Using smart lighting systems to reduce energy costs in warehouses: A simulation study

Abstract

Lighting influences private and working life. At the same time, it is a critical contributor to energy consumption. Although there exist manifold technical solutions for lighting to become "smart", todays lighting systems are often kept simple, and they are frequently not adjusted to the user's behaviour. This is especially the case for production and logistics facilities such as warehouses, where large areas have to be illuminated and where lighting is often fully turned on while the warehouse operates.

This paper presents a simulation model that was developed to evaluate the cost benefits that may result from using smart lighting systems in warehouses. The simulation model allows varying warehouse design and order picking process parameters, such as the length and number of aisles and cross aisles or the number of order pickers in the warehouse. In addition, three different operating strategies for the lighting system representing different degrees of "smartness" have been implemented and are compared to a conventional lighting system. A structured simulation study allows gaining insights into how smart lighting systems interact with system design and process parameters and how both, collectively, influence warehouse operating cost. The results of the simulation model and data obtained from a practical case indicate that smart lighting systems have a great potential to reduce energy consumption in warehouses compared to conventional lighting, and that they can contribute to improving the environmental footprint of warehouses above and beyond savings in cost.

Keywords: *Warehousing; Order Picking; Intelligent Lighting; Smart Lighting; Energy consumption; Energy Cost; Simulation*

1. Introduction

Warehouses are key nodes in each supply chain. Within warehouses, order picking has often been considered as a significant contributor to internal logistics costs (Tompkins et al., 2010). For some companies, especially in the e-commerce sector, it may, in fact, be one of the largest cost drivers altogether (Boysen et al., 2019). In many sectors, efficiently executing order picking processes has become a key contributor to the performance and the competitive success of companies (van Gils et al., 2018). To improve the efficiency of order picking, prior research has focused on the development of mathematical models that assign products to storage locations, that restructure customer orders into so-called batches that can then be picked in individual tours, and/or that route the order pickers through the aisles of the warehouse (see, e.g., de Koster et al., 2007). The objective of these models usually is to generate the shortest possible routes for a given set of orders, which enables the order pickers to complete the set of orders as quickly as possible (and which, simultaneously, contributes to maximizing warehouse throughput).

What has received less attention in the literature so far is that further costs (despite those directly associated with the order picker) may depend on how warehousing processes are organized. One example is the cost of lighting that may account for up to 65% of the facility's total electricity expenditures, and that are therefore a main contributor to the energy costs of a warehouse (Dhoorna and Baker, 2012; Richards, 2014). While traditional lighting systems often made it necessary to fully turn on lighting during the operating hours of the warehouse, smart lighting systems now enable companies to provide the very lighting intensity required by the warehouse order pickers. Artificial light provided in the warehouse could hence be adjusted based on the amount of daylight available in the facility or based on user preferences or the presence of the order pickers in the picking area (Yasodha et al., 2015; Liu et al., 2016). The presence of the order pickers in the warehouse, however, depends on how the warehousing processes are organized, and it is therefore subject to management control. The use of smart lighting systems could lead to a significant reduction of energy consumption and costs and may thus also contribute to a reduction of warehousing-related emissions contributing to environmental sustainability (Bartolini et al., 2019).

Commentato [E1]: Könnte man hier als Abkürzung definieren (SLS), dann sparen wir uns am Ende ein paar Zeichen…

Given that the installation of smart lighting systems often leads to high investment costs, the profitability of such systems needs to be carefully evaluated before the investment is made. In an industrial context, such an evaluation is, however, not easy because of the at times complex interactions between the lighting system's functionality and the operational processes taking place in the facility. If a warehouse manager, for example, decides to organize warehousing in a way that leads to warehouse order pickers being present in the aisles of the warehouse almost permanently, using presence sensors to adjust lighting would not lead to a substantial reduction in the required lighting energy. If order pickers would visit certain zones of the warehouse only relatively infrequently, in contrast, automatically dimming light in the affected zones during periods where order pickers are not present could contribute to lowering energy consumption and saving costs. Warehouse managers could even decide to change storage assignments, batches and picker routes to intentionally generate zones where a reduction in the lighting intensity can be beneficial to the company, even though this may affect the throughput of the warehouse. The interdependencies mentioned here have, however, not been investigated in a scientific study so far.

The purpose of the paper at hand is to investigate the cost savings potential of smart lighting systems in a warehousing context. A simulation model was implemented in the software Plant Simulation by Siemens PLM Software for the purpose of our research. The simulation model allows varying warehouse design and order picking process parameters, such as the length and number of aisles and cross aisles or the number of order pickers working in the warehouse at the same time. In addition, four different operating strategies for the lighting system have been implemented. A structured simulation study allows gaining insights into how smart lighting systems interact with system design and process parameters and how both, collectively, influence warehouse operating costs.

The next section presents a brief overview of the related literature. Section 3 further motivates this research by presenting insights on potential cost savings that may be obtained from using smart lighting systems in warehouses obtained in a case study. Section 4 then describes the simulation model, and Section 5 presents a selection of results. The paper concludes with a discussion of main insights and an outlook on future research opportunities in Section 6.

2. Literature review

Two streams of research are of relevance for the work at hand. The first one proposes methods for improving the efficiency of order picking warehouses (Section 2.1). Research in this area mainly focuses on reducing the time required to complete a single or a set of customer order(s). The second stream of research investigates the potentials of smart lighting systems, both from an energy consumption and from a user perspective (Section 2.2). Both research streams are discussed in the following and interdependencies between these two streams are highlighted in Section 2.3.

2.1. Management of manual order picking

Prior research on manual order picking mainly focused on the development of mathematical models that aim on minimizing order picking time or the distance that needs to be travelled in the warehouse to fulfil a set of customer orders. To achieve these goals, researchers developed solution approaches for the different planning problems that occur in order picking. Among the most relevant planning problems are layout design, routing, storage assignment, and batching. Layout design determines the shape of the warehouse, the number of cross aisles and picking aisles, the location of the depot, and the number and height of shelves, for example (Caron et al., 2000; Roodbergen and Vis, 2015). Routing aims on finding the shortest route through the warehouse for completing a set of customer orders (e.g., Scholz et al., 2016; Celik and Süral, 2019; Hwang et al., 2004). Storage assignment deals with the allocation of items to the storage locations of the warehouse, taking into account customer demand, volume, or item weight (e.g., Reyes et al., 2019). The storage assignment can be random, such that items are assigned to the closest open location (Petersen and Aase, 2004), for example, or it reserve dedicated locations for the items to be stored, and allocate items to storage locations based on item features such as demand frequency (Li et al., 2016). Some models also considered the correlation of item demands in assigning items to shelf locations (in this case, items that are frequently ordered together should be stored next to each other; see Glock and Grosse (2012), for example). Finally, batching determines whether customer orders should be recombined to form orders that can be picked more efficiently (e.g., Grosse et al., 2014; Zulj et al., 2018).

Recent research on manual order picking has combined some of the above-mentioned planning problems (see, for a review, van Gils et al., 2019), included human factors in order picking models to improve both performance and human well-being (e.g. Grosse et al., 2015; Glock et al., 2019), or considered the implications of digitization on order picking performance (e.g., Hanson et al., 2017; Winkelhaus and Grosse, 2019). Although most researchers developed mathematical optimization models to solve the described planning problems, simulation models have also been quite popular in order picking research. Simulation studies were conducted to gain insights into the impact of picker blocking on warehousing performance (Heath et al., 2013; Franzke et al., 2017), to study the effect of different warehouse design and process parameters on order picking performance (Hwang and Cho, 2006), or to compare the performance of different goods-to-person order picking systems, for example systems using automated guided vehicles (Bozer and Aldarondo, 2018). For a more detailed overview of the literature on order picking, we refer to the reviews of de Koster et al. (2007) and Boysen et al. (2019).

Interdependencies that exist between the above-mentioned planning problems and smart lighting systems are discussed in Section 2.3.

2.2. Characteristics of smart lighting systems

In most warehouse applications, lights are switched on when work begins and spaces are often unnecessarily illuminated, e.g. during breaks (Park et al., 2015). Smart lighting systems that adjust the intensity of artificial light to the user's behaviour or available sunlight can lead to substantial energy savings in such applications, contributing to environmentally friendly warehousing processes (cf. Bartolini et al., 2019). One basic building block of most smart lighting systems are light emitting diodes (LEDs) that have different advantages for many lighting applications (Shur and Žukauskas, 2011). One key advantage of LEDs, as compared to traditional lighting systems, is their high luminous efficiency with up to 200 lm/W in industrial applications. In comparison, incandescent bulbs have approx. 15 lm/W and fluorescent lamps approx. 100 lm/W. In addition, LEDs have a long lifespan ranging from 50,000 to over 100,000 hours (Chang et al., 2015; Schratz et al., 2013), provide the possibility to customize spectral power distribution, provide fast modulation rates, and are robust and stable independent of the amount of shifting (Shur and Žukauskas, 2011). The electrical control of LEDs and the opportunity for networked lighting systems can make traditional lighting 'smart'. Basically, smart lighting systems are based on the intelligent interplay of light sources, sensors and external influences (such as daylight and the behaviour of the users), which becomes a closed system through regulation (Chew et al., 2017). These systems are energy efficient and can be adapted to complex and changing situations as needed.

Sensor-based lighting provides the possibility to reduce energy consumption based on motion or daylight sensing, prevents energy waste and increases visual comfort. These sensors enable the system to switch off or dim lights to a lower level if no motion is detected for a predefined time or sufficient sunlight is available, which saves energy (Chung and Burnett, 2009; Chun et al., 2015). A lot of scientific research investigated the potential energy savings resulting from motion, occupancy and daylight sensing in office or street lighting (e.g., De Bakker et al., 2018; Leccese, 2013; Chun et al., 2015). In these applications, the literature reports a wide range of energy savings resulting from the use of smart lighting systems. Through the combined use of daylight and occupancy sensors, average energy savings ranging from 13% (Higuera et al., 2015) to 73.2% (Nagy et al., 2016) that can be achieved compared to traditional lighting systems have been reported. It is important to note that these savings depend on occupant usage patterns and other external factors (von Neida et al., 2001).

Further benefits of smart lighting systems in industrial settings that extend beyond energy savings are discussed in Füchtenhans et al. (2019).

2.3. Smart lighting systems in warehouses

Given the vast amount of research on smart lighting systems in home or office applications, it is surprising that these systems have not attracted much attention in the industrial engineering literature so far. There are a few notable exceptions though. Chen et al (2014) investigated energy savings that may result from a combination of artificial lighting controls combined with daylighting in considering of the heating energy consumption in an industrial building. They reported electricity saving potentials for an On/Off control of around 36.1 % and by a dimming controller of around 41.5 %. A new method for designing a lighting control system for industrial buildings was presented by Wang et al. (2015). Tähkämö et al. (2014) analyzed the environmental impacts of an entire fluorescent luminaire combination in an industrial context via a life cycle assessment. The result show that the energy consumption is the dominant factor regarding all other environmental impacts. The benefits of smart lighting systems in a warehousing context have, however, not been investigated at all so far.

Commentato [CG2]: Würde es Sinn machen, für diese Quelle noch in einem Satz zu sagen, auf was für Energieeinsparungen die gekommen sind? Das haben wir oben ja für Office und Street Lighting gemacht. Oder ist deren Untersuchung zu weit vom Thema weg?

Commentato [M3R2]: Erweitert.

Commentato [CG4]: Mir ist nicht ganz klar, was hier konkret gemeint ist.

Commentato [M5R4]: Somit besser verständlich?

The potential of smart lighting systems to reduce energy consumption depends, among other factors, on how the planning problems discussed in Section 2.1 are solved. The decision on the specific type of the lighting system to use, as well the mounting height and spacing of the luminaire can be combined with layout design. Motion detectors and daylight sensors can facilitate setting up individual lighting zones for each order picker or aisle-specific lighting

Commentato [CG6]: Höhe und Tiefe wovon? Bezieht sich das auf die Abmessungen des Lagers? Das ist m.E. im Layout Design abgedeckt. Oder geht es um die Positionierung der Leuchtmittel?

Commentato [M7R6]: Bezieht sich auf die Positionierung der Leuchtmittel levels, and this functionality can be considered in storage assignment and batching decisions. Warehouse managers could, for example, decide which areas or aisles should be fully illuminated (e.g., the fast-moving zone near the depot), and which zones should only be illuminated when order pickers are present (e.g., the slow-moving area).

Beside the visual and non-visual effects of light, smart lighting systems enable wireless network access due to the visible light communication (VLC) technology (Karunatilaka et al., 2015). A potential use case for VLC arises in order picking warehouses where handhelds can receive data in predefined areas via the VLC technology. Closely linked are VLC-based indoor positioning systems (IPS) that enable the localization of objects or people in buildings comparable to GPS-based positioning in outdoor environments (Sharma et al., 2018; Karunatilaka et al., 2015). This functionality enables to define activity zones around order pickers and to tailor lighting towards the order pickers' need by simultaneous data transmission.

Some of the features of smart lighting systems discussed above are considered in the simulation model proposed in the next section.

3. Case study

To further motivate the research at hand, we present a short case study that exemplifies a successful implementation of a smart lighting system and that highlights the benefits obtained for the company. The case study data was collected at an Italian company that produces brass valves for the water and gas sector. The facility of the company occupies an area of 4,300 m^2, with 800 m^2 devoted to production and assembly (including offices), and 3,500 m^2 to warehouse space. The warehouse has a rectangular shape of approx. 75 m x 45 m and is arranged with parallel aisles of pallet racks (see Figure 1), where picking is manually performed. In the production and assembly department, the activities are usually organized in three shifts of eight hours per day and for five days per week, while the warehouse operations run in two shifts of eight hours per day and for five days per week.

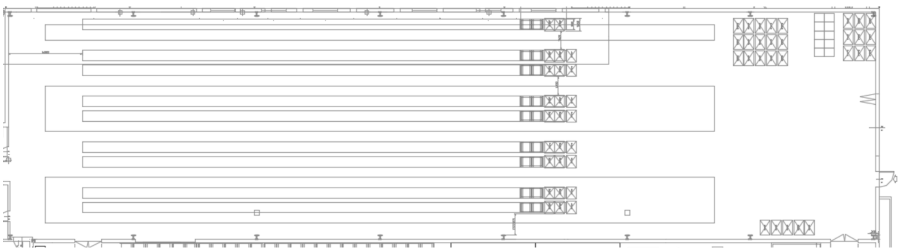

Figure 1: Layout of the warehouse considered in the case study

After an extensive energy audit that included all areas/facilities and activities of the company, it was found that energy consumption resulting from lighting is responsible for up to 30% of the total energy requirement of the facility. Therefore, the company decided to improve the lighting infrastructure due to its significant impacts on costs. In addition, the company was aware of the impact good lighting conditions have on the quality of work and on the well-being of order pickers, which was seen as an additional benefit of the new lighting infrastructure.

Initially, the company had operated fluorescent lamps in the production and assembly areas and metal-halide lamps in the warehouse. The modification of the lighting system was planned by referring to the EN standard 12464-1. The initial phase involved a survey and an analysis of the lighting devices currently installed to realize, where possible, a 1:1 replacement with new lamps to keep the cost of implementing the new infrastructure low (this is often referred to as retrofitting). During the re-design phase, the objective was to reuse the existing positions of the lamps even if the whole installation needed to be adapted in order to meet the technical regulations of lighting requirements with a careful consideration on an energy efficient solution. In the warehouse area, lamps were installed on a plain grid with no difference made between the different areas of the warehouse (racks, aisles etc.) since the lamp configuration had been defined before the actual warehouse arrangement. An area-by-area project was conducted taking into account different constraints as each area required different lighting levels according to different levels of visual tasks conducted in accordance to the EN standard 12464-1. A smart lighting system consisting of daylight sensors and motion detectors was installed to ensure an appropriate automation of the lighting system and its proper adjustment to the required lighting levels while considering different natural light components. The system thus makes it possible to adjust the lighting level of entire aisles to their usage: if an order picker works in the aisle, the light is fully switched on, and otherwise the lighting intensity is reduced.

Commentato [CG8]: Das verstehe ich nicht ganz.

Commentato [M9R8]: Ist es so deutlicher?

After the installation of the smart lighting system, the company collected data for 12 months to assess the benefits of the system. The results were significant in terms of reduced energy consumption. Consumption for lighting, in the final electricity balance, decreased by around 60% in the production and assembly areas, and by 80% in the warehouse. Actual data on energy consumption (in kWh) before and after the installation of the smart lighting system of the two areas are shown in Figures 2 and 3. As can be seen, in particular for the warehouse, daylight sensing, for example, guarantees greater savings during summer periods. The installation of the smart lighting system improved the lighting quality of approx. 50 lux in the aisles of the warehouse (at the floor level) and approx. 80 lux for workstations (at the working surfaces level). The total cost of the modification was approx. 18,000 € (2,500 € per kW of installed lighting power). The payback of the investment was 1.1 years for the production and assembly area and 1.9 years for the warehouse. Due to the benefits achieved from installing the smart lighting system, the company plans to install a related system also in outside areas devoted to parking and walkways.

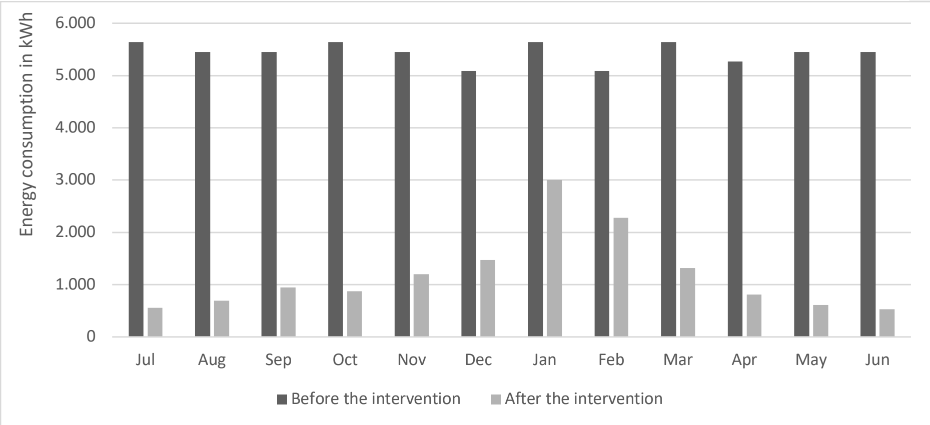

Figure 2: Lighting energy consumption [kWh] in the warehouse

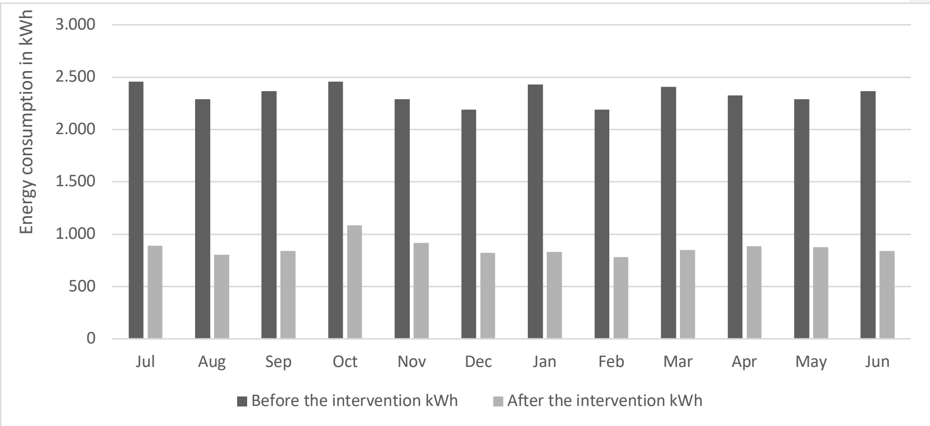

Figure 3: Lighting energy consumption [kWh] in the production and office area

The results obtained in the case study were considered, where possible, in developing a simulation model for assessing the benefits of smart lighting systems in warehouses. The simulation model is described in more detail in the next section.

4. The simulation model

Simulation is a powerful tool for analysing different design alternatives or control strategies with practical feedback for real-world systems. It allows evaluating the correctness and efficiency of a design or control strategy before the system is actually established or in operation. Simulation models are therefore often used to determine the performance of warehouses under different layouts and operating policies to evaluate processes (Verriet et al., 2013). The simulation model developed for the purpose of this research aims on assessing the energy savings potential of smart lighting systems in warehouses for different warehouse sizes and operating policies. We assume a conventional, rectangular warehouse with parallel aisles and multiple blocks (illustrated in Figure 1), as this is the warehouse layout that has most frequently been analysed in the literature (e.g., Masae et al., In Press) and that can also very frequently be observed in practice. The dimensions of the warehouse (number of shelves and levels per shelf, width of the aisles, height of the shelves etc.) and several process parameters can flexibly be adjusted in the simulation model. Based on the selected warehouse dimensions, the simulation model determines the number of storage locations and the consequent number of items stored in the warehouse. We consider three different lighting strategies (b-d) for evaluating the benefits of smart lighting systems and compare these strategies to a conventional lighting system (a):

a) Conventional lighting (CL): This strategy assumes that all aisles (picking aisles and cross aisles) of the warehouse are fully illuminated while the warehouse operates, regardless of whether or not the aisles are occupied. This strategy works with traditional light sources (fluorescent lamps) that are still frequently used in warehouses (Ries et al., 2017).

b) *LED lighting* (LED): This strategy is identical to the CL strategy except for the fact that light emitting diodes (LEDs) are used, which are considered the basic technology for every modern lighting system.

c) *Sensor-based lighting with cross aisles fully illuminated* (SFI): Picking aisles are only fully lighted while an order picker works in an aisle; aisles that are empty are operated at 20% of the regular lighting intensity. For this, motion detectors are installed in picking aisles which enable that cross aisles used by the order pickers for travelling from one picking aisle to the next are always fully illuminated. This lighting strategy corresponds to the one implemented at the case warehouse described in Section 3, and it is illustrated in Figure 4a.

d) *Sensor-based lighting with activity zone* (SAZ): Here, an IPS enables that the lighting system tracks the warehouse order pickers and fully illuminates individual activity zones with a radius of 10 m around the order picker; all areas of the warehouse not covered by an activity zone are again operated at 20% of the regular lighting intensity. This lighting strategy is illustrated in Figure 4b. The implementation of the smart lighting strategies (c) and (d) is realized using LED light sources.

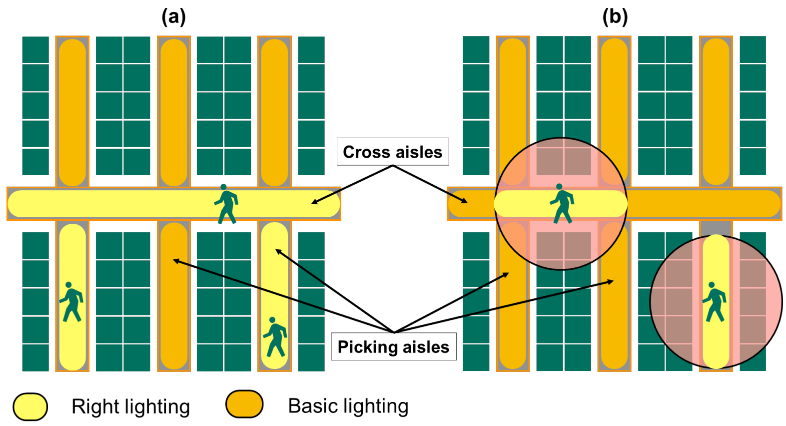

Figure 4: Sensor-based lighting systems considered in the simulation model (left: SFI, right: SAZ)

Orders arriving at the warehouse are assumed to consist of 20 items each (see Pan and Wu (2011) and Franzke et al. (2016) for a similar assumption). The demand for the items stored in the warehouse is assumed to be either Pareto or uniformly distributed. To evaluate the performance of the four lighting strategies for alternative warehouse operating policies, we implemented the following managerial decisions into the simulation model:

a) *Storage assignment*: Assigning items to the storage locations of the warehouse according to a particular pattern may generate zones in the warehouse that are more frequently visited by the warehouse order picker than others, which may make it beneficial to reduce the lighting intensity in less frequented zones. We consider two different storage assignments, namely I) random storage and II) demand-based storage. If the random storage policy is used, items are assigned randomly to storage locations in the warehouse. If the demand-based storage policy is used instead, then frequently-requested items are stored in close proximity of the depot, and items that are requested only infrequently are assigned to storage locations farther away from the depot.

b) *Pick policy:* We implemented two different pick policies, namely pick-by-order and pick-by-batch. If the pick-by-order policy is selected, each order arriving at the warehouse is assigned to an order picker, who then collects all items contained in the order. If the pick-by-batch policy is used instead, then batches are generated from the available orders according to their distance from the depot. The latter policy entails that order pickers work only in specific zones of the warehouse, and it avoids cases where (many) order pickers have to travel through large parts of the warehouse. If orders are batched, then picks in different areas of the warehouse are combined in an order to generate activity zones where ideally only a single order picker works. This may help to concentrate the activity of order pickers into specific zones of the warehouse, whereby each order picker only needs to traverse a smaller area. This could enable the system to reduce the lighting intensity due to a shorter overall working time. Figure 5 illustrate a warehouse that is divided into zones and each zone is assigned to an order picker.

Commentato [M10]: Batching erläutert + Abbildung

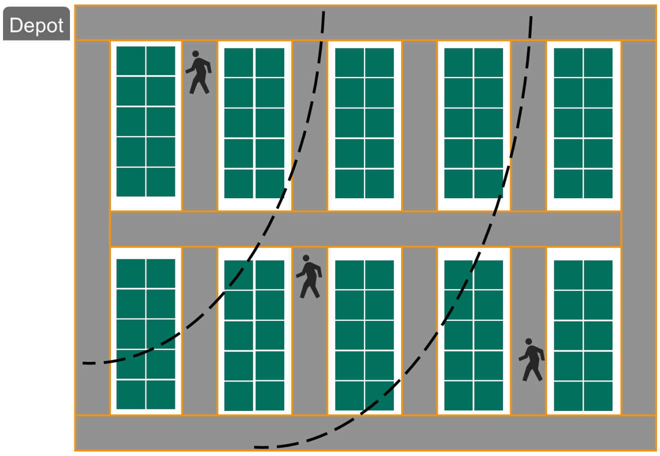

Figure 5: Warehouse divided into three zones with three assigned order picker

c) *Number of order pickers*: If several order pickers work in the warehouse in parallel, this could lead to situations where there is work activity in several aisles at the same time, such that the light intensity can be reduced only in a few aisles. We therefore consider the case where multiple order pickers work in parallel in the warehouse.

Table 1 summarize all simulation parameters and their respective attributes/values considered in this study, leading to a total of 72 combinations (scenarios) that are analysed to evaluate the influence of the different lighting strategies on energy cost.

Simulation Parameters	**Attributes/Values**
Storage assignment	Random storage / demand-based storage
Pick policy	Pick-by-order / pick-by-batch
Number of order pickers	1, 3, 5
Order size per order picker	20

Warehouse size	Small / Medium / Large
Demand structure	Pareto distribution / uniform distribution

Table 1: Simulation parameters used in this study

The three warehouse sizes are further specified in Table 2. We use the same warehouse layout for all simulation runs, namely a warehouse with a rectangular shape and multiple blocks with the depot in the upper left corner of the warehouse next to the first picking aisle.

	Small	**Medium**	**Large**
Number of shelves	16	30	80
Number of shelf levels	4	5	6
Number of cross aisles	2	3	5
Number of picking aisles	8	15	40
Number of products (storage locations)	1280	3000	9600
Area in the picking aisles to be illuminated (in m²)	392	728	1936

Table 2: Warehouse size and layout parameters used in the simulation study

Table 3 summarizes the parameters assumed in the simulation study that are fixed for every scenario. An extensive number of runs was made to validate the model and ensure that it works according to the assumptions and descriptions stated in this section. We discussed the simulation model, its results as well as the underlying assumptions and parameters (in particular those summarized in Table 3) with warehouse experts from industry in three workshops to ensure the practical applicability of the model. The experts agreed with the overall setup of the simulation model and only minor changes were proposed and included in the final version of the simulation model (e.g., the number of products in relation to warehouse size).

Warehouse parameters	**Description**
Picking and cross aisle width	2m
Height, length, width of every shelf	6m high, 20m long, 1m deep
Average walking speed of order pickers	1 m/s

Expected value of the picking time	10s (on the first level), + 15s (other levels)
Standard deviation of the picking time	2.5s (on the first level), + 5s (other levels)
Lighting parameters	
Electricity consumption (regular light intensity)	7 W/m^2 for CL, 4 W/m^2 for LED, SFI, SAZ
Light intensity in empty aisles	20% of regular light intensity
Electricity costs	0.18 EUR/kWh
Illumination radius	10m

Table 3: Parameters assumed in the simulation experiment

The routing policy employed in this simulation study works as follows: Upon receipt of an order, the order picker travels to the item with the longest distanced from the depot contained on the pick list. The picker then continues to the item with the second longest distance from the depot and proceeds in this fashion until the last item on the pick list has been retrieved. Each tour starts and ends at the depot. The simulation model automatically selects the shortest route between any two picks or between a pick and the depot.

Obviously, there are interdependencies between the managerial decisions implemented in the simulation model that are investigated in more detail in Section 5. To evaluate the performance of the four lighting systems defined above, we track the following three performance measures during our simulation runs: I) electricity usage in kWh, II) electricity cost in €, and III) the time required by the order picker(s) to complete the given set of orders.

At the beginning of each simulation run, 20 picklists are assigned to each order picker considered in that run. We assume that in case an order picker finishes all picklists assigned to him/her ahead of other order pickers, he/she does not support the others. This way, the number of active order pickers in the warehouse decreases towards the end of every simulation run, and the simulation terminates when the last order picker has completed all 20 picklists. The simulation model was implemented in the software Plant Simulation by Siemens PLM Software and run on an Intel Core i5-6300HQ CPU with 2.30 GHz and 16 GB RAM.

After verifying that the simulation works as intended, experiments were performed to operationally validate the simulation. Subsequently, the simulation was run to gain insight into how the managerial decisions defined above influence the energy consumption of the different lighting systems. As mentioned earlier, the conceptual simulation model and all parameter values used during the simulation were primarily validated in discussions with warehouse experts in workshops on smart lighting systems.

Commentato [SZ11]: Please explain these numerical values…. instead of W/m^2 as lighting parameter we should have illumination requirement (unit of measure lux) and then after a proper lighting project we can evaluate the W/m^2

in the introduction you mentioned that for LED in industrial application we can have up to 200 lm/W, thus if we mention 7W/m2 this is theoretically equal to an illumination level of 1400 lux …. But I suppose in warehouse we can keep 300 lux

moreover in the industrial case mentioned the starting case was approximately CL= 5 W/m^2 LED= 2 W/m^2

Commentato [SZ12]: is this an arbitrary value or are there any prescription? E.g. for safety reasons

Commentato [SZ13]: What is it?

Commentato [CG14]: In der aktuellen Ergebnisdarstellung stellen wir aktuell eigentlich nur den Energieverbrauch dar, wenngleich wir auch einige Male von Kosten sprechen. Vielleicht kann man auch die anderen beiden Performancegrößen noch aufgreifen? Am Ende der Simulation wäre sicher eine Art Amortisationsrechnung/Diskussion zum Konkreten Kosten-Nutzen-Verhältnis hilfreich, und da könnten wir die Größen II und III dann auch brauchen.

Commentato [E15]: Ist III) Zeit auch in den Ergebnissen aufgegriffen?

5. Results

Within this simulation study, we analyze the influence of different parameters and their respective attributes/values to energy consumption, relating costs and working time. In the following, the results are described during a systematic analysis across all characteristics. In the first part, the impacts of different warehouse sizes and storage assignments (Section 5.1) are considered. Section 5.2 shows the difference due to different number of order picker, following by an analysis of observed pick policies (Section 5.3). Following this, the impacts of the demand distribution will be considered in Section 5.4 and the final section 5.5 observed the average energy savings across all scenarios with consideration of the correlation of working time and energy consumption.

5.1. The impact of warehouse size and storage assignment

We start with studying the influence of different warehouse sizes and different storage assignments on energy consumption. We first assume that only a single order picker works in the warehouse.

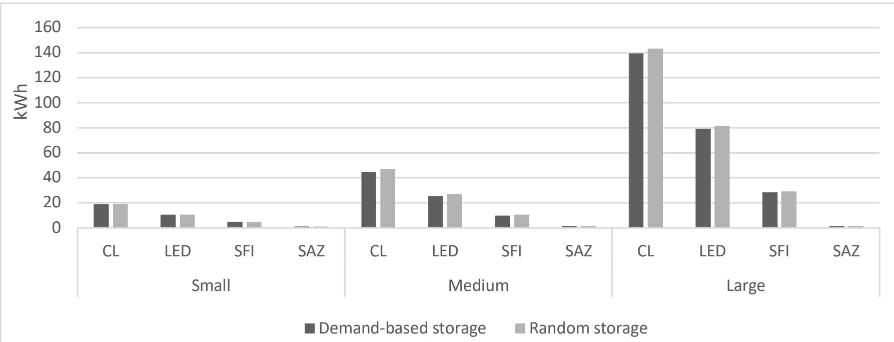

Figure 6: Energy consumption of the lighting strategies for different warehouse sizes and storage assignments

Figure 6 presents the energy consumption of the four lighting strategies for different warehouse sizes and storage assignments. As can be seen, the absolute energy savings (these correspond to the differences between the energy consumption of the lighting strategy CL and the energy consumption of the other three lighting strategies) are higher for larger warehouses due to the larger surface that needs to be illuminated. For the case of a large warehouse and demand-based storage, the simulation model revealed that the energy consumption can be reduced by 79% with SFI and by 98% with SAZ compared to CL. These results match those of the case study outlined in Section 3 well, where a reduction in energy consumption of around 80% was reported. Given an energy price of 0.18 EUR/kWh as assumed in Table 3, energy cost can be reduced from 29.51 Euro with CL to 16.78 Euro with LED, to 7.48 Euro with SFI, and to 1.79 Euro with SAZ for an average twelve-hour workday (all for the large warehouse). For SFI and SAZ, 43% of the reduction in energy consumption is due to the refitting of fluorescent lamps with LED lighting. Still, a remarkable (further) reduction of 36% and 55%, respectively, results from making warehouse lighting smart in addition. In the case of demand-based storage, the reduction in energy consumption for the different lighting strategies are up to 5.5% higher than in the case of random storage. The reason for this result is that order pickers need more time to retrieve all products when a random storage allocation is used, which leads to longer operating periods that can benefit from reducing light intensity. It is worth noting that the average time required to complete the given set of orders increased with the size of the warehouse. Given that aisles not occupied by an order picker were illuminated at 20% light intensity, a longer total order picking time resulted in a larger (total) energy consumption. In fact, order pickers needed, on average, around 7 hours to complete the orders in the small warehouse, around 9.5 hours in the medium warehouse, and around 11.5 hours in the large warehouse. The total order picking time in combination with the surface to be illuminated explain the huge differences in energy consumption obtained for the different warehouse sizes.

5.2. The impact of storage assignment and the number of order pickers

This section investigates the influence of the number of order pickers employed in the warehouse on energy consumption under different storage assignments. The energy consumption is nearly the same for both storage assignments over all scenarios we analysed. An increase in the number of order pickers led to a larger energy consumption for the random storage assignment. The case with 3 order picker constitute an exception of this trend. Therefore, Figure 7 present the energy consumption of a large warehouse for all four lighting strategies and a single, three, five and in addition seven order pickers. A larger energy consumption with for an increase in the number of order pickers could be explained by the fact that the random storage assignment generates no clusters in the warehouses in which order pickers have to pick multiple times during the completion of an order. Consequently, their field of activity is larger, which leads to an increase in energy consumption.

Commentato [CG16]: Das interessante oder komische ist hier, dass sich die Vorteilhaftigkeit für drei Picker umkehrt; gibt es da eine Erklärung? Mir fällt für den Moment leider nichts ein. Wäre es eine größere Angelegenheit, das nochmal für 7 Picker durchlaufen zu lassen, um zu sehen, wie es dann aussieht? Vielleicht hat das was mit der Routing-Policy zu tun – man started ja mit dem Pick, der am weitesten weg ist, und bei drei Pickern ist die Wahrscheinlichkeit vielleicht groß, dass man in jeden entfernteren Winkel einmal hinein muss; danach könnte es sich um das Depot herum konzentrieren, nur gleich das die ursprüngliche Aktivierung entferner Zonen nicht mehr aus. Bei einer größeren Anzahl an Pickern kehrt sich das um. Das ist aber nur eine Hypothese.
Kann man mit Simplant eine Art Heatmap generieren, die zeigt, in welcher Zone des Lagers die Picker die meiste Zeit verbringen?

Commentato [M17R16]: Headmap kann in Plant nicht abgerufen werden. 7 Picker bestätigen die These, d.h. die Kosten sind mit 7 Picker für eine Demand-based storage auch teuerer.

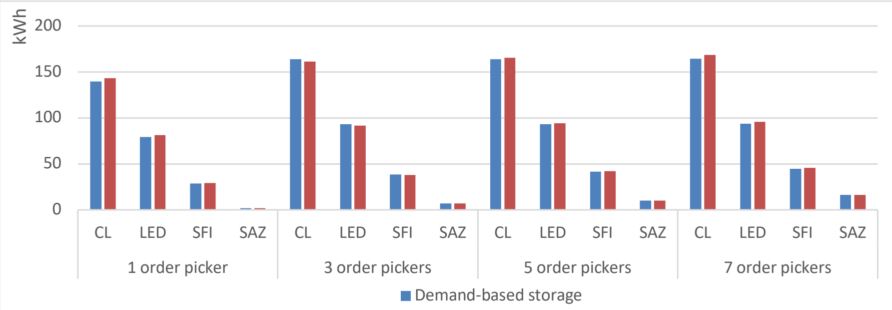

Figure 7: Energy consumption for a large warehouse with demand-based and random storage assignment with different numbers of order pickers

Figure 8 presents the average energy consumption for alternative numbers of order pickers for the four lighting strategies for the large warehouse. The averages were calculated across all simulation runs for the respective number of order pickers and the lighting strategy in question. The figure shows that an increase in the number of order pickers working in parallel in the warehouse leads to a higher energy consumption for all lighting strategies. The energy savings that result for SFI and SAZ decrease in the number of order pickers, as more and more aisles have to be illuminated. For the LED system, the percentage energy savings compared to CL are independent of the number of order pickers employed in the warehouse, and they amount to 43%. SFI obtained savings in the range of 70% to 78%, and SAZ obtain savings in the range of 89% to 98% compared to CL.

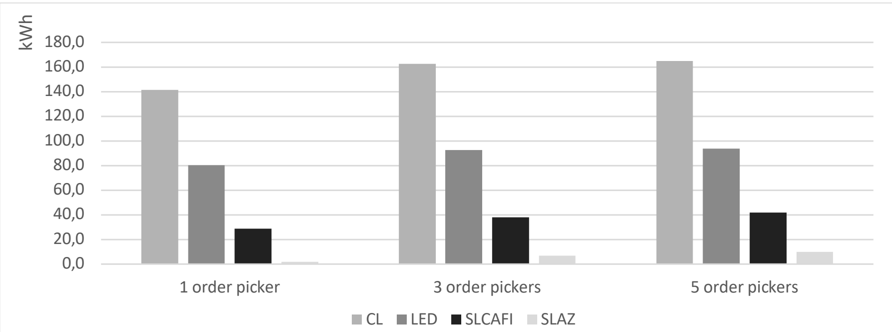

Figure 8: Average energy consumption of the four lighting strategies for alternative numbers of order pickers

5.3. The impact of the pick policy

We now investigate the influence of the two different pick policies on energy consumption, again for the large warehouse. Figure 9 compares the pick-by-order policy to the pick-by-batch policy for demand-based storage and random storage and for different numbers of order pickers for the LED and SFI lighting system. Interestingly, we found that the pick-by-order strategy outperformed the pick-by-batch strategy for demand-based storage, while the opposite performance was observed for the random storage strategy. We attribute these results to the implementation of the pick-by-batch policy. Even though demand-based storage ensures that most picks occur closer to the depot, orders may still contain (a few) picks farther away from the depot, that in the case of batching lead to activity zones spread across the warehouse that may make it necessary to illuminate many aisles at once. The pick-by-order policy would, in turn, lead to a situation where most order pickers work close to the depot with many overlaps in the use of aisles, which helps to lower energy consumption. The results change for random storage where picks are distributed more uniformly over the warehouse. In this case, pick-by-batch outperforms pick-by-order.

Figure 9: Energy consumption of two lighting strategies for a large warehouse and different pick policies and storage assignments

5.4. The impact of the demand distribution

We now study the influence of the demand distribution on the relative performance of the lighting strategies both for the cases of random and demand-based storage assignment. Figure 10 presents the average energy consumption of the four lighting strategies across all numbers of order pickers. We consider a medium-size warehouse in order to show that the effects also occur for smaller areas. As can be seen, the demand-based storage assignment benefits from a Pareto-distributed demand, as the higher demand for a set of items leads to zones in the warehouse (close to the depot in this case) where the order pickers are present most of the time, while zones farther away from the depot are less and less frequented; these latter zones benefit especially from smart lighting systems. As expected, a random storage assignment is not able to turn the higher demand for a set of items the Pareto distribution brings about into a reduction in energy consumption; the results are therefore quite similar to the uniformly distributed demand in this case.

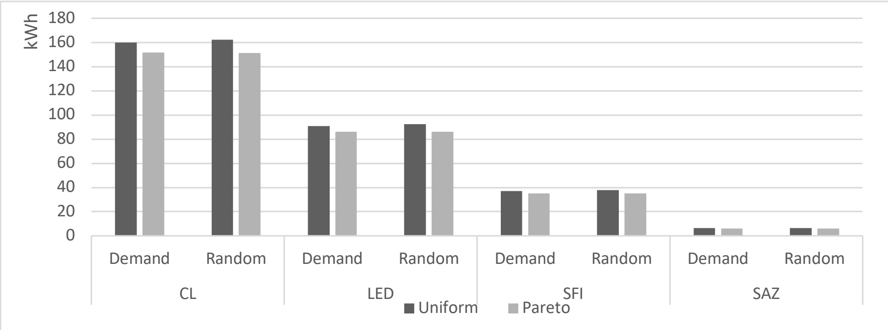

Figure above: large warehouse; figure below: medium size warehouse

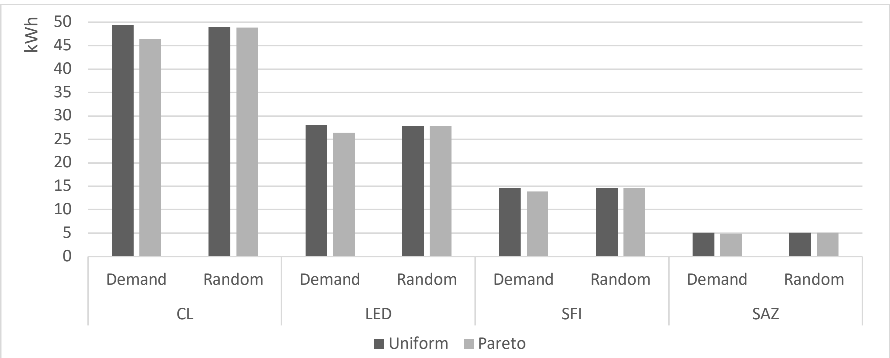

Figure 10: Energy consumption for alternative demand structures and storage assignment policies

5.5. *Average savings in energy consumption*

We finally present an overview of the energy savings the different lighting systems achieved on average across the different scenarios we analyzed. The purpose of this analysis is to illustrate the cost savings potential of smart lighting systems. Figure 11 displays the average

Commentato [CG18]: Der Satz stammt noch von den alten Daten vermute ich; es stimmt so nun ja nicht mehr, d.h. auch für das random assignment ist Pareto nun besser als uniform. Kann man das erklären?

Commentato [M19R18]: Für ein großes Lager find ich dazu keine passende Erläuterung. Für ein medium-size warehouse sind die Daten wie zu erwarten.

Commentato [M20]: Löschen, da medium-size zeigt die Effekte besser?

Commentato [CG21]: Würde es ggf. noch Sinn machen, zu prüfen, wie sich das Ergebnis für die Pareto-Verteilung ändert, wenn wir die Verteilung manipulieren? Je mehr sich die Nachfrage auf wenige Produkte konzentriert, desto größer müsste der Effekt ja sein. Das ist zwar logisch, wäre aber sicher interessant und würde die Intuition bestätigen; solche Zusatzdaten könnte man auch in den Anhang packen und hier nur kurz zusammengefasst ansprechen.

Commentato [M22R21]: Ich werde das nochmal nachsimmulieren. Die Nachfrage ist jedoch bereits so gebaut, dass nur sehr wenige Produkte eine sehr große Nachfrage hat und dies dann sehr schnell rapide abfällt. Ich würde hier vermuten, dass dabei keine großen änderungen entstehen. Auch weil nur eine begrenzte anzahl an lagerplätze existieren.

Commentato [CG23R21]: Wenn es nicht zu viel Arbeit macht, das nochmal zu prüfen, könnten wir die Daten nochmal generieren und rein sehen. Wenn es nicht allzu spannend ist, nehmen wir entweder nur einen kurzen Satz dazu auf (These results were confirmed also for …), oder wir lassen es ganz weg.

Commentato [M24R21]: Da die Pareto-Version bereits etwas manipuliert wurde, um Unterschiede zu sehen, hat eine noch stärkere Änderung keinen bemerkenswerten Einfluss mehr auf das Ergebnis.

Commentato [CG25]: Dieses Unterkapitel böte sich vielleicht auch für eine Amortisationsrechnung an – hier haben wir grobe Durchschnittszahlen bezogen auf die drei Lagergrößen, und vielleicht könnte man grob überlegen, ab wann sich denn dann die entsprechenden Systeme lohnen. Vielleicht passt das hier besser als im letzten Kapitel.

Commentato [M26R25]: Die Amortisationsrechnung wird in der Diskussion eingebaut. Folgt sobald die Daten vorliegen.

energy consumption per hour for the different warehouse sizes investigated in this study, averaged across all scenarios considered in the simulation. In combination with the previous results, these averages shows in addition that the savings are also representative for mixed scenarios with different parameters other than those presented in this study. For all warehouse sizes, introducing LED technology led to energy savings of around 43% compared to the CL strategy. The energy reduction resulting from SFI as compared to CL ranges between 61% and 77%, and SAZ led to energy savings ranging between 70% and 85% compared to CL. The absolute energy savings depend on the warehouse size.

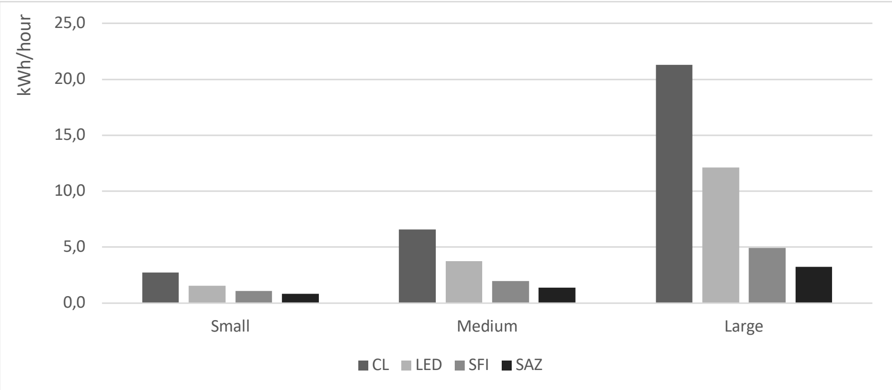

Figure 11: Average energy consumption of the lighting strategies for alternative warehouse sizes

Across all different scenarios, we analyse the correlation between the average working time for the respective scenario and the energy consumption for the different lighting strategy. Table 4 shows that the correlation for CL and LED are the same due to the fact that the only difference is the consumption factor of the lighting technology. SAZ indicates a smaller correlation because the energy consumption does not increase linear with the time like in SFI. Illuminating just a small activity zone around every order picker requires not as much energy as compared to illuminating an entire cross or picking aisle. The simulation experiments also show that the energy consumption of the different lighting strategies considered are approximately linear in their development over time. The difference in the energy consumption between any two of the systems increases linearly as well. This is caused by a large share of energy waste due to illuminating unused aisles, for example cross aisles where no order picker is present. The simulation results demonstrate that smart lighting systems can reduce this kind of energy waste resulting in lower energy cost.

CL	LED	SFI	SAZ
0,914	0,914	0,942	0,549

Commentato [CG27]: Das wirkt hier etwas von den obigen Abbildungen losgelöst; gilt das generell, oder in Bezug auf bestimmte Abbildungen? Müsste man vielleicht noch etwas weiter ausführen.

Table 4: Correlation between working time and energy consumption for all combinations

Commentato [CG28]: Ich bin mir noch nicht ganz sicher, was wir damit machen. Einerseits ist es interessant, dass sich die Korrelation unterscheidet; ich bin aber noch nicht sicher, ob wir das ausreichend erklärt haben. Daneben habe ich mich gefragt, ob wir mit diesen Ergebnissen hier starten sollten – oder ob es besser wäre, erst die im Folgenden präsentierten Ergebnisse zu Energieeinsparungen zu präsentieren und dann etwas später auf die Korrelationen einzugehen.

6. Discussion and conclusion

This paper is the first to evaluate the energy and cost reduction potential of smart lighting systems in a warehousing context. A simulation model of an order picking warehouse was developed to assess the benefits of smart lighting systems by varying warehouse design features and operating strategies. In particular, we considered a variable number of order pickers, different storage assignments, and batching policies. In addition, four different lighting strategies that represent different technical degrees of "smartness" were implemented in the model. The results of the simulation model showed that smart lighting systems can achieve energy savings up to almost 90% compared to the conventional full-time illumination of warehouses. Besides a significant energy and cost reduction, smart lighting systems can reduce carbon dioxide emissions and contribute to reducing the environmental footprint of warehousing.

The results are in line with case study data showing an actual example of the benefits of smart lighting systems, and thus support managers in successfully implementing a (gradual) shift from traditional lighting to smart lighting in warehouse practice. This work also aids managers in operating such systems, as well as when deciding on whether or not smart lighting systems should be implemented. It is important to note that, depending on the technology of the smart lighting system and the size of the warehouse as well as the desired illumination level, respective investments can be very cost-intensive. Thus, it is not surprising that managers often ask for the return-on-investment when deciding about the implantation of such systems. Based on our simulation results, the case study data and the discussions in the expert workshop, a possible amortization of two different sensor-based smart lighting system may be as follows.

xx

Commentato [E29]: Marc: hier ggf 2 beispiele zur amortisation ergänzen, semi und full, gerne auf die Parameter oben beziehen („für das große lager mit xxx Parametern, wie im case…"

Commentato [M30R29]: Folgt, wenn die realen Daten von Herr Bauer vorliegen.

The potential benefits of smart lighting systems, however, extend beyond reductions in energy consumption, costs, and emissions. Light, in general, enables vision, affects human behaviour and performance and it influences the circadian timing system as well as human mood and motivation (Boyce, 2014). LEDs in combination with smart lighting control can lead to an increase in light quality, an improved regulation of the circadian rhythm and an increase in productivity (Hye Oh et al., 2014; Karlicek, 2012). It has been shown that different light colour temperatures influence human physiology (Yasukouchi and Ishibashi, 2005), such that higher colour temperatures result in higher attention, and it is therefore often used in work areas. Studies "human centric lighting" (HCL) also reported that lighting adjusted to the order pickers' needs contributes to the well-being of employees and to preventing accidents at work (Pandharipande and Caicedo, 2015). Smart lighting systems can thus contribute to improved ergonomic working conditions in warehouses, leading to an increase in performance and quality.

Besides these, the ability to network enables the integration of smart lighting systems into the existing building management technology, and hence it can be centrally monitored and controlled. This facilitates detecting the temporal power decrease of LEDs due to pollution or aging via sensors. This data can be used to define maintenance intervals more accurately, which also helps to reduce unscheduled maintenance operations resulting from disruptions (Vanus et al., 2016).

This study has limitations. First, we consider only a standard warehouse layout with a fixed depot localization. Analysing different warehouse layouts or another arrangement of the depot would be interesting to investigate whether other layouts or depot arrangements reduce energy costs and consumption. Furthermore, routing strategy for the order pickers are not controllable, therefore, their impact are not part of this simulation study. The proposed simulation model could be extended in future research by include further warehouse layouts and routing strategies that are currently not covered in the model implementation. Additionally, we fixed the number of order sizes per order picker and we implement only one kind of batching policy, which depends to the distance between depot and pick-up places.

Another promising direction for future research is the development of an indoor positing system based on VLC, which can be used to generate heat maps and identify activity zones to support managerial decisions regarding storage reassignments. In addition, HCL and VLC need to be studied in more detail, in particular in empirical approaches, to fully evaluate the advantages of smart lighting systems in improving warehouse operations on profound data. These and other promising ideas that consider the application of smart lighting in industrial settings can be addressed in an extension of this paper. In conclusion, smart lighting systems are one example of how digital technologies can improve operations performance, environmental impact as well as positively affect human work, contributing to increased sustainability.

Acknowledgements

Supported by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag.

Commentato [CG31]: Das muss möglicherweise vom Paper runter, wenn wir einreichen; das könnte man aber auf die Title Page machen, die auch die Autorendetails beinhalten, dann vergessen wir es nicht.

REFERENCES

Bartolini, M., Bottani, E., & Grosse, E. H. (2019). Green warehousing: systematic literature review and bibliometric analysis. Journal of Cleaner Production. 226, 242-258.

Boyce, P. R. (2014). Human Factors in Lighting, Boca Raton: CRC Press, 3rd ed., pp. 115-120, 233-234, 287-288.

Boysen, N., de Koster, R., & Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. European Journal of Operational Research. 277(2), 396-411.

Calzavara, M., Glock, C. H., Grosse, E. H., & Sgarbossa, F. (2018). An integrated storage assignment method for manual order picking warehouses considering cost, workload and posture. International Journal of Production Research, 57 (8), 2392-2408.

Chen, Y., Liu, J., Pei, J., Cao, X., Chen, Q., & Jiang, Y. (2014). Experimental and simulation study on the performance of daylighting in an industrial building and its energy saving potential. Energy and Buildings, 73, 184-191.

Çelik, M., & Süral, H. (2019). Order picking in parallel-aisle warehouses with multiple blocks: complexity and a graph theory-based heuristic. International Journal of Production Research, 57(3), 888-906.

Chang, M.-H., Sandborn, P., Pecht, M., Yung, W. K. C., & Wang, W. (2015). A return on investment analysis of applying health monitoring to LED lighting systems, in: Microelectronics Reliability, 55(3-4), 527–537.

Chew, I., Karunatilaka, D., Tan, C. P., & Kalavally, V. (2017). Smart lighting: The way forward? Reviewing the past to shape the future, Energy and Buildings, 149, 180–191.

Chun, S. Y., Lee, C. S., & Jang, J. S. (2015). Real-time smart lighting control using human motion tracking from depth camera, Journal of Real-Time Image Processing, 10(4), 805-820.

Chung, T. M., & Burnett, J. (2007). On the Prediction of Lighting Energy Savings Achieved by Occupancy Sensors, Energy Engineering, 98(4), 6-23.

De Bakker, C., Van de Voort, T., & Rosemann, A. (2018). The energy saving potential of occupancy-based lighting control strategies in open-plan offices: The influence of occupancy patterns, Energies, 11(2), 1-18.

De Koster, R., Le-Duc, T., & Roodbergen, K. J. (2007). Design and control of warehouse order picking: A literature review, European Journal of Operational Research, 182(2), 481-501.

Dhoorna, J., & Baker, P. (2012). An exploratory framework for energy conservation in existing warehouses, International Journal of Logistics Research and Applications, 15(1), 37-51.

Franzke, T., Grosse, E. H., Glock, C. H., & Elbert, R. (2017). An investigation of the effects of storage assignment and picker routing on the occurrence of picker blocking in manual picker-to-parts warehouses. The International Journal of Logistics Management, 28(3), 841-863.

Glock, C. H., & Grosse, E. H. (2012). Storage policies and order picking strategies in U-shaped order-picking systems with a movable base. International Journal of Production Research, 50(16), 4344-4357.

Grosse, E. H., Glock, C. H., & Ballester-Ripoll, R. (2014). A simulated annealing approach for the joint order batching and order picker routing problem with weight restrictions. International Journal of Operations and Quantitative Management, 20(2), 65-83.

Grosse, E. H., Glock, C. H., Jaber, M. Y., & Neumann, W. P. (2015). Incorporating human factors in order picking planning models: framework and research opportunities. International Journal of Production Research, 53(3), 695-717.

Haas, H., Yin, L., Wang, Y., & Chen, C. (2016). What is LiFi?, Journal of Lightwave Technology, 34(6), 1533-1544.

Hanson, R., Falkenström, W., & Miettinen, M. (2017). Augmented reality as a means of conveying picking information in kit preparation for mixed-model assembly. Computers & Industrial Engineering, 113, 570-575.

Heath, B. L., Ciarallo, F. W., & Hill, R. R. (2013). An agent-based modeling approach to analyze the impact of warehouse congestion on cost and performance. The International Journal of Advanced Manufacturing Technology, 67(1-4), 563-574.

Higuera, J., Hertog, W., Peralvarez, M., Polo, J., & Carreras, J. (2015). Smart Lighting System ISO/IEC/IEEE 21451 Compatible, in: IEEE Sensors Journal, 15(5), 2595-2602.

Hye Oh, J., Ji Yang, S., & Rag Do, Y. (2014). Healthy, natural, efficient and tunable lighting: four-package white LEDs for optimizing the circadian effect, color quality and vision performance, Light: Science & Applications, 3(2), e141.

Karlicek, R. F. (2012). Smart lighting-beyond simple illumination, IEEE Photonics Society Summer Topical Meeting Series, 147–148.

Karunatilaka, D., Zafar, F., Kalavally, V., & Parthiban, R. (2015). LED based indoor visible light communications: State of the art, IEEE Communications Surveys and Tutorials, 17(3), 1649-1678.

Leccese, F. (2013). Remote-Control System of High Efficiency and Intelligent Street Lighting Using a ZigBee Network of Devices and Sensors, IEEE Transactions on Power Delivery, 28(1), 21-28.

Liu, J., Zhang, W., Chu, X., & Liu, Y. (2016). Fuzzy logic controller for energy savings in a smart LED lighting system considering lighting comfort and daylight, Energy and Buildings, 127(9), 95-104.

Luo, J., Fan, L. & Li, H. (2017). Indoor Positioning Systems Based on Visible Light Communication: State of the Art. IEEE Communications Surveys and Tutorials, vol. 19, no. 4, pp. 2871-2893.

Masae, M., Glock, C.H., & Grosse, E.H. (In Press). Order picker routing in warehouses: A systematic literature review. Working paper, TU Darmstadt.

Nagy, J., Yong, F. Y., & Schlueter, A. (2016). Occupant centered lighting control: A user study on balancing comfort, acceptance, and energy consumption, Energy and Buildings, 126, 310-322.

Pan, J. C. H., & Wu, M. H. (2012). Throughput analysis for order picking system with multiple pickers and aisle congestion considerations. Computers & Operations Research, 39(7), 1661-1672.

Pandharipande, A, & Caicedo, D. (2015). Smart indoor lighting systems with luminaire-based sensing: A review of lighting control approaches, Energy and Buildings, 104, 369–377.

Park, J., Lee, H., & Kim, Y. (2015). A study on the appropriate position for an illumination sensor for lighting control based on actual residence environments, International Journal of Applied Engineering Research, 10(10), 26769-26776.

Pathak, P. H., Feng, X., Hu, P. & Mohapatra, P. (2015). Visible Light Communication, Networking, and Sensing: A Survey, Potential and Challenges. Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2047-2077.

Richards, G. (2014). Warehouse Management: A complete guide to improving efficiency and minimizing costs in the modern warehouse, Kogan Page Publishers, London.

Ries, J. M., Grosse, E. H., & Fichtinger, J. (2017). Environmental impact of warehousing: a scenario analysis for the United States. International Journal of Production Research, 55(21), 6485-6499.

Schratz, M., Gupta, C., Struhs, T., & Gray, K. (2013). Reducing energy and maintenance costs while improving light quality and reliability with led lighting technology, Conference Record of 2013 Annual IEEE Pulp and Paper Industry Technical Conference, Charlotte, NC, 43-49.

Scholz, A., Henn, S., Stuhlmann, M., & Wäscher, G. (2016). A new mathematical programming formulation for the single-picker routing problem. European Journal of Operational Research, 253(1), 68-84.

Sharma, R., Charan Kumari, A., Aggarwal, M., & Ahuja, S. (2018): Optimal LED deployment for mobile indoor visible light communication system: Performance analysis, in: AEU - International Journal of Electronics and Communications, 83, 427–432.

Shur, M., & Žukauskas, A. (2011). Light emitting diodes: Toward smart lighting, in: International Journal of High Speed Electronics and Systems, 20(2), 229-245.

Tähkämö, L., Bazzana, M., Zissis, G., Puolakka, M., & Halonen, L. (2014). Life cycle assessment of a fluorescent lamp luminaire used in industry–a case study. Lighting Research & Technology, 46(4), 453-464.

Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2010). Facilities planning. John Wiley & Sons.

Van Gils, T., Ramaekers, K., Caris, A., & de Koster, R. B. (2018). Designing efficient order picking systems by combining planning problems: State-of-the-art classification and review. European Journal of Operational Research, 267(1), 1-15.

Vanus, J, Stratil, T., Martinek, R., Bilik, P., & Zidek, J (2016). The Possibility of Using VLC Data Transfer in the Smart Home. IFAC-PapersOnLine, 49(25), 176-181.

Verriet, J. H., Hamberg, R., Caarls, J., & van Wijngaarden, B. (2013). Warehouse Simulation Through Model Configuration. Proceedings - 27th European Conference on Modelling and Simulation, ECMS, 629-635.

Von Neida, B., Manicria, D., & Tweed, A. (2001). An analysis of the energy and cost savings potential of occupancy sensors for commercial lighting systems, in: Journal of the Illuminating Engineering Society, 30(2), 111-125.

Yasodha, K., Sumathi, S., & Sheela, P. (2015). A smart energy efficient lighting system based on intelligent controller and sensors, International Journal of Applied Engineering Research, 10(3), 5427-5434.

Yasukouchi, A. & Ishibashi, K. (2005). Non-visual Effects of the Color Temperature of Fluorescent Lamps on Physiological Aspects in Humans. Journal of Physiological Anthropology and Applied Human Science, vol. 24, no. 1, pp. 41-43.

Wang, L., Li, H., Zou, X., & Shen, X. (2015). Lighting system design based on a sensor network for energy savings in large industrial buildings. Energy and buildings, 105, 226-235.

Žulj, I., Kramer, S., & Schneider, M. (2018). A hybrid of adaptive large neighborhood search and tabu search for the order-batching problem. European Journal of Operational Research, 264(2), 653-664.