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IFAC PapersOnLine 59-10 (2025) 799–804

A Simulation-Based Approach to Improve Energy Efficiency and Environmental Performance in Warehouses: The Case of IKEA

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Abstract: Given the relevance of warehouse sustainability in the realm of the Logistics 5.0 paradigm, this study evaluates the environmental and economic impacts of green warehousing (GW) measures and provides a practical application to a real business case. A discrete-event simulation approach is applied to the IKEA distribution centre located in Northern Italy to assess strategies for optimizing energy self-consumption from on-site photovoltaic (PV) systems. Three scenarios are identified and investigated: substituting the current mobile material handling equipment (mMHE) fleet with forklifts fully powered by Li-Ion batteries charged through opportunity charging, replacing old PV panels with high-efficiency models, and the combination of both measures. Results are provided in terms of energy, environmental and economic impact, and demonstrate that implementing a Li-Ion mMHE fleet improves energy efficiency and environmental sustainability, achieving a return on investment (ROI) of 26% with a payback period (PBP) of 4 years. Additionally, replacing PV panels increases renewable energy generation by 47%, although some inefficiencies were noted due to on-site energy demand/supply mismatch. Finally, the integration of both GW measures significantly enhances energy and environmental performance, leading to savings that exceed those observed in both scenarios previously evaluated. Findings are discussed and future research directions are outlined.

Keywords: Warehouse, Sustainability, Energy efficiency, Logistics, Discrete event modelling and simulation.

1. INTRODUCTION

The logistics industry has been shaped by several trends like e-commerce and mass customization, leading to increased demand for warehouse space (Perotti et al., 2024). These challenges have led to significant changes in logistics facilities, altering their roles within the supply chain over time and increasing their complexity. As a result, logistics facilities and associated warehousing operations have increased their environmental impact in terms of greenhouse gas (GHG) emissions (Oloruntobi et al., 2023). Thus, policymakers and stakeholders are increasingly pushing logistics facilities to reduce their environmental impact in line with United Nations sustainability development goals (SDGs) for 2050 (European commission, 2020). These changes have been further driven by the new concept of Logistics 5.0 which represents a transformative phase in supply chain management, integrating advanced digital technologies and emphasizing human-centric operations (European Commission, 2020). This paradigm shift is particularly relevant when it comes to warehousing, as it emphasizes the optimization of resources and processes by balancing automation and human collaboration and improving energy efficiency while reducing the environmental impact. The implementation of sustainable warehousing practices within the framework of Logistics 5.0 can significantly contribute to the achievement of environmental goals. In the industrial landscape companies have stated considering sustainable warehousing as a key challenge, leading to the implementation of energy efficiency measures and strategies aimed at reducing their environmental impact. The crucial role that logistics facilities play in addressing environmental concerns has also been recognized in the literature. Specifically, the green warehousing (GW) concept offers a framework for achieving more sustainable and cost-effective warehouse operations (Bartolini et al., 2019; Dubey et al., 2017). In this context, Perotti & Colicchia (2023) have identified key GW measures categorized by areas of intervention. Among these, the integration of material handling equipment and renewable energy sources, such as photovoltaic (PV) systems, stands out as the most common and promising measures in ambient-temperature warehouses, which are generally the most common with respect to other types such as refrigerated or multi-temperature warehouses (Dobers et al., 2019). Implementing these measures can yield a variety of advantages, both tangible and intangible (Cannava et al., 2024; Meneghetti & Monti, 2015). These include direct benefits such as reduced energy costs, decreased emissions, as well as intangible benefits like improved company reputation and increased appeal to external stakeholders.

However, the existing literature reveals a gap in empirical studies that assess the quantitative impact of GW practices, especially in ambient-temperature warehouses (Oloruntobi et

10.1016/j.ifacol.2025.09.136

al., 2023; Baglio et al., 2020). Furthermore, these types of facilities are widely used in the logistics sector due to their various functions wide versatility. Additionally, most analyses have focused on transport emissions, overlooking warehousing's potential for environmental optimization (Perotti et al., 2024). To address this gap, this research employs a simulation-based approach to quantitatively evaluate the environmental and economic impact of the GW measures in a real ambient-temperature warehouse. Specifically, the study investigates how integrating renewable energy sources and adopting efficient material handling equipment can impact the energy consumption and GHG emissions of the warehouse addressed. The simulation is applied to a real warehouse, i.e. IKEA distribution centre located in Northen Italy, and incorporates all its structural features and warehousing processes, which were gathered through semi-structured interviews. The actual energy profile of the warehouse is simulated to validate the model. This validation process also helps identify areas where improvements can be made. Then, the most suitable GW measures are then identified and incorporated into the model. Finally, the impact of GW measures is simulated, and results are reported by evaluating their performance across energy, environmental, and economic dimensions.

The paper is structured as follows: Section 2 presents the simulation-based approach and scenario selection; findings and reflections are addressed in Section 3. Lastly, conclusions are drawn in Section 4.

2. METHODOLOGY

The analysis focuses on an international retail company with a logistics distribution centre located in the northern part of Italy. The modelling and simulation were conducted using DesignBuilder, a tool commonly used in building energy simulation studies (Cannava et al., 2024; Dadras Javan et al., 2023). The software is an advanced 3D modelling tool that facilitates various simulation scenarios in a discrete event environment. Various building's features along with the type of warehousing activities and related technological solutions in place are collected and then incorporated into the simulation software. The data collection was performed by means of semi-structured interviews with company managers (sustainability manager, facility manager) and integrated with the analysis of secondary sources. This process incorporated both logistics and energy performance data by consulting various company reports and job roles, ensuring a comprehensive understanding of the warehouse's requirements. An on-site visit was also performed to integrate the data collected. Then, a 3D digital model of the warehouse is developed using this data, allowing for a comprehensive analysis of the building's energy profile and an evaluation of its energy and environmental performance. For each scenario, a single simulation run is conducted, with each run lasting about 30 minutes. The initial step involves simulating the base-case scenario to quantify the current energy consumption and environmental impact of the warehouse. This simulation also serves to validate the model by comparing the results with actual consumption data. This simulation provided detailed information on energy consumption, broken down by major energy sources (such as electricity, fuel, and electricity generation) and by end-use categories (i.e., material handling, cooling, heating and lighting), and environmental impact in terms of CO_2e emissions. The results obtained were analysed to identify potential areas for improvement and highlight any critical issues. As a result, the most appropriate GW measures were selected to address the specific needs of the warehouse being studied. Each selected GW measure was then simulated and evaluated individually, with the results compared across energy, environmental, and economic performance indicators.

2.1 Business case: base-case scenario

To show the practical application of the proposed simulation-based approach, an ambient-temperature warehouse owned by IKEA S.p.A., an international retail company recognized for its commitment to environmental sustainability, has been selected and investigated. The warehouse is used as a national and international distribution centre with storage/picking, cross-docking and office areas. The building has a total floorspace and clear building height of 177,000 m^2 and 19 m respectively. The work schedule is organized into three shifts per day, operating throughout the entire day for 310 days each year. The warehouse utilizes two types of LED lighting: large, suspended bulbs with a luminous efficiency of 200 lm/W in the storage and cross-docking areas, and compact bulbs with a luminous efficiency of 100 lm/W in the office spaces (Kaminska & Ozadowicz, 2018). Natural light is also incorporated through skylights on the rooftop. A heat pump system provides heating, ventilation, and air conditioning (HVAC) for the office areas. MH, storage, and retrieval operations are conducted both manually and automatically. The warehouse is equipped with both mobile and fixed MH equipment. The mobile material handling equipment (mMHE) includes a fleet of electric forklifts that are powered partially by lead-acid batteries and partially by lithium-ion (Li-Ion) batteries. Charging activities are performed based on the forklift battery type: forklifts powered by lead-acid batteries require two full charges daily, while those powered by Li-Ion batteries benefit from multiple fast partial charges during operators' breaks (i.e., opportunity charging). Details about the warehouse's mMHE fleet and its energy consumption during battery charging can be found in Table 1. The number of forklifts for each type has been not reported due to confidentiality reasons.

Table 1. Features of the mMHE fleet

	Fleet size [No.]	Battery type	Charge time [h]	Unit Charge energy [kWh]	Daily charging frequency	Fleet Energy consumption [MWh/year]
Pallet trucks	138 (58%)	Lead acid	2	3	1	5
Order pickers		Lead acid	7	10	2	236
Reach trucks		Lead acid	7	20	2	380
Counterbalanced forklifts		Lead acid	7	24	2	1,086
Order pickers	97 (42%)	Li-Ion	2	1.2	4	41
Reach trucks		Li-Ion	2	2	4	61
Counterbalanced forklifts		Li-Ion	2	2	4	292

The fixed material handling equipment (fMHE) comprises three automated storage and retrieval systems (AS/RS) that operate continuously 24 hours a day. The available warehouse rooftop space is full covered by on-site PV panels installed in 2010 with a power capacity of 5 MWp. Simulations are performed considering three different scenarios: implementation of a mMHE fleet fully powered by Li-Ion batteries; replacement of PV panels by new high-efficiency ones; and the combination of these two scenarios.

2.2 mMHE fleet fully powered by Li-Ion batteries

In the base-case scenario, lead-acid forklifts are charged twice overnight (from 11:00 p.m. to 6:00 a.m.) and again in the late afternoon (from 2:00 p.m. to 09:00 p.m.). This charging strategy does not impact the operational performance of the warehouse. However, it is energy-inefficient and time-consuming (Modica et al., 2021; European Standard, 2005). This strategy does not capitalize on the potential for energy self-consumption of mMHE energy loads, as it fails to use the PV energy produced. For these reasons, the opportunity charging strategy supported by Li-Ion batteries is pointed out as an effective GW measure to improve energy efficiency and enhance the PV energy self-consumption (Cannava & Perotti, 2025; Cannava et al., 2024). Moreover, the implementation of fast partial charging technology enables the achievement of over 50% of total battery capacity within just half an hour, while simultaneously reducing charging losses in comparison to traditional charging methods (Basso et al., 2019). Specifically, utilizing high-frequency chargers (fast chargers), during the most advantageous time periods can enhance the self-consumption of PV energy generated. For the economic analysis, the initial investment cost of each Li-Ion forklift has been collected based on Toyota Material Handling manufacturer's website: counterbalanced forklift - 13,145 €/forklift-year; reach truck – 14,911 €/forklift-year; order pickers – 8,240 €/forklift-year

2.3 Replacement of old PV panels with high-efficient ones

The PV panels installed on the warehouse rooftop experience an annual efficiency decline of 8%, as emerged from the semi-structured interviews performed with company managers. From the results of the base-case scenario (Section 3.1), it is evident that the on-site PV energy produced does not fully meet the building's energy demand. For this reason, the replacement of PV panels by new high-efficiency ones – to cover the entire rooftop space of the warehouse – is identified as suitable GW measure to mitigate the warehouse' energy demand/supply mismatch. The new PV model simulated is the BP Solar 5170 monocrystalline, which has a rated electric power output of 250 W per module and a module heat loss coefficient of 30 W/m²-K.

2.4 Combined implementation of mMHE fleet fully powered by Li-Ion batteries and PV panels replacement

By increasing the capacity of the PV panels, a higher renewable energy generation is expected. Meanwhile, the use of mMHE fleet with Li-Ion batteries is designed not only to reduce energy consumption but also to enhance energy self-consumption. This improvement could be further amplified by increasing PV energy generation. The objective of this combination is to investigate the correlation between the GW measures proposed and potential combined benefits.

3. RESULTS AND DISCUSSION

3.1 Base-case scenario

The simulation results of the base-case scenario highlighted potential areas of improvement as shown in Figure 1. First, the energy demand of the building remains consistent throughout the year, with no significant peaks in energy usage. This indicates that the building's energy demand is not influenced by seasonality. Second, MHE and lighting are the primary sources of energy consumption, together accounting for up to 80% of the building's total energy demand. This is mainly due to the high throughput capacity required by the warehouse and the large surface area that must be illuminated. Third, the monthly average self-consumption rate is relatively high compared to the building's total energy demand (i.e., 78 %). This underscores the effective use of renewable energy sources., although the PV energy production is still below the building's electricity demand. Consequently, the monthly energy produced does not meet the monthly energy demand of the warehouse. For these reasons, the most suitable GW measures selected to address the identified gaps are: (I) the implementation of a mMHE fleet fully powered by Li-Ion batteries – MHE is the main source of consumption of the logistics building (i.e., accounting for up to 60% of the total energy demand). Therefore, reducing this energy consumption is crucial for maximizing energy savings and minimizing environmental impact. Additionally, the opportunity charging strategy supported by Li-Ion batteries is demonstrated to be significantly more energy-efficient than the traditional charging strategy (powered by lead-acid batteries and performed overnight), as discussed in Section 2.2; (II) replacement of PV panels by new high-efficiency ones – although renewable energy generation is nearly entirely self-consumed, it still does not meet the monthly energy demand of the building, even during peak generation period. Therefore, high-efficiency PV panels are selected to replace the existing ones (i.e., base-case), utilizing the same rooftop space available on the warehouse. The energy consumption (EC) by month for each main energy end-use, PV self-generation/-consumption, and the related average self-consumption rate (ASCR) of the base-case scenario are reported in Figure 1.

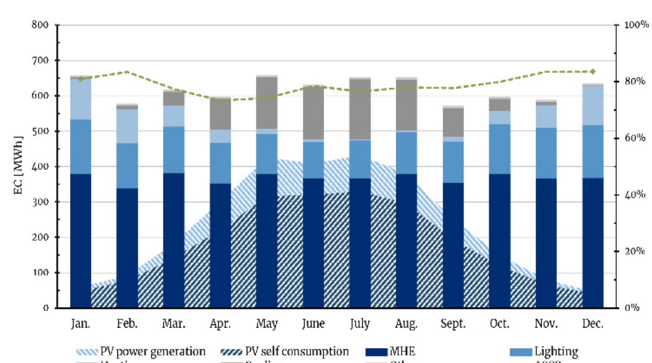

Figure 1. Base-case scenario: monthly electricity consumption breakdown and PV energy self-produced/consumed

The results obtained by the simulated scenarios are reported in Figure 2 in terms of net total energy (NTE), and in Table 1 in terms of energy, environmental and economic performance.

3.2 Scenario A: mMHE fleet fully powered by Li-Ion batteries

Findings indicate that Scenario A improves building energy performance by decreasing monthly NTE (i.e., electricity purchased from the grid), resulting in a lower carbon footprint for warehousing activities. Specifically, the Energy Use Index (EUI) is equal to 21.9 kWh/m^2 compared to 29.5 kWh/m^2 of the base-case scenario. Additionally, the CO_2e emission intensity factor is equal to 5.8 kgCO_2e/m^2 compared to 7.6 kgCO_2e/m^2 of the base case scenario. These KPIs are globally adopted to measure the energy and environmental efficiency of the buildings, allowing for benchmark analyses between different logistics facilities, regardless their floorspace. However, the energy and environmental savings are not obtained due to an increase in energy self-consumption since the renewable energy produced is limited and has already been heavily utilized (see Section 3.1). Thus, the consistent decrease in energy consumption can be attributed to the higher efficiency of the charging process. Specifically, the high-frequency charger operating at 300 Hz has an efficiency rate of 88%, compared to just 78% for the traditional charger operating at 50 Hz (European Standard, 2016, 2005). From an economic perspective, this GW measure results in long-term cost savings, as smaller batteries are sufficient to cover the entire working day thanks to the adoption of an opportunity charging strategy (Modica et al., 2021). This shift has led to a reduction in investment costs, resulting in a return on investment (ROI) of 26% and a payback period (PBP) of 4 years. Moreover, this measure does not significantly influence the operational performance of the warehouse as the operator's breaks are effectively leveraged.

3.3 Scenario B: Replacement of PV panels with high-efficiency ones

The results of Scenario B highlight the significant benefit of generating renewable energy on-site to fulfil the energy needs of the warehouse. Specifically, replacing the existing PV panels with new, high-efficiency models increased energy generation by 47% compared to the base-case scenario. This change could potentially cover 60% of the total energy demand of the building, i.e. an increase from the 37% coverage in the base-case scenario. However, the monthly ASCR significantly dropped down to 59 % compared to the 77% of the base-case scenario (see Table 1). The decline in self-consumption is largely attributed to a misalignment between energy generation and demand. In particular, surplus energy from PV system is produced during times of low energy demand, while there is not enough energy available during peak demand periods. This energy mismatch highlights the building's energy system's inability to effectively utilize the generated solar energy, which has both economic and environmental implications for the solution adopted: a ROI of just 3% and a PBP of 30 years. Hence, approximately 41% of the PV energy produced is sold back to the grid, with the selling price heavily influenced by the national electricity market and its regulations. Renewable energy sales tariffs are frequently subject to change, influenced by European Union agreements and different national regulations. Technological advancements in the renewable energy sector also impact these tariffs, as highlighted in the literature (Prahastono et al., 2019). Typically, such progress leads to a decrease in tariffs, since the economic incentives for selling renewable energy. This trend is encouraging companies to boost their energy self-consumption. A potential solution to cope with these needs could involve adjusting their warehousing processes to match the increase in PV production (see Section 3.2).

3.4 Scenario C: combined implementation of the proposed GW measures

The results obtained highlighted the strong correlation between the two GW measures investigated. The energy and environmental performance of the warehouse substantially improved compared to the base-case scenario. Specifically, the energy and environmental savings achieved are higher than all the previous scenarios investigated. In fact, the EUI and CO_2e emission intensity factor are both equal to 20.1 kWh/m^2 and 5.1 kgCO_2e/m^2 respectively. The significant decrease is primarily ascribed to the combined effect of the two GW measures. The energy surplus generated from the rise in PV power generation is effectively utilized by the building loads (e.g., mMHE) due to the adoption of the Li-ion battery opportunity charging strategy for the entire mMHE fleet. For this reason, the ASCR is increased up to 65% compared to 59% of Scenario B, where only the replacement of PV panels is implemented. This indicates that simply installing PV panels, while maintaining a low ASCR due to a lack of synchronization between the building's energy demand and PV generation, can yield to energy losses and increasing emissions. Adopting renewable self-consumption strategies can lead to significant energy and environmental advantages, while also contributing to a more resilient and sustainable energy grid system. This approach provides companies with an opportunity to establish a sustainable competitive advantage and enhance their energy resilience (Cannava et al., 2024; Prahastono et al., 2019). From an economic perspective, the potential benefits of increasing energy self-consumption are further highlighted. The ROI and PBP for implementing both GW measures are 26% and 4 years, respectively. This highlights that the economic benefits of PV panels are significantly affected by the energy self-consumed on-site. Hence, if self-consumption strategies are implemented alongside the installation of PV panels, the economic cost-effectiveness improves considerably. The energy self-consumption can be further increased by performing fast partial battery charging during peaks of PV production. However, it is important to consider that this approach may have implications for warehouse operational efficiency, as it would require the rescheduling of operator's breaks in accordance with the PV production profile.

6. CONCLUSIONS

This paper presented a simulation-based approach to evaluate the energy, environmental, and economic impacts of various GW measures. The simulation results were analysed and discussed with respect to different KPIs, such as monthly EC, EUI, CO_2e emission intensity, ROI and PBP. The simulation results highlight the potential of renewable energy sources to reduce both energy consumption and environmental impacts when implemented along with self-consumption strategies.

These measures aim to enhance energy self-consumption, ultimately decreasing dependence on the national electricity grid and mitigating risks related to external factors such as energy disruptions, geopolitical issues, and disasters. From a managerial perspective, this research

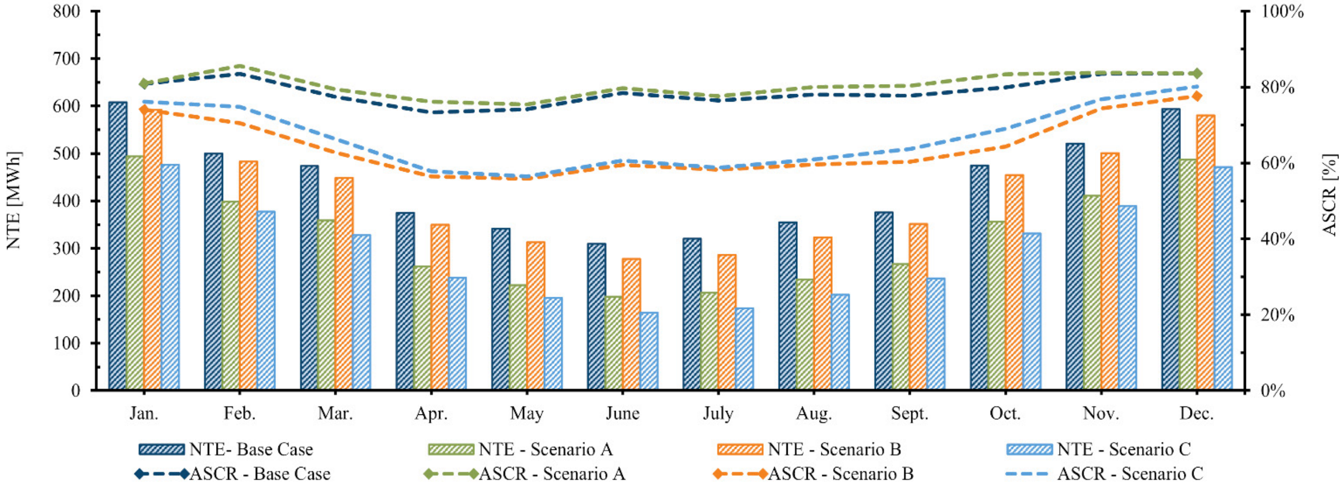

Figure 2. Multiple scenario investigation: energy performance

Table 1. Monthly energy consumption [MWh] breakdown and resulting energy, environmental and economic KPIs for each scenario.

Month	As Is Scenario		Scenario A		Scenario B		Scenario C	
	Electricity [MWh]	Self-consumed [MWh]	Electricity [MWh]	Self-consumed [MWh]	Electricity [MWh]	Self-consumed [MWh]	Electricity [MWh]	Self-consumed [MWh]
Jan	657	49	543	49	657	65	543	67
Feb	577	77	477	79	577	94	477	100
Mar	616	142	505	146	616	167	505	177
Apr	596	221	491	230	596	247	491	253
May	657	316	544	321	657	344	544	348
Jun	630	321	524	326	630	352	524	359
Jul	651	331	542	335	651	365	542	368
Aug	650	295	537	303	650	327	537	335
Sep	570	195	468	201	570	219	468	232
Oct	595	120	482	126	595	140	482	151
Nov	587	67	478	67	587	86	478	89
Dec	633	40	526	40	633	53	526	55
Total [MWh]	7.420	2.172	6.116	2.222	7.420	2.460	6.116	2.532
Self-consumption ratio	77 %		79 %		59 %		65 %	
EUI [kWh/m²]	29.5		21.9		27.9		20.1	
CO_2e emission intensity [$kgCO_2e/m^2$]	7.6		5.8		7.1		5.1	
ROI	-		26 %		3 %		12 %	
PBP [years]	-		4		31		8	

provides valuable insights for companies aiming for Net-Zero targets and encourages logistics managers to evaluate the energy consumption and environmental impact related to their logistics processes, with a specific focus on warehouses. Additionally, the simulation-based approach helps practitioners identify the most suitable GW measures based on the specific needs and characteristics of each facility, thereby supporting evidence-based decision-making. From an academic perspective, this paper offers further empirical foundation for Logistics 5.0 by leveraging sustainable warehousing processes, promoting the adoption of GW measures and ensuring the development of adaptive, resilient, and sustainable warehouses. Despite addressing this notable gap, the study has certain limitations. First, it does not consider the maintenance and installation costs the GW measures investigated. This data may significantly influence the economic outcomes, despite their high variability and strong correlation with individual cases Furthermore, the simulation analysis focuses exclusively on electricity consumption, overlooking other sources such as fuels, refrigerants, waste, and water, which typically have a limited impact. However, this contribution has the potential to lay the groundwork for several research directions: (I) the simulation analysis can be expanded to include other consumption sources; (II) an in-depth analysis of self-consumption strategies to minimize the energy demand-supply mismatch by increasing the resilience of warehousing processes and operation; (III) a broader investigation on how GW measures can impact on the supply chain performances from a Logistics 5.0 perspective; (IV) to extend the application of the simulation-based approach to a variety of industrial sectors (e.g., manufacturing, FMCG sector, pharma) to further validate the effectiveness of this research approach.

ACKNOWLEDGEMENTS

This research is part of a broader project financed by the European Union NextGenerationEU (National Sustainable Mobility Center CN00000023, Italian Ministry of University and Research Decree n.1033—17/06/2022, Spoke 10 ‘‘Sustainable Logistics’’). We would like to thank IKEA S.p.A. that have actively contributed to making this research possible, and for providing data and technical support during the analysis.

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