The Role of Digital Technologies in Improving Energy Efficiency at Logistics Facilities: A State-of-the-Art

Cannava L.[1] *, Perotti S.[1], Petrillo A.[2]

a. 1 Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Via Lambruschini 4/B, 20156 – Milano – Italy (luca.cannava@polimi.it; sara.perotti@polimi.it)

b. 2 Department of Engineering, University of Naples "Parthenope", Isola C4, Centro Direzionale Napoli, 80143 – Napoli – Italy (antonella.petrillo@uniparthenope.it)

Abstract: The logistics industry is facing increasing challenges that have been further amplified by recent disruptions. In this context, warehouses have been playing an ever-crucial role. They have been transitioning from simple storage centres into high-functional facilities where several and heterogeneous processes are performed to guarantee efficiency and service level fulfilment. These dramatic changes have often made them highly energy intensive. To cope with these changes, a wide array of digital technologies is now available and has started to be gradually introduced by companies at their logistics facilities to reduce energy consumption and improve the environmental sustainability of warehousing operations. Nevertheless, on the academic side, although a mounting number of papers have been found addressing the adoption of digital technologies at logistics facilities with an energy efficiency perspective, a clear overview of the solutions in place and their impact on warehousing processes has been largely neglected so far. This contribution aims at addressing this research gap by offering a state-of-the-art of the role of digital technologies in improving energy efficiency at logistics facilities. The study is based on a systematic review approach performed by means of the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) protocol. The research is part of a broader Italian funded PNRR Research project "Centro Nazionale per la Mobilità Sostenibile" (MOST) – Spoke 10 "Sustainable Logistics". Results indicate that the impact of digital technologies on warehouse processes is still underexamined, and research has mainly focused on specific technical issues or single warehousing processes rather than providing a holistic approach. The study provides a comprehensive framework offering guidance for technology implementation. Implications are discussed and streams for future investigation are identified.

Keywords: Green Logistics; Warehouse; Digital Technologies; Energy Efficiency., PRISMA.

I. INTRODUCTION

In Europe the logistics industry accounts for 7.9% in terms of total number of people employed, with a turnover of € 1.437,4 billion in 2019 [1]. In this context, in-house transport, warehousing, and support activities represent the core business accounting for 38% of the European market value and 30% worldwide [2]. Apparently, the warehouse itself might seem like a plain component of the supply chain [3]. However, it involves several heterogeneous processes to ensure efficiency and effectiveness of the entire value chain. Over the past few years, a significant evolution of both warehouse role and features has been observed [4], which has led to a shift in priorities to address increasingly complex challenges [5]. Hence, the focus has progressively shifted from pure transport processes to a more holistic perspective, with a particular attention to warehousing operations ([5]; [6]) Some of the substantial factors contributing to this development are the expanding e-Commerce sector and the growing demand for mass customisation, which has also led to an increasing need for warehouse space and buildings. At the same time, a wide range of high-automated solutions has gradually been introduced in warehouses [7] often leading to a significant increase in energy consumption. Overall, logistics facilities need a considerable amount of energy to carry out all the warehousing processes, whereby the related environmental impact is remarkable and deserves attention [8]. On the other hand, companies and stakeholders are increasingly being pressured to adopt energy-efficient solutions to achieve the net-zero energy goal, while at the same time ensuring high performance and flexibility. In this context, the concept of green warehousing has started to emerge. Green warehousing has been defined by Bartolini et al. [9] as "a managerial concept integrating and implementing environmentally friendly operations with the objective of minimizing energy consumption, energy cost and GHG emissions of a warehouse".

In the transition towards this new sustainable paradigm, digital technologies play a central role. The use of digital solutions is becoming key to automate data collection and speed up the transition process towards net-zero warehouses, which should minimize energy demand as a result of energy efficiency improvements and produce as much energy as it consumes from renewable energy sources [10]. Digitalization has become a powerful resource [11] and could benefit any field substantially. One of the main issues supported by digital transformation is sustainable energy consumption and resource usage [12] while improving performance in the meantime. Although the impact of digitalization is varied and cross-sectorial, a specific attention can be paid to logistics facilities. Digital technologies enable the collection of large amounts of data from various energy systems and logistics processes. This data can be displayed and analysed in real-time allowing energy consumption tracking, giving the opportunity to make promptly adjustments to optimize energy usage and reduce wastage. Anyway, some scholars assert that the implementation of digital technologies in warehouses is still immature [13]. Some others state that and companies are gradually moving towards implementation of digital technologies to stay up to date in the uncertain and complex paradigm [14]. However, increasing challenges have been highlighted in identifying the best suitable technologies to adopt in the logistics facilities [15].

The application of digital technologies and energy-efficient measures in logistics facilities are various and hard to categorize due to their deeply interdependent application fields and to a highly fragmented body of knowledge. For this reason, the main objective of the present work is to shed light on this arena and to promote a deeper understanding of digital technologies at logistics facilities from an energy efficiency point-of-view. Energy efficiency has become a widely used buzzword comprehensively defined by EU Commission [16] as "the ability to achieve maximum ratio of the output of performance, service, goods or energy, to input of energy".

To ensure robustness to our analysis and to identify, assess and summarise the role of digitalization towards energy efficiency improvement in warehouses, we used a systematic literature review (SLR) approach based on the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) protocol.

The remainder of the paper is structured as follows. Section 2 analyses the methodology used for conducting the review. Section 3 reports the results, whereas a discussion is offered in Section 4. Finally, conclusions are reported, and future research directions are also highlighted.

II. RESEARCH METHODOLOGY

The research is based on a SLR approach grounded on the PRISMA protocol. SLR is widely used to create strong foundations for all academic enquiries [17] and it is well suited to our research, whose purpose is to detect the impact of digital transformation on energy consumption and energy efficiency at logistics nodes. For this reason, the following research questions (RQs) have been defined.

- ***RQ_1***: What digital technologies can help reduce energy consumption at logistics facilities?
- ***RQ_2***: What areas of consumption are mostly impacted by the implementation of digital technologies to achieve energy efficiency goals? And which warehousing processes are mainly affected?

To address these RQs, according to the guidelines of the SLR, a scientific database was first selected [18]. Then, the identification and selection of the papers for the final review was carried out in line with the PRISMA guidelines which specifically address how literature reviews should be reported and structured.

As a first step, it is essential to define how to identify and select documents to be included. Thus, the Scopus database was selected for the purposes of this study, which provides a comprehensive coverage of peer reviewed scientific literature and help minimise the loss of information by identifying the pertinent literature [19]. Then keywords were selected to perform the query in the database, based on the keyworks that are most frequently used in the literature for the topic under examination. They were identified through a snowball approach, which is the most popular method of sampling in qualitative research. According to the RQs, a set of keywords combining logistics facilities, digital technologies and energy efficiency is defined and used in the Scopus search engine. It should be noted that for those keywords pertaining to the digital domain, the label of specific technologies – such as Artificial Intelligence, Internet of Things, Digital Twin – were intentionally excluded not to restrict the analysis and include those papers where digital technologies at warehouses were discussed at a higher level, i.e., not focusing on a specific category. The keywords and search string used to identify the first sample are summarised in Table 1 and Table 2, respectively.

TABLE I. Keywords used for paper identification.

Warehouse-related	Digital-related	Energy efficiency-related
Warehous*	Digital	Energy consumption
Logistic* site*	Smart	Energy us*
Logistics facilit*	Tech*	Energy efficiency
Logistics node*	Innovat*	
Logistics hub		

TABLE II. Search string resulting from keyword selection.

Search string
TITLE-ABS-KEY (("energy efficien*" OR “energy consumption” OR “energy us*”) AND ("logistic* node*" OR "logistic* facilit*" OR "logistic* site*" OR "logistic* hub*" OR "warehous*") AND ("smart" OR "tech*" OR "innovat*" OR "digital"))

No constraints were applied to the timeframe and subject areas. To ensure high quality, the search was limited to peer-reviewed journals and conference proceedings only [20] and the language was restricted to English being the dominant language in the field of transport and warehousing [21]. These assumptions led to the identification of the initial sample of 258 papers from Scopus.

As a second step of the PRISMA protocol, is it essential to define the basic criteria for screening the papers collected. The basic exclusion criteria were identified and summarized as follows:

- EC_1: Papers not related to warehousing (e.g., data warehouse, information warehouse, etc.).
- EC_2: Papers where digital technologies are addressed in general context (e.g., urban life, healthcare, manufacturing, etc.) rather than logistics field

This screening phase was performed by carefully reading the title, abstract and keywords of the papers. As a result, 162 papers were excluded from the initial sample.

As a third step, eligibility and exclusion criteria were defined and papers were further filtered based on a full-text reading. The in-depth exclusion criteria defined for this phase are hereinafter reported:

- EC_3: Papers where logistics facilities are not the main focus of research but are merely mentioned.
- EC_4: Papers with a focus on technical problems related to digital technology adoption rather than on their implications on warehousing performances.
- EC_5: Papers where digital technologies are not the main focus of research but are merely mentioned.

During this final step, we only included those papers that specifically refer to the impact of digital technologies on energy efficiency performances at logistics facilities applying the in-depth exclusion criteria previously mentioned. As strongly suggested by the PRISMA protocol, this procedure has been performed independently by three researchers to avoid subjectivity or prejudices. A final sample of 38 academic papers published in peer-reviewed journals or conference proceedings eventually remained as a result. The PRISMA statement flow diagram shown in Figure 1 clearly depicts all the identification, screening, eligibility and exclusion steps of the SLR process.

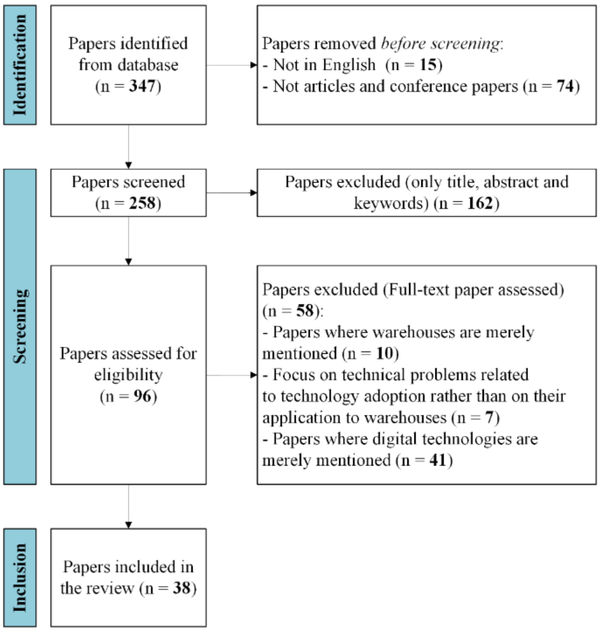

Figure 1. Review process according to the PRISMA guidelines

III. Findings

A. Descriptive analysis

The final sample of 38 selected papers has been analysed descriptively by publication year, document type, and methodological approach with the aim of identifying key features and trends within the selected documents. The analysis of the documents by type over time is reported in Figure 2.

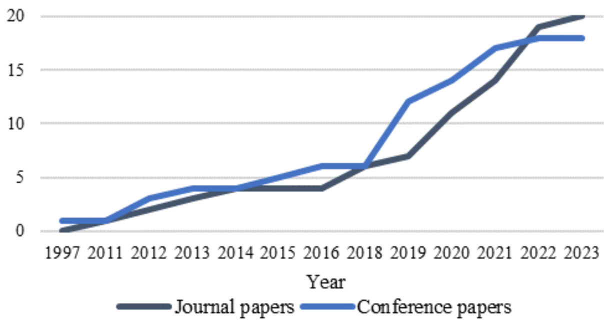

Figure 2. Papers distribution over time by document type

Results show that the number of papers has increased considerably over time showing a steady increase from 2018 onwards. In this timeframe, conference papers account for 47%, whereas journal papers are 53% of the examined sample, thus underlying that the subject of our research is new, and future journal papers are presumably expected in the years to come.

Looking at the method(s) used in the examined papers, the classification proposed by Glock et al. [22] has been taken into account, that includes: conceptual work, survey, case study, examples, data analysis, decision support model, analytical model, and simulation.

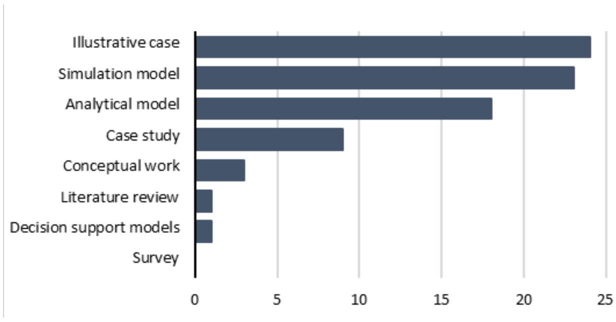

Figure 3. Papers distribution for methodological approaches

As shown in Figure 3, it should be noted that many papers use mixed-method approaches. Most papers are based on illustrative cases (24) or adopt simulation models (23) to evaluate the impact of digital technologies on energy consumption at logistics facilities. Analytical approaches are also quite common (18), followed by case studies (9). Finally, conceptual works (3), literature reviews (1) and decision support models (1) are least common. Results indicate a significant gap within the existing literature body, as most studies primarily rely on simulation methods and exemplary data. A need for additional empirical research seems to emerge to gain a more comprehensive knowledge of the influence of digital technologies in warehousing.

B. Content-wise analysis

A critical analysis of the selected papers has been performed to address the RQs previously defined. Based on the SLR results, nine main clusters of digital technologies have been identified – i.e., Artificial intelligence (AI), Internet of Things (IoT), Digital Twin (DT), Sensors and Remote Control (SRC), Machine learning (ML), Augmented/Virtual reality (AR/VR), Cloud/Edge computing (CC), Big Data Analytics (BDA), 5G – and the papers distribution by technology cluster is reported in Figure 4.

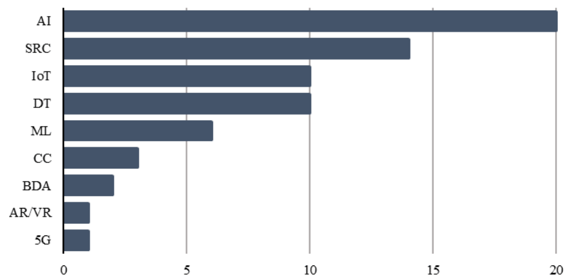

Figure 4. papers distribution by digital technology analyzed.

Findings indicate that most papers focus on AI (16) or SRC (14) as the primary technologies considered when tackling energy efficiency in warehousing. IoT (10) and DT (10) are also quite common followed by ML (6), CC (3) and BDA (2) which are still facing challenges in terms of adoption within this particular application domain. Lastly, 5G (1) and AR/VR (1) are the least commonly mentioned technologies employed for reducing energy performance in logistics facilities.

Looking at RQ$_2$ (i.e., What areas of consumption are mostly impacted by the implementation of digital technologies to achieve energy efficiency goals? And which warehousing processes are mainly affected), different impacts on energy performance have been identified depending on the technology being considered. The same happens in terms of application fields.

Accordingly to several scholars ([9] ; [11] ; [23] ; [24]) the main end-use types within logistics facilities are lighting, heating, ventilation, and air conditioning (HVAC), refrigeration, Material Handling Equipment (MHE) and other (e.g., water, waste). As shown in Figure 5, an analysis was conducted on each digital technology to investigate the specific of end-use types impacted by their implementation.

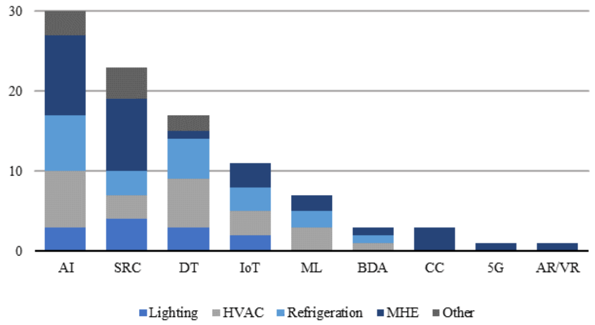

Figure 5. Main end-use types impacted by digital technologies in logistics facilities.

Results suggest that MHE emerges as the primary end-use type impacted by the adoption of various digital technologies, and particularly by AI and ML, whereas to a lesser extent by IoT and ML. However, different considerations arise regarding the impact of CC, 5G, and AR/VR, as their implementation primarily affects MHE. Looking at HVAC and refrigeration, it emerges that most of the analyzed technologies have an impact on these end-use types, especially in case of DT, followed by AI, IoT and ML. Conversely, the impact of SRC and BDA on HVAC and refrigeration appears to be lower. Looking at lighting, it seems to be influenced only by specific digital technologies such as SRC, DT, AI and IoT. Other end-use types have received limited attention, with their reduction being influenced exclusively by the implementation of SRC, DT and AI.

Finally, the relationship between digital technology adoption and warehousing processes has been addressed. To this extent, many papers adopt a broad perspective and tackle warehousing in general terms, without delving into specific processes (16), while others concentrate on particular aspects such as order picking (15), storage (3), receiving (3), and packing and shipping (3). On the other hand, in terms of digital technology, the implementation of AI, DT, and IoT is generally discussed from a general warehouse perspective, rather than targeting specific processes, even though AI, along with SRC, is often examined for order picking processes, packing and shipping. No specific digital technology application has been directly associated to storage and receiving processes, and various digital technologies has been examined in these cases. Finally, Figure 6 shows the primary warehousing processes impacted by digital technologies implementations in logistics facilities.

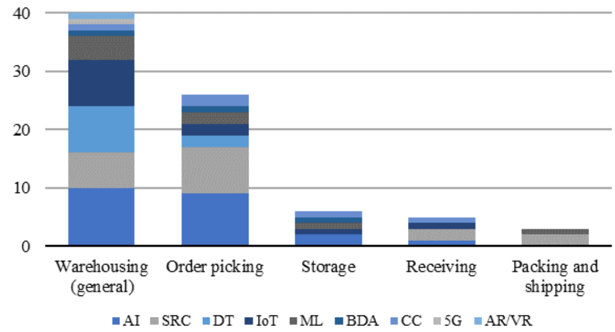

Figure 6. Main warehousing processes impacted by digital technologies in logistics facilities.

IV. DISCUSSION

The review of the 38 papers offers interesting elements for discussion. Firstly, the number of papers addressing digital technologies in logistics facilities from an energy efficiency perspective has grown over in time, moving from 2011 where the contributions was limited, to the last years where a significant increase has been observed, especially from 2018 onwards. This trend also reflects the growing attention paid by stakeholders to concerns about energy savings.

Findings indicate a lack of a thorough investigation of the implications of digital technologies on warehouse processes, as research has mainly focused on specific technical issues or single warehousing processes rather than adopting a comprehensive and all-encompassing perspective. A relationship between some digital technologies and warehousing processes has been identified. For instance, AI is employed and discussed across all types of warehouse processes. However, in most cases implications on logistics aspects are overlooked, thus giving priority to purely technical aspects (e.g., [25] ; [26] ; [27]). Instead, IoT is highly compatible with all warehousing processes with greater attention given to its implications on these processes as a primary focus [28]. Furthermore, some technologies seem to have an impact mainly on specific processes, such as order picking (e.g., DT, SRC, BDA), storage (e.g., CC), packing and shipping (e.g., ML).

Nevertheless, results shows that energy efficiency in logistics facilities can be achieved through various means, and each technology has a distinct tendency to impact energy performance through different ways (e.g., main end-use types). For instance, MHE seems to be impacted by all kind of digital technologies analyzed. Among these technologies, especially fin case of AI, IoT and SRC, routing issues through energy consumption optimization emerge as the aspect most frequently addressed. (e.g., [29] ; [30]). Looking at other end-use types, a strong relationship between HVAC, refrigeration and DT has been observed. Anyway, DT is predominantly employed as an individual technology in case of HVAC and refrigeration (e.g., [31] ; [32]) as opposed to other end-use categories where it is more commonly integrated with other technologies. (e.g., AI, ML, BDA). Finally, a limited number of digital technologies have been found with a specific impact on lighting, as particular objectives are required in its optimization (e.g., interface to the operators, environmental features gathering). SRC, IoT and AI meet these characteristics and enable substantial energy savings to be attained ([28] ; [33]).

V. Conclusions

Logistics facilities have been achieving a key role in value chains, and the sustainability paradigm has been progressively incorporated to reduce the environmental impact of warehousing and improve energy efficiency. This contribution aims to address a gap in the green warehousing literature and offers a state-of-the-art of the role of digital technologies in improving energy efficiency at logistics facilities. The study is based on a SLR approach performed by means of the PRISMA protocol.

The study provides a comprehensive framework of the main digital technologies that can help reduce energy consumption at logistics facilities. Nine main clusters of digital technologies have been identified, and the related consumption areas and warehousing processes impacted were analysed.

MHE has emerged as the predominant area of consumption of most digital technologies, followed by HVAC and refrigeration which are impacted primarily by DT, AI, IoT, and ML. In addition, many digital technologies are commonly implemented without delving into specific warehousing processes, especially for AI, DT, and IoT. On the other hand, only some technologies have an impact on specific processes, with order picking being the most mentioned. This indicates a research gap regarding other kind of warehousing processes (i.e., receiving, storage, packing and shipping).

This study offers both academic and managerial implications. From an academic perspective, this research fills the gap found in literature, by providing a state-of-the-art of the role of digital technologies in improving energy efficiency at logistics facilities. From managerial perspective, this study offers a guideline for practitioners willing to understand how digital technologies can enhance energy efficiency and promote environmental sustainability in their logistics facilities.

Despite the relevance of the research topic, some limitations may be detected, and streams for future research can be highlighted. First, papers published in non-peer-reviewed journals, books and papers written in languages other than English were excluded. This may have led to the case that few relevant studies have been lost. Second, lack of quantitative data precludes a comprehensive assessment of the tangible impact of the digital technology clusters on energy reduction within logistics facilities. Moreover, most studies primarily rely on exemplary data, stressing the need for further research supported by empirical data to gain a more comprehensive knowledge of the influence of digital technologies in logistics facilities. Finally, even though digital technologies are reported individually, they are deeply interdependent in their implementation. Future studies could explore the relationship between each digital technology and identify the optimal energy-efficient combinations for each warehousing processes, conducting a comparative study of individual technologies and combinations.

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