018; Karlicek et al. 2012; Tan et al. 2018), is based on the entire range of technologies touched upon above.

2.2. Insights from previous literature reviews

This paper is the first literature review that discusses SLS in the context of industrial environments. There are, however, other literature reviews that evaluated SLS mainly from a technical point of view. We present a brief overview of these reviews next and summarise them in Table 1.

Ongoing developments in the field of solid-state lighting and LEDs, as discussed further in Section 3.1.1., have been addressed by a few reviews. Reviews in this area considered, for different application areas, technical aspects of LEDs such as form factor flexibility, radiation and modulation rate as well as economic aspects such as luminous efficiency and lifetime. Reviews that focus on solid-state lighting and LEDs are listed in the first row of Table 1. Another set of literature reviews focused on the energy efficiency of lighting systems for different light control strategies using daylight and motion sensors and different light sources (cf. second row of Table 1). However, production or logistics application requirements were not considered in detail in these works. VLC and connected indoor positioning systems (IPS) have been reviewed a few times recently. These reviews focused on the transmission speed, system architecture and interfaces, dimming schemes, multi-user techniques, measuring accuracy as well as related topics like IoT and light fidelity (Li-Fi) (cf. third row of Table 1). Other researchers reviewed various SLS aspects such as performance properties with a focus on specific application areas like smart cities, street lighting, office buildings and smart homes (see fourth row of Table 1). Another SLS aspect that has been reviewed in different use cases is the biological and nonvisual effect of light within the HCL approach (see last row of Table 1). In addition to reviews that deal with specific technical aspects of lighting systems, works that provide broad overviews of the state-of-the-art in smart lighting are rare. One paper that attempts to provide a bigger picture of SLS is Chew et al. (2017). The authors reviewed SLS works with a focus on energy savings and connectivity options as well as the integration of VLC technology. Again, insights for industrial environments, such as production, logistics or warehousing, were not provided. The limitations of existing literature reviews in this regard are addressed in this paper.

Table 1. Reviews on SLS with different focus areas.

Focus area	Literature
Solid-state lighting/LED technology	Tsao et al. (2010); Thejo Kalyani and Dhoble (2012); Shur and Zukauskas (2005); Shur and Zukauskas (2011); De Almeida et al. (2014); Chang et al. (2012); Aman et al. (2013); Neary and Quijano (2009); Mayhoub and Carter (2010)
Energy efficiency via light technologies	Choubey and Bhujade (2019); Wagiman et al. (2019); Dubois et al. (2015); Zografakis, Karyotakis, and Tsagarakis (2012); Yun et al. (2012b); Pandharipande and Caicedo (2015); Montoya et al. (2017); Lowry (2016); Li (2010); Haq et al. (2014); Han et al. (2010); Guo et al. (2010); Galasiu and Veitch (2006); De Bakker et al. (2017); Williams et al. (2012); Aries and Newsham (2008)
VLC, Li-Fi, IPS	Afzalan and Jazizadeh (2019); Kumar and Singh (2019); Matheus et al. (2019); Udvary (2019); Vappangi and Mani (2019); Zafar, Karunatilaka, and Parthiban (2015); Wu, Wang, and Youn (2014); Sharma et al. (2018); Pathak et al. (2015); Ndjiongue and Ferreira (2018); Medina, Zambrano, and Navarro (2015); Mathews et al. (2017); Luo, Fan, and Li (2017); Lian et al. (2019); Khan (2017); Karunatilaka et al. (2015); Jovicic, Li, and Richardson (2013); Ji et al. (2018); Hassan et al. (2015); Burchardt et al. (2014); Haas et al. (2016); Elgala, Mesleh, and Haas (2011); Cevik and Yilmaz (2015); Al-Ahmadi et al. (2018); Wang et al. (2015a)
Other aspects	Thiel, Ensslin, and Ensslin (2017); Silva, Khan, and Han (2018); Gutierrez-Escolar et al. (2017); Dubois and Blomsterberg (2011); Vanus et al. (2016); Ochoa, Aries, and Hensen (2012); Lobaccaro, Carlucci, and Löfström (2016); Dubois et al. (2015)
HCL	Begemann, van den Beld, and Tenner (1997); Navara and Nelson (2007); Figueiro (2013); Boyce (2010); Van Bommel and Van den Beld (2004)

2.3. Literature search approach and sample generation

The aim of literature reviews is to structure a defined research area and to evaluate and synthesise research evidence and arguments relevant to a previously specified research topic. It is a key tool for many research disciplines that helps maintain an overview of the growing body of academic literature (Tranfield, Denyer, and Smart 2003). Identifying and discussing the existing scientific literature in a systematic and transparent way is important for identifying research gaps. The systematic literature review methodology used in this paper was developed with reference to Newbert (2007) and Glock and Hochrein (2011).

This paper systematically collects and analyses the literature with a focus on the application and technical characteristics of SLS. The aim of this review is to identify the streams of research that have emerged in the various areas of SLS and to assess the state-of-knowledge in each area in terms of application fields and technologies used. To meet these objectives, we have to consider research from several disciplines. The literature search and selection strategy consists of three main steps: (a) define relevant keywords, (b) search two scholarly databases, and (c) identify relevant papers.

In systematic literature reviews, it is important to include all relevant papers in the literature sample and to ensure that every step of sample generation is transparent and reproducible. The Scopus and Business Source Premier scholarly databases, which cover the research fields relevant for this paper, were used to search for pertinent papers. Based on the insights obtained from Sections 2.1 and 2.2, we defined three groups of keywords associated with SLS and their application fields (see Table 2). Each keyword from Group A was combined with each keyword from Group B to generate the first part of the final list of keywords related to smart and energy-efficient lighting approaches that contained $10 \cdot 3 = 30$ keyword combinations. The term 'intelligent lighting' is used as a synonym for SLS in the literature and, therefore, part of the keywords. Group C includes the second part of relevant phrases and established terms of technical systems or applications. The database search retrieved papers that either contain a keyword combination from Groups A and B (e.g. energy efficiency and illumination, indoor and light, etc.) or a sole keyword from Group C in the title.

Table 2. Keyword groups used in the literature search.

Group A	Group B	Group C
Intelligent	Light	Smart factory
Smart	Luminaires	Light management
Energy efficiency	Illumination	Human centric lighting
LED		Smart city
Artificial		Smart office
Energy saving		Office light
Inverse		Smart home
Indoor		Lighting system
Interior		Light control
VLC (for visible light communication)		Lighting design
		Street lighting
		Light communication

The Scopus database permits excluding non-relevant subject areas to reduce the number of irrelevant papers retrieved during the search. Excluded subject areas are 'Chemistry', 'Physics and Astronomy', 'Agricultural and Biological Sciences', 'Biochemistry, Genetics and Molecular Biology', 'Medicine', 'Chemical Engineering', 'Dentistry', 'Pharmacology', 'Toxicology and Pharmaceutics', 'Immunology and Microbiology', 'Veterinary', 'Nursing', 'Neuroscience' and 'Health Profession'. For each paper identified during the search, the title was checked and, if the work seemed relevant for this review, the abstract was read to evaluate the paper's relevance. Papers identified in the literature search were subjected to several selection filters. The language of the papers was limited to English and the year of publication was limited to 2000–2019. In addition, only works that appeared in peer-reviewed academic journals were considered relevant, and only those papers were considered that obviously focus on SLS with practical relevance. Consequently, academic papers that address tunnel lighting, lighting in mines, lighting in connection with flora and fauna, photovoltaic systems, traffic lights, vehicle lighting, airport runway lights, entertainment lighting, emergency lighting or underwater illumination were not considered relevant for this literature review. In total, 514 papers were identified that met the selection criteria, and these papers were read completely and subjected to further analysis. In the last step, a 'snowball approach' was employed by screening the sampled papers' reference lists for additional relevant works. At the end of the literature search step, a total of 384 papers were considered relevant and included in the final sample. Due to space restrictions, only a subset of the final sample can be discussed in this work. A table summarising the complete sample and a classification is provided as supplemental data in the online appendix. The following descriptive results are based on an evaluation of the complete sample.

2.4. Descriptive results

The descriptive analysis of the 384 sampled papers includes a bibliographic evaluation as well as a summary of technical systems and application areas of SLS together with the research objectives of the reviewed papers. Figure 1 shows the number of works published per year together with a fitted trend line. SLS research

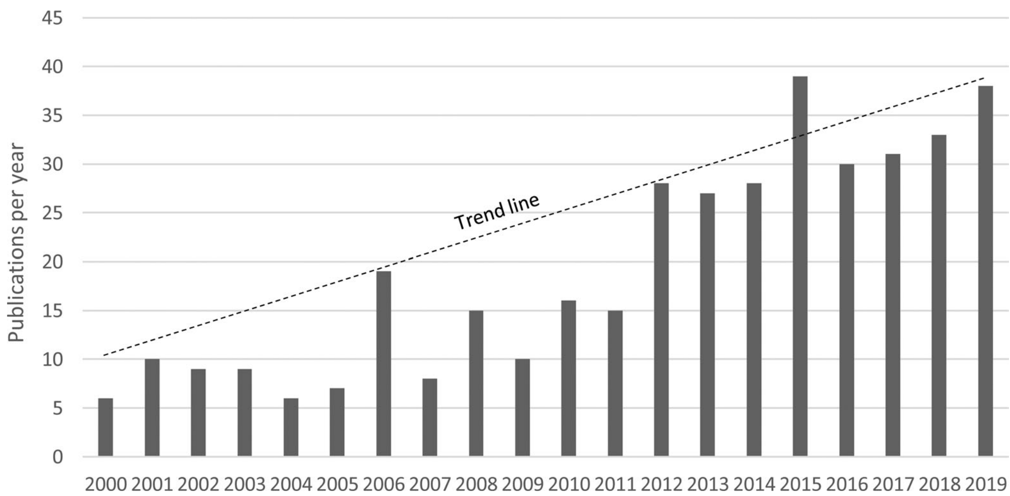

Figure 1. Number of papers published per year.

output has increased quite substantially in recent years, with 254 of 384 (~ 66%) papers published between 2012 and 2019. This trend highlights the increasing relevance this topic enjoys in academic research. The increased interest may have been reinforced by the huge diversity of this topic, which results from both the broad usability of light itself and different research streams, especially due to developments in solid-state lighting/LED technology.

Figure 2 presents journals that published more than two papers included in the final sample and the respective number of publications. Journals were assigned to thematic categories according to the SCImago Journal and Country Rank (2020). The analysis shows that the sampled papers were published primarily in technically oriented journals that focus on facilities and buildings. *Energy and Buildings (72)*, *Lighting Research & Technology* (40) and *Building and Environment* (27) were the three most common outlets for research in this area. Only a small proportion of studies was published in business and management or industrial engineering journals, which indicates a research gap in these disciplines.

In approximately 63% of the papers dealing with light bulb technology, LEDs are compared with other light bulbs, or they are selected as the only illumination

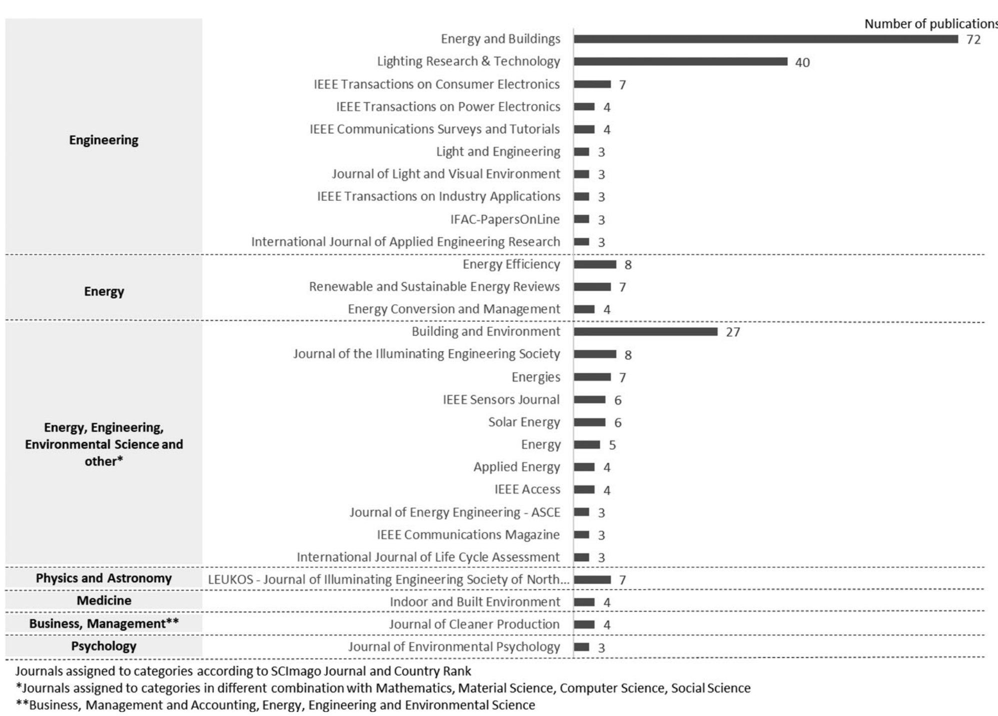

Figure 2. Number of papers per journal.

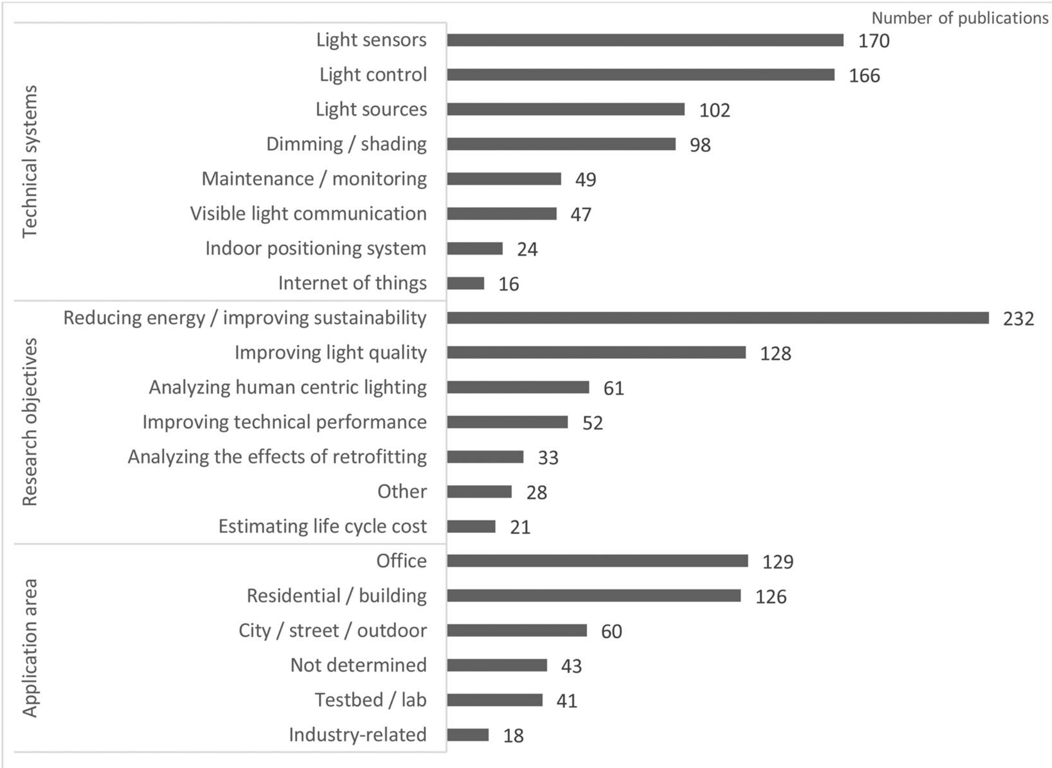

Figure 3. Technical systems, research objectives and application areas of SLS.

technology. Papers that address conventional light sources use them primarily as a benchmark technology to evaluate the advantages of LEDs. A closer look at the technical details reveals that topics that have frequently been investigated in the sampled papers are light sources, daylighting, motion or occupancy sensing and dimming, and light control. Other characteristics of SLS that have received some attention, as outlined in Section 2.1, but less than those mentioned earlier, are VLC, IPS, IoT, and maintenance and monitoring. Figure 3 summarises these points and gives an overview of the research objectives of the sampled papers as well as the identified number of publications for each category. More than half of the papers deal with improving sustainable lighting solutions with a clear focus on energy reduction. Further research objectives are the improvement of the system's technical performance, analysing the effects of retrofitting, estimating life cycle costs, improving light quality, or analysing HCL.

Examining the investigated application areas, we see that offices were most frequently studied (31% of the sampled works), followed by residential and general indoor environments (30%). Some technical studies only used test environments (10%) or designated no application area (10%). Street or city lighting was another research area (15%) with different requirements and use cases. Surprisingly, industry-related applications of SLS (such as in production and logistics facilities) received little attention (4%).

In the following sections, we use the identified literature to discuss the most important technical systems and application areas in view of the research objectives shown in Figure 3. The application area testbed/lab does not provide further benefits for our discussion in Section 3.2 or afterwards and, therefore, we do not consider this specific application area in the discussion. We apply this knowledge in Section 4 to derive propositions on how SLS can be integrated into warehouse order picking, an application area that did not receive any attention in the research stream at hand so far.

3. Literature review of smart lighting systems

We briefly discuss the state-of-knowledge of SLS with regard to technical systems and characteristics (Section 3.1) as well as application areas (Section 3.2). The structure of this section follows the classification from the descriptive results of Section 2.4 by referring to example publications in each category. We focus on papers that obviously study SLS with practical relevance and possible usability in order picking warehouses, which facilitates transferring the results and deducing the propositions in Section 4.

3.1. Technical characteristics of SLS

3.1.1. LED

In recent years, LEDs have advanced substantially, and they now offer more energy-efficient lighting and improved light control opportunities, such as shorter switching times, efficient dimming techniques, a broader spectral power distribution as well as a higher light intensity (Park, Lee, and Kim 2015; Wang and Linnartz 2017; Wang et al. 2012). LED-based lighting is the foundation of most current lighting systems and for several emerging technologies that cannot be realised without LEDs. The first crucial improvement of LEDs compared to traditional lighting systems (e.g. incandescent bulbs and fluorescent lamps) is their energy consumption. According to the literature, the luminous efficiency of LED luminaries is approximately 100 lm/W in home environments or street lighting and up to 200 lm/W in industrial environments, while incandescent bulbs have approx. 15 lm/W and fluorescent lamps approximately up to 100 lm/W (Chang et al. 2015). Other advantages include their long lifespan that ranges from 50,000 to over 100,000 h (Schratz et al. 2013; Vahl, Campos, and Filho 2013), their robustness and stability independent of the amount of shifting, and a high natural colour rendering with flicker-free light. Novel LED technologies can adjust both colour temperature and light intensity due to dimmable bicolour LED lamps (Lee et al. 2016; Cupkova et al. 2019). The heat radiation of traditional lighting systems does not exist for LEDs, so that coolants and lubricants combined with dust cannot burn in. This usually results in lower maintenance/replacement cost (Chew et al. 2017). An easy way to convert an existing lighting system to LED luminaires are so-called retrofit lamps that replace existing conventional luminaires with LEDs; the LEDs can also be adapted to customer-specific requirements while avoiding traditional technical standards (Dubois et al. 2015; Santamouris and Dascalaki 2002).

Although other light sources comply with some requirements of SLS technologies, only LEDs satisfy all of them. This may be the reason why all SLS that are currently available on the market, to the best of the authors' knowledge, use LEDs (see also Section 2.1 and Chew et al. 2017). LEDs themselves, however, do not qualify as a SLS yet according to this definition; they provide the technical basis for different SLS technologies and use cases and need to be combined with sensors and control systems to become 'smart' (see also Afshari et al. 2014).

3.1.2. Sensor-based lighting

A basic control option that has long been in use can be described as sensor-based lighting. Motion, occupancy or other external factors can be detected by sensors, enabling the system to adapt lighting to the situation. To reduce energy consumption and light pollution, artificial light is only (fully) switched on if motion or occupancy is detected by the sensor systems. If the workplace is empty, lighting is switched off or dimmed to a predefined lower level (Chung and Burnett 2001; Chun, Lee, and Jang 2015). Daylight sensors are used in places where natural daylight can provide sufficient or partial brightness. They detect daylight and complement it with artificial light if required (Caicedo and Pandharipande 2016; Caicedo, Pandharipande, and Willems 2014). Daylight and motion sensors have been especially popular in office buildings in the past (Yang and Nam 2010; Gilani and O'Brien 2018). Motion sensors are particularly suitable for places that are only infrequently visited or used (Liu et al. 2016).

Sensor-based systems can save energy without compromising functionality or safety standards (Pandharipande and Caicedo 2015; Kaminska and Ozadowicz 2018), depending on the use case and user behaviour. Possible energy savings have been discussed in many scientific studies with different assumptions and different methods. The most commonly used methods are simulation and measuring energy consumption in real or test systems (cf. Roisin et al. 2008; Bodart and De Herde 2002; Yun, Kim, and Kim 2012; Gentile and Dubois 2017). Due to the various study setups used, a large energy savings range has been reported. Moreover, the reported energy savings result from a comparison to traditional lighting systems with low luminous efficiency that usually do not use motion and daylight sensors. Hence, the reported energy savings range from 17% to 60% for motion-based light control (Von Neida, Manicria, and Tweed 2001). For daylight sensing, energy savings above 40% have been reported (Chew et al. 2017). Studies that examined combined motion and daylight sensors reported a wider range and higher average energy savings, from 13% (Higuera et al. 2015) to 73.2% (Nagy, Yong, and Schlueter 2016). The results therefore imply that the savings depend on different internal and external factors, such as window size and orientation, available hours of sunshine, and occupant usage patterns (Chew et al. 2017; Von Neida, Manicria, and Tweed 2001). Moreover, the application area determines the savings that can be achieved, with office buildings showing the highest potential both in terms of energy savings and with respect to retrofitting (Santamouris and Dascalaki 2002).

Sensor-based lighting has benefits beyond reduced energy consumption. SLS, including LEDs and sensor-based light control, can adapt illumination levels to the user's preferences and task in question, which can positively stimulate his or her circadian rhythm and increase well-being and productivity (Karlicek 2012; Oh, Ji Yang, and Rag Do 2014). Depending on the use case und the degree of customisability, these systems can support employees, make work easier and prevent accidents (Veitch, Stokkermans, and Newsham 2013). The lighting system can also be integrated into network systems (e.g. building management systems), enabling central monitoring and control of light (Vanus et al. 2016). Thus, information collected with light sensors can be used for other applications as well, such as the control of window blinds based on solar radiation.

3.1.3. Maintenance

In addition to energy consumption, the cost of lamp replacements and other maintenance work has to be considered when evaluating SLS (Maniccia et al. 2001). SLS use LEDs that are robust and stable, with good switching capability and low heat output, leading to much lower maintenance costs than for traditional lighting systems (Salata et al. 2015). The decreased power output of LEDs due to contamination, soiling and aging can be identified using sensor systems, allowing maintenance intervals to be more precisely defined based on operational experience (Füchtenhans, Grosse, and Glock 2019b). Networking and digitisation of all essential lighting system components enable real-time quick and easy monitoring within building management systems. By integrating SLS into building management systems, unplanned failures, malfunctions and downtime can be recognized early and thus significantly reduced, which ensures compliance with safety regulations and operational demands for lighting (Sahin, Oguz, and Büyüktümtürk 2016; Chang et al. 2015). Malfunctions in light management systems usually affect the workflow and impair safety standards, so intelligent maintenance analyses, which should also detect light management system failures, are required (Kamsu-Foguem and Mathieu 2014). Based on such networked systems, light component manufacturers can provide light as a service to enable remote maintenance and continuous monitoring of systems as well as regular system optimisation. Information about lighting components that need to be replaced during maintenance can be retrieved via network systems so that there is no need to reprogramme or install new components, minimising maintenance activity duration (Chi et al. 2015).

3.1.4. Visible light communication (VLC)

LED lighting provides additional functionalities beyond illumination, such as optical wireless communication (OWC), for example. OWC systems use visible, infrared or ultraviolet light as a wireless, fast data transfer propagation medium (Elgala, Mesleh, and Haas 2011). Visible light technology can eliminate the capacity bottleneck of radio-based wireless networks due to a 10,000 times greater spectrum than radio techniques (Koonen 2018; Ji et al. 2018). Based on new technical developments of LEDs that allow high-speed pulsation without considerable effects on lighting output and without being visible to the human eye, VLC opens up new potentials as an OWC technology (Lian et al. 2019). A VLC system consists of two parts: transmitter and receiver.

The achievable data rates of the transmitter depend on the light source, ranging from often-used phosphor-coated blue LEDs with relatively low data rates to more advanced red, green and blue (RGB) LEDs to laser-based lighting technologies with data rates of up to 100 GB/s (Haas 2018; Tsonev, Videv, and Haas 2015). The receiver uses a photo detection device such as a photodiode contained, for example, in smart phones or tablets. LEDs' high switching capability can be used to transmit data from the transmitter to the receiver by using intensity modulation, following a modulation scheme. The illuminating light is modulated to high frequency flickers, much higher than the refresh rate of a monitor, and is, therefore, not visible to humans (Haas 2018; O'Brien et al. 2008). This connection between transmitter and receiver can only take place in the line of sight. Therefore, the optimal transmitter deployment and location needs to be evaluated accordingly (Sharma et al. 2018; Karunatilaka et al. 2015).

OWC and, in particular, VLC, is a highly energy-efficient technology with advantages in network bandwidth, high-speed networking, data protection security as well as environmental compatibility for humans and nature with different application scenarios (Sharma et al. 2018). Therefore, this technology has attracted great research interest in recent years and gained popularity both as a substitute and a complement for radio-frequency (RF) communication systems (Koonen 2017; Ji et al. 2018). VLC uses and extends the existing SLS infrastructure and is therefore often used as a dual system for illumination and communication (Lian et al. 2019). In contrast to comparable wireless technologies, VLC can also be used in places where wireless connectivity is disrupted; it does not emit radiation and cannot penetrate walls or other obstacles (Pathak et al. 2015; O'Brien et al. 2008). An extension of VLC is the light fidelity (Li-Fi) concept. Li-Fi describes a complete wireless communication network to realise a secure, high speed, bi-directional system that supports user mobility and multi-user access (Burchardt et al. 2014; Haas 2018).

3.1.5. Indoor positioning systems (IPS)

LED-based communication systems also allow indoor positioning and tracking. Global satellite-based positioning systems have been developed for outdoor applications, and they do not achieve the desired accuracy indoors (if they work there at all). Reasons for this inaccuracy are multi-path and attenuation effects caused by internal factors that block or distract the satellite signals (Lian et al. 2019). Traditional IPS use different RF technologies such as RFID, ultra-wideband (UWB) and Wi-Fi, for example (Gu, Lo, and Niemegeers 2009). Installing Wi-Fi access points or infrared transmission equipment is necessary for the application of these systems, which may lead to high installation and maintenance costs (Luo, Fan, and Li 2017). In addition, RF communication is in some situations limited or banned, such as in hospitals, gas stations and airplanes. Compared to global satellite-based positioning systems and RF systems, VLC-based positioning (VLP) allows accurate positioning and tracking of objects or people in buildings (Kuo et al. 2014; Lian et al. 2019). For the exact determination of the receiver's position in indoor environments, triangulation-trilateration, proximity, and fingerprinting are the most commonly used methods (Lian et al. 2019; Chizari et al. 2017). VLC and VLP enabled by SLS provide more secure and power-efficient communication systems that allow higher network data transmission rates than other RF technologies; they may make Wi-Fi systems obsolete (Chew et al. 2017; Lian et al. 2019).

3.1.6. Human centric lighting (HCL)

Natural sunlight and artificial light create different light conditions with different visual effects. However, lighting provides more than just brightness for visual perception. Lighting design and light quality have a large impact on a person's health, well-being and alertness (Van Bommel and Van den Beld 2004; Veitch 2001). Based on different technical systems of SLS like LEDs, light control, and sensors, light's effect on people can be designed and managed. Therefore, the concept of HCL covers the visual, biological and emotional effects of light on humans and the environment to include these soft effects into light planning. A distinction is made between visual and non-visual lighting effects. The visual effect describes the light quality and the dominance of visual performance that should be realised by finding an optimal illumination level adapted to the use case and the surroundings; this is the main purpose of traditional lighting technologies (Bellia, Bisegna, and Spada 2011). The non-visual effects of light describe the impacts of colour temperatures, light intensity and the light spectrum on people; they can also be characterised as biological effects. These biological effects are traced back to the reaction to blue light due to a third photoreceptor in the human eye (Brainard et al. 2001; Brainard et al. 2015). Different colour temperatures, light intensities and light sources with various light spectra influence humans' circadian rhythm and physiological processes, such as pupil diameter and melatonin production (Schratz et al. 2013; Knez 2001; Yasukouchi and Ishibashi 2005; Lu et al. 2016). This affects performance and work efficiency, concentration, and the sleep-wake cycle. Investigations revealed that a higher level of attention can be fostered by a higher colour temperature and is therefore ideal in a work environment (Newsham et al. 2005; Veitch et al. 2008). Therefore, employees' attention and concentration after a break can be affected significantly by an increased light level and cool, white light colour temperatures. However, ambient lighting in residential buildings often has a lower colour temperature, since less concentration is required and a comfortable atmosphere is desired (Van Bommel and Van den Beld 2004; Park et al. 2010). HCL is used to adapt light to the actual conditions and to support humans' natural daily biological rhythm. This is intended to reduce or ideally eliminate the negative effects of artificial lighting, such as in shift work (Juslèn, Verbossen, and Wouters 2007b). Alongside the discussed biological effects that can be influenced by novel solid-state lighting, sensor-based intensity regulation and colour control, the perception of light and the aesthetics of ambient lighting need to be considered in light planning and have a large impact on workers' overall well-being (Veitch, Stokkermans, and Newsham 2013; Afshari et al. 2014). In addition to the pure light perception and the optimal control of light by systems, employees' loss of control and lack of self-determination to control the light must also be considered, as this can have negative psychological consequences (Afshari and Mishra 2016).

3.1.7. Summary

The literature review summarised different technical solutions for controlling and maintaining lighting systems and discussed light's effects on humans. Overall, most papers considered individual parts of SLS as described in Section 2.1. Examples are improvements or comparison of different luminaires (Yoomak and Ngaopitakkul 2018), light control, dimming schemes for LEDs and visible light communication (Zafar, Karunatilaka, and Parthiban 2015; Doulos et al. 2017), and enhancements for VLC-based IPS (Shawky et al. 2017). The interplay of all these solutions in one controlled system defined for specific use cases could be of further interest in the near future.

3.2. SLS application areas

Three main SLS application areas can be identified: office environments, residential areas in the context of smart homes (often referred to as general buildings) and outdoor environments, street lighting in particular. Only a few studies considered specific industrial environments such as operating requirements in production or logistics facilities (but not in warehousing). The different SLS application areas are discussed next.

3.2.1. Office environments and related facilities

To achieve an appropriate illumination level on different surfaces in a room as well as energy savings, sensor-based lighting is an important method of appropriately controlling light. As Figure 3 shows, many papers investigated these systems in offices and related facilities. Depending on the specific use case, energy savings and related time-out settings differed dramatically. For that purpose, investigations are made for typical offices, conference rooms, restrooms, or classrooms (Maniccia et al. 2001). Another aspect that should be considered is lighting control at the room and desk levels. Energy savings differ by looking at the light quality of different zone sizes within offices, and the potential energy savings are higher for motion-based lighting at the desk level compared to the room level (De Bakker, Van de Voort, and Rosemann 2018). However, saving energy is not the only objective in the context of office buildings. Productivity can be improved if HCL strategies are implemented (Veitch et al. 2008; Newsham et al. 2005; Park et al. 2010).

3.2.2. Residential environments

In the context of residential and home automation, a cooperation of various wired and wireless devices, such as sensors and other applications connected via networks to provide user convenience and create personalised and safe ambient space, is called a smart home system (Vanus et al. 2016). It allows automating a wide range of devices, including entertainment systems, home appliances and alarm systems. Due to their network connection, home devices represent important components within the Internet of Things (IoT) technology that can be used to sense, monitor and control the energy consumption of different applications such as lighting systems (Al-Ali et al. 2017). If energy management systems consider energy prices, energy flows can be organised such that supply and demand are balanced at minimal electricity costs. For this purpose, forecasting models and technologies for renewable energy generation considering weather forecasts are implemented into energy management systems (Lobaccaro, Carlucci, and Löfström 2016). LEDs, in connection with smart networks, the IoT and VLC systems can provide an eco-friendly lighting technology that also provides wireless access for the home network (Vanus et al. 2016). In addition to residential environments, specialised indoor use cases can be identified, for example, libraries, hospitals and retail environments (Wang, Liu, and Yang 2018; Ding et al. 2015; Yilmaz 2018).

3.2.3. Outdoor environments

Another SLS application area discussed in the literature can generally be defined as outdoor illumination, where a strong focus has been directed towards street lighting. By considering different weather and external light conditions as well as reflective properties of road surfaces and surroundings, light quality and visibility are two of the most important factors in street lighting research. In addition to external factors, the correct selection of lighting components, such as luminaires, in combination with factors such as light spot mounting height, optimal luminaire spacing, and road surface properties is important (Yoomak and Ngaopitakkul 2018; Markvica, Richter, and Lenz 2019). Lighting systems can adapt the illumination level to provide better overall visual and comfort performance based on current conditions. By considering these external factors, adjustments enable energy savings (Abdullah et al. 2019). Furthermore, energy consumption can be reduced by turning street lamps on when motion is detected. Sensor-based lighting systems are, therefore, able to save energy and adjust the brightness automatically to the given conditions (Maithili et al. 2017). Another benefit of light reduction includes reduced light pollution, which makes an important contribution to ecological sustainability (Gutierrez-Escolar et al. 2017).

3.2.4. Industrial environments

As already mentioned, SLS have been discussed infrequently in industrial contexts. The following presents a brief discussion of all 18 sampled works that discuss SLS in a production or logistics application.

Depending on the industry, daylighting is often not sufficiently available in industrial facilities. Similar to desk level lighting in offices, task lighting depending on the available daylight is very important in an industrial environment to improve the visual performance and better control the biological and psychological effects of lighting. A performance improvement can also be achieved due to controllable lighting technology by generating feelings of autonomy and job satisfaction (see Juslèn, Wouters, and Tenner 2005; Juslèn and Tenner 2007; Juslèn, Wouters, and Tenner 2007). Adapted and localised lighting leads to an increased well-being and productivity, and employees feel less sleepy during shift work, especially at night (cf. Juslèn, Verbossen, and Wouters 2007b; Juslèn and Fassian 2005). An increase in bright light exposure inhibits the release of melatonin and thus improves the adjustment to night shift work (Lowden, Akerstedt, and Wiborn 2004). Adapting the level and colour of light for different light conditions to worker and task needs increases employees' health and alertness and leads to improved safety and fewer failures in the industrial working environment (Van Bommel and Van den Beld 2004).

Due to the various industrial environment requirements, the structural circumstances as well as the machines, work pieces and storage facilities need to be taken into account when planning the light installation and the luminaire type (Hadwan, Carter, and Newsham 2006). This affects the visual comfort and energy savings potential, depending on the use case and the use of sensors and light bulbs (see Chen et al. 2014; Cimini et al. 2015; Wang et al. 2015b; Elia 2008). Here, luminaires and light sources need to be constructed such that they have the same advantages for the more extreme industrial environment conditions as in home and office conditions. This influences durability, performance, cost–benefit and life cycle assessment; LEDs are superior compared with traditional lighting such as fluorescent lamps (see Kaya 2009; Tähkämö et al. 2014; Preston and Woodbury 2013; Füchtenhans, Grosse, and Glock 2019b). However, in the area of data transmission with VLC, the technology has to be adapted to the industrial environment requirements to guarantee data security and performance (cf. Li et al. 2014; Pathamuthu, Kumar, and Kumar 2016).

Comparable to other application areas, some studies focused on the effects of light on employees at workplaces and during shift work (Juslèn, Verbossen, and Wouters 2007b; Lowden, Akerstedt, and Wiborn 2004). Likewise, a few papers investigated possible energy reduction in connection with daylight and different light sources as well as developments in suitable light control and sensors for industrial environment use, such as in a single floor factory or a factory building with elevators (Chen et al. 2014; Cimini et al. 2015; Elia 2008). Altogether, SLS have been studied very rarely in production and logistics, and the potential that SLS offers for industrial environments has only been discussed rudimentarily in the literature. We argue, and will show in Section 4, that SLS could lead to many benefits in the context of Industry 4.0 production networks and smart logistics (Fragapane et al. 2020; Ivanov et al. 2020; Zheng et al. 2020) as well as supply chain management using IoT systems (Ben-Daya, Hassini, and Bahroun 2019; Lee et al. 2018).

3.2.5. Summary

The literature review provided an overview of the most common SLS use cases. Many studies with various lighting systems have been undertaken, especially for offices, residential buildings and street lighting. In industrial environments, however, these systems have received little attention in the literature so far, even though there is great potential for improvement through SLS. In this area, warehouse order picking represents an example application that is well suited to discuss promising potentials of SLS, and that has not been studied in the literature yet. Therefore, the next section reflects the findings of the literature review to discuss the potential of SLS for improving the operational efficiency in order picking. The developed propositions offer an important step towards smart factories.

4. Potentials of SLS in warehouse order picking

This section draws on the knowledge of technical characteristics of SLS and the SLS applications identified in the literature review and is, in addition, supported by the results obtained in a set of expert workshops. The process diagram, listed in Appendix 1, illustrates the connection between this section and the rest of the paper. The objective is to highlight the potential of SLS in warehouse order picking and to develop propositions that point out ways to realise this potential.

4.1. Order picking in warehouses

We selected warehouse order picking as a generic example of the industrial environment, because this task is performed manually in many companies (De Koster, LeDuc, and Roodbergen 2007), and because warehouses often have large areas with zones that are either not permanently occupied or that may use daylight, which leads to use cases for sensor application. In cases where daylighting is not available in the warehouse, artificial lighting is provided. However, illumination levels are sometimes below the recommended value for manual work (Van Bommel and Van den Beld 2004) in practice, and improving light conditions may help enhance work quality. Due to different job requirements for order picker, light quality has an indirect economic impact in such a scenario, in the sense that poor visibility may induce slower operations, promote errors, and increase accident risks (Dewa, Pujawan, and Vanany 2017; Kolus, Wells, and Neumann 2018). In addition, manual order picking requires efficient routing through warehouses and a quick identification of storage locations or the tracking of pallets and transport equipment to reduce search times (Masae, Glock, and Grosse 2020). Thus, there are various potential use cases for SLS in order picking.

Order picking can be defined as the process of retrieving items from their storage locations in warehouses

(Grosse et al. 2015). These activities are essential to logistics operations and account for more than 50% of warehouse operating costs, not just because these activities are labour-intensive and time-consuming (Tompkins et al. 2010; Frazelle 2002). A typical manual order picking process can be described as follows: an order picker reads the information on a pick list or handheld device (setup), moves to the appropriate shelves (travel), searches for the required items (search), and physically picks them (pick). The design of order picking systems is characterised by the warehouse layout, the assignment of items to storage locations, and worker routing through the warehouse, among others (De Koster, Le-Duc, and Roodbergen 2007; Grosse et al. 2015; Masae, Glock, and Grosse 2020). To guarantee efficient order picking operations, managers need to consider operational costs, employees' requirements, information availability and workers safety together.

4.2. Workshop methodology

To develop propositions that reflect the practical relevance and applicability of SLS in warehouse order picking, three workshops with warehouse managers and professionals from leading companies from the lighting industry were organised. In the first session, the results of the systematic literature review were presented to and discussed with the workshop participants. The primary focus of the discussions was to gain insights into how well the technical properties of the SLS match the requirements of modern warehouses. The discussions were complemented by individual, semi-structured interviews with the workshop participants to gain insights into the specific lighting requirements of the warehouses operated by the interviewees. The semi-structured interviews and their evaluation were based on the methodology outlined in Ayres (2008) and applied according to Grosse et al. (2016). To make it easier for the interviewees to evaluate the role of SLS in warehousing, the manual warehouse order picking process was broken down into the individual steps setup, travel, search and pick (Grosse et al. 2015). Refill activities or redistribution in a warehouse follows the same steps than those just outlined and, therefore, were not considered separately. For each of these steps and considering the results of the literature review, the authors discussed in the second session with the workshop participants how the technical components of SLS as shown in Figure 3 could be used to improve order picking efficiency. As suitable efficiency measures, energy savings (Section 4.3.1), operational performance (Section 4.3.2) and worker well-being (Section 4.3.3) were proposed and agreed on in the workshops (cf. Figure 4). Based on this, we developed propositions that will be presented in Section 4.3. We used the third workshop session with the experts to discuss and validate the developed propositions. The insights presented in the following are mainly based on the results of the literature review, but were enriched by the results of the discussions and interviews with the workshop participants.

4.3. Propositions development

As a result of these workshops, Figure 4 was developed, which shows a trend for the estimated possible impact of SLS (light technology) on order picking outcomes in each process step. The rating was agreed on during discussions with the workshop participants taking into account the requirements warehouse managers defined for the order picking process as well as the technical possibilities of market-ready lighting technology. Figure 4 was used as starting point to develop the propositions that highlight the potentials of SLS in order picking and to present a systematic discussion of the identified interdependencies

	Order picking process steps			
Light technology	Setup	Travel	Search	Pick
LED	++	+++	+++	+++
Motion detection / daylight sensing	+	+++	++	+++
Building management systems	++	++	++	++
VLC	+++	+++	++	++
IPS	+	+++	+++	++
HCL	++	++	+++	+++

+++ highly relevant; ++ relevant; + limited relevant

	Order picking outcomes
Impact	Energy savings (S. 4.3.1)
	Operational performance (S. 4.3.2)
	Worker well-being (S. 4.3.3)

Figure 4. Usage potentials (relevance) and performance impact of SLS for the basic order picking process steps.

between SLS and the three efficiency measures. The design and management of order picking are linked in many areas to SLS with various impacts on efficiency. SLS may influence order picking in different ways and with various impacts. The discussed propositions may be seen as examples and, therefore, should illustrate the versatile opportunities that SLS integration into order picking design and management offers. In addition, the propositions outline research opportunities and implementation guidelines for practitioners.

4.3.1. Energy savings

Proposition 1: SLS may lead to substantial energy savings in warehouses

In most warehouses, large surfaces have to be illuminated. In a survey of warehouses, Baker and Perotti (2008) observed warehouse sizes between 144 m^2 and 76,600 m^2. Fifty-eight percent of the surveyed warehouses were larger than 10,000 m^2. SLS require the replacement of traditional light sources with LEDs and offer tremendous potential for reducing energy expenses in such facilities. Therefore, retrofitting conventional lighting with LEDs can lead to energy savings of more than 50%, and depending on the initial situation, with payback periods of less than three years (cf. Wang, Liu, and Yang 2018; Füchtenhans et al. 2019c). Using LED technology in warehouses may help reduce energy consumption during all steps of the order picking process.

In addition to using LEDs, SLS may further contribute to reducing energy usage in warehouses by means of daylight and motion sensing integrated into building management systems (see Section 3.1.2). Artificial light control that considers available daylight has been discussed in the office and residential building context for several years. However, practical light control is often based on simple switch on and off due to a lack of knowledge of how to manage light control systems appropriately and due to the sometimes high investment costs associated with SLS. With respect to the latter aspect, calculating the SLS payback period is sometimes difficult due to an inaccurate estimate of the lighting system's energy benefits (Aghemo, Blaso, and Pellegrino 2014). Consequently, the large energy saving potential of controllable lighting systems are often not exploited, and lights are switched on and spaces are unnecessarily illuminated during working hours. Many warehouses admit daylight via windows in the facility's outer walls or ceiling. During sunshine hours, light control may then reduce the artificial light intensity to save additional energy. Depending on the warehouse layout and the location of windows, daylight sensors may support all steps of the order picking process. A case study with a 3,500 m^2 warehouse and possible use of daylight in certain areas reported energy savings of around 80%, based on a 1:1 replacement of fluorescent lamps with LEDs and on using daylight and motion sensors (Füchtenhans et al. 2019c).

Another warehouse attribute that managers could exploit is that during operating hours, large zones are often not permanently occupied by workers. While completing pick lists, order pickers travel through the warehouse to retrieve requested items from storage locations. In warehouses that employ few workers, especially aisles that contain infrequently requested items are empty from time to time, such that fully illuminating them is unnecessary. Warehouse managers could employ motion sensors to identify aisles that are unoccupied, and then either switch off or dim lighting in these aisles as long as they are empty (Füchtenhans et al. 2019c). Given that setup steps are usually completed at a depot that is highly frequented by warehouse workers, motion sensors offer potential for reducing energy consumption, especially in picking aisles, and thus mainly support the travel, search and pick steps.

Proposition 2: SLS may influence warehouse processes

As mentioned earlier, a typical order picking process consists of four main steps: setup, travel, search, and pick. The sequence in which these steps are executed, and the location in the warehouse where they take place, depend on how items are assigned to the warehouse storage locations, how orders are batched (restructured), and how the picker is routed through the warehouse. We pointed out in Proposition 1 that lightly frequented zones or aisles are typical for order picking warehouses; the usage of aisles is, however, subject to management control. Warehouse managers could, for example, assign frequently requested items to zones close to the warehouse depot to intentionally generate areas where order pickers work most of the time; areas that are less frequented may then benefit from motion sensors and reduced light intensities during times of disuse. Similarly, managers could decide to restructure (batch) incoming orders and assign picks in close proximity to a single order picker to reduce worker travel distances in aisles where no items need to be retrieved (the literature refers to 'proximity batching' in this context, see Cergibozan and Tasan (2019)). Finally, managers could also decide to route order pickers in a way that maximises the use of certain aisles, while leaving other aisles unoccupied for longer time intervals. This could be achieved by considering energy costs in the objective function of the routing problem under the functional constraints of SLS (we refer the reader to the work of Goeke and Schneider (2019), who showed that in cases where multiple order pickers work simultaneously in a warehouse, there is potential for overlaying order picking tours to maximise the parallel use of certain aisles, while leaving other aisles empty for longer time periods);

the light intensity in such aisles could then be reduced. We note, however, that generating aisles or zones in a warehouse that are less frequented to save energy may lead to longer order picking tours, which may increase labour cost for the warehouse workers. Therefore, processes should not be modified by considering energy costs in isolation. Given that storage assignment, batching and picker routing mainly influence the pick locations and worker travel, we argue that these two process steps are most influenced by SLS.

4.3.2. Operational performance

Proposition 3: SLS may reduce order picking errors

Pick errors are often a significant problem in warehousing practice, and they are a major source of low service levels. Pick errors include both the picking of wrong items, the picking of an incorrect number of items, or the skipping of items on the picklist. One source of pick errors may be poor lighting conditions that make reading item information difficult, either from a paper pick list, a mobile device, the shelves or the items themselves (Veitch, Stokkermans, and Newsham 2013; Dewa, Pujawan, and Vanany 2017; Kolus, Wells, and Neumann 2018; Stockinger et al. 2020). Despite adjusting the way information is presented to the workers (e.g. by increasing font sizes), warehouse managers can provide an appropriate lighting level to order pickers to reduce reading mistakes. In country-specific workplace regulations, lighting requirements are often relatively low. Within the technical workplace regulation in Germany, for example, the minimum illumination for warehouses ranges from 50 to 300 lux, depending on the work area. In warehouses with reading tasks, such as in the search and pick steps in order picking, only 200 lux are required, although it should actually be three to four times higher to ensure clear reading (BAUA 2020). The quality of lighting depends on several aspects, such as mounting height, luminaire spacing, lighting angle, and surface properties (Yoomak and Ngaopitakkul 2018). SLS have advantages in this respect, first because they can offer a higher lighting intensity than traditional light sources and second because they may provide individual lighting zones where the lighting intensity is adjusted to the worker's needs. While SLS may not be able to reduce pick errors completely (other pick error sources, such as incorrect labelling, are not affected by lighting), they may help reduce them. SLS support error reduction especially during the search for items and during the pick; the setup is often performed at a well-illuminated depot, and errors during travel (such as entering the wrong aisle) are often not caused by low lighting levels, but instead result from other factors (such as blocked aisle entrances or a lack of concentration).

Proposition 4: SLS may reduce search times

Prior order picking research has shown that misplaced items or transport equipment often disrupt order picking processes. Order pickers arriving at a pick location often find out that items or entire pallets are not located where they should be, or upon return to the depot they discover that trolleys or carts they need for their next tour are missing. The workers then have to search for the items or devices, jeopardising the efficiency of the order picking process (Glock et al. 2017). One issue that contributes to this problem is that the position of objects is difficult to track in a warehouse environment. A GPS signal can usually not be used for indoor applications, and other IPS require the installation of equipment (e.g. Bluetooth transmitters) the company may consider too costly. VLC-based IPS have the advantage that the transmitters are automatically installed together with the lighting system; the tracking of object positions then requires only additional receivers. While tracking the position of all items stored in a warehouse may be too costly, this technology could at least support the tracking of pallets and transport equipment to reduce search times. The setup and search steps may especially benefit from this kind of support, as extended search times most often occur during these two process steps.

Proposition 5: SLS facilitate the implementation of optimal order picking policies

One stream of research in order picking focuses on the development of optimal order picker routing policies (see Masae, Glock, and Grosse 2020). Given a certain number of items that need to be picked, solution methods developed in this research stream find the shortest tour that starts at the depot, visits all pick locations, and then returns to the depot. While simple routing heuristics lead to routing patterns that may be similar for subsequent orders and that are usually easy to memorise (albeit at the expense of longer travel distances), optimal routes may differ quite substantially from order to order. Prior research has therefore discovered that order pickers may find optimal routes confusing, inducing them to deviate from these routes (Glock et al. 2017; Elbert et al. 2017; Gademann and Velde 2005). To make it easier for order pickers to correctly execute order picking tours, warehouses can use handheld devices for communicating the tours to the order pickers. These devices make it necessary to track the position of the order pickers in the warehouse and could hence benefit from the indoor positioning ability SLS offers.

A further process that may benefit from SLS is the real-time (online) updating of orders. Especially in an e-commerce application, where small orders arrive frequently during the working day, adding another order to an order picking tour that is in progress at the time the order arrives may help improve warehouse throughput. If an order picker that is currently travelling through the warehouse passes through a region of the warehouse where an item requested in a new order is stored, it may make sense to ask this order picker to collect this item on his/her current tour instead of starting a separate tour for the new order. Earlier research has proposed methods that compute optimal updated tours (e.g. Masae, Glock, and Vichitkunakorn 2020b), but they again require that the system knows the position of the order picker at the time of the update. The applied technology also allows other warehouse operations, such as refill or redistribution activities, to be scheduled in a way that fewer disruptions or delays occur. Again, VLC-based IPS may reduce the barriers for implementing such methods. Since picker routing mainly influences the travel step, we argue that this step benefits the most from VLC-based IPS and the use of optimal order picking tours.

Proposition 6: SLS improve warehouse data transmission and collection

As mentioned previously, SLS offer the opportunity to transmit data using the VLC concept. In warehouses, workers often use handheld devices that provide information on travel directions, item locations and required item quantities. If the required information can be sent to the devices wirelessly without having to connect them to a docking station, the setup step is shortened and the entire order picking process becomes more efficient. In a warehouse environment, some wireless data transmission technologies (such as RF technologies like Wi-Fi and Bluetooth) may be prone to errors due to physical barriers and frequency interference with other signals on a similar bandwidth (cf. Section 3.1.4). VLC is not subject to such effects and can transmit signals error-free as long as light reaches the device's photodiode. Since the signal transmission between transmitter and receiver can only take place in the line of sight, VLC also offers a high degree of data protection, whereby depending on the data protection level, data transmission can only be given in specific areas. While the entire order picking process benefits from information availability, we see potential especially in shortening the setup step, eliminating the need for handheld synchronisation.

In addition to transmitting data, VLC-based IPS can also collect anonymized position and motion data in the warehouse. This enables warehouse managers to produce heatmaps that support analysing the use of aisles over time. If aisles are frequently congested (the literature refers to 'picker blocking' when multiple order pickers work in the same aisle, see Hong, Johnson, and Peters (2012). Picker blocking may slow down the order picking process when workers cannot pass each other within an aisle or when a shelf a worker wants to access is blocked by another order picker), managers may use this information to relocate items within the warehouse, or combine it with (anonymized) position data of order pickers through IPS to change routes to reduce congestion. The travel and pick steps, especially, would benefit from this type of support. In addition, this information could be used to verify if the demand structure has changed, and if a storage reassignment is necessary to maintain an ABC assignment structure.

4.3.3. Worker well-being

Proposition 7: SLS improve warehouse worker well-being

In many warehouses, only some parts are (mainly) illuminated by daylight, and warehouses that do not admit daylight at all are also common in practice. In the e-commerce sector, where companies usually promise short delivery times, warehouses often operate using shift models. Artificial light influences worker well-being in such environments. Compared to traditional lighting systems, SLS with LEDs may adjust light wavelengths and colour temperatures with narrow bands and control light spectrum and intensity (see Section 3.1.6), and they also offer the opportunity to establish individual lighting zones that adapt the provided light to worker needs. Light can thus be used to stimulate the workers' circadian rhythms and influence their mood, motivation and productivity (Boyce 2014; Van Bommel and Van den Beld 2004). In an order picking context, which is characterised by a combination of physically and mentally exhausting work, this could translate into generally improved worker productivity and higher concentration during the search and pick process, leading to fewer errors; it can also help prevent sickness and accidents during travelling and picking. All steps of the order picking process may benefit from improved worker well-being; search and pick benefit from lower error rates, and travel and pick benefit from reduced injury risk.

5. Conclusion

Lighting is omnipresent in private and working life. Technical developments have made lighting smart, with many different use cases and application areas discussed in the literature. The contribution of this paper is twofold. In the first part, an extensive literature review was conducted to describe the state-of-the-art of SLS technologies and application areas, which pointed towards a clear research gap in considering SLS in industrial environments. In the second step, warehouse order picking was selected as a generic example that has not been studied so far to identify possible use cases of SLS. Based on the insights obtained from the literature review and by mapping SLS with the processes of warehouse order picking, we developed propositions that highlight the potentials of SLS in this area. In each proposition, we discussed how SLS can be used in the order picking process steps and how they may affect the order picking performance indicators energy consumption, operational performance and worker well-being. We discussed and validated the obtained propositions within workshops with warehouse experts from industry and professionals from leading companies of the lighting industry. While the propositions formulated in this paper were developed for a warehouse order picking scenario, they may be transferred to other areas from the production and logistics domain, such as assembly lines or quality control. For these areas some of the propositions may hold and, in addition, they could open up further benefits of SLS in industrial environments.

The developed propositions offer manifold opportunities for future research and illustrate the advantages of SLS that go beyond energy efficiency. For example, comprehensive network systems that use VLC and IPS and the integration of SLS into building management systems can provide improved data availability and anonymous location data. Data collected by these systems could be used in simulation studies and optimisation models to identify bottlenecks (in terms of picker congestion) and to improve warehouse layouts, picker routes, storage assignments and batching strategies. Case studies could investigate energy savings in industrial environments resulting from retrofitting measures from conventional lighting to LEDs with different light control strategies. By adding energy costs to the objective function of mathematical models for order picking, and considering the functional constraints of SLS, future research could develop new order picking planning models.

Based on the existing HCL literature, field studies could investigate the visual and non-visual effects of light on the well-being and productivity of order pickers. Further aspects to be investigated are how improved light quality and individual lighting zones increase concentration and attention and reduce fatigue during the search and pick processes, and how they can help prevent pick errors and accidents during the pick process. In addition, SLS life cycle analyses and payback periods are decisive factors that should be considered in future investigations to support managerial decision-making. Therefore, practitioners, managers and researchers can use the propositions presented in this paper as guidance for considering SLS in future work.

Due to the large number of publications and the broad research interest from many different disciplines, our paper has some limitations. It was not possible, and it was also not our intention, to discuss the strengths and weaknesses of all individual lighting technologies or to look closely at the technical details of the individual systems. Disadvantages were only discussed to a limited extent in this paper, as they mainly consist in investment costs, greater efforts for implementation and overall maintenance requirements due to more complex technologies. However, these disadvantages are negligible on an operational level. Since we present and discuss mainly the potentials of SLS on the operations of warehouse order picking processes, these disadvantages can be seen as a starting point for further research opportunities, for example by analysing the maintenance requirements for different technologies depending on the use case. Given the broad variety of purposes SLS could be used for, it is not easy to estimate the investment cost associated with such systems, or the cost savings resulting from their use. Costs vary from case to case depending on the users' behaviours, the application scenario and the exact system type used. For example, based on the discussions in the expert workshop, we estimated the return period of a simple SLS for a warehouse with 7500 m^2 and an annual lighting duration of 7000 h. Assuming that LEDs, and motion and daylight sensors need to be installed, and considering maintenance costs, a return period between 5 and 6 years was assessed realistic.

We also note that lighting in production and logistics facilities is a complex topic, where suggestions usually depend on the specific use case. For this reason, we considered the order picking process as a generic example, with the understanding that other industrial environment use cases (such as assembly) have their own standards and requirements. The insights into SLS synthesised in this review and discussed in the order picking example can serve as a starting point for the further integration of SLS into industrial contexts and for utilising the various advantages these systems offer.

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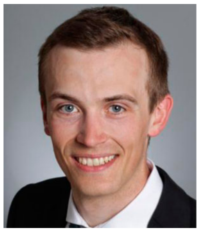

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Appendix

Appendix 1. Process diagram showing the structure of the paper and the methodologies used in the different sections