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Integrating a novel smart control system for outdoor lighting infrastructures in ports

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ABSTRACT

Lighting is amongst the most energy-demanding ports' operations due to the strict legislative illuminance limits ensuring the safety and the visual comfort of ports' end-users. Lighting exceeds 70% of a port's energy demand in most cases. In parallel, they should be harmonised during the energy transition. This research proposes a novel replicable typology of smart-controlling the outdoor lighting infrastructures in three stages: the reallocation and replacement of the obsolete luminaires, the integration of the daylight harvesting techniques, and the implementation of the occupational-based dimming strategy based on the actual data. A typical Mediterranean port was used as a testbed, the port of Rethymno. The innovative aspect of the proposed typology is that it improves two existing smart lighting control techniques and combines them to a complete typology that responds fast and accurately to any possible lighting conditions' alteration in each space distinctively. The system incorporates high replicability and applicability to a great variety of needs, technologies, and spaces. The energy wastes are diminished while the end-used visual comfort is significantly enhanced. The system's energy savings potential and impacts on the port's infrastructures are quantified, discussed and evaluated. The suggested tool leads to a 56.8% decrease in the port's lighting operations' annual energy demand, which may reach up to 90% in some months. The port's environmental footprint is also reduced to half than the baseline levels. In conclusion, the investment is viable and feasible, leading to an investment paid back in less than ten years in some instances.

1. Introduction

The ever-growing energy demand does not allow the entire fossil fuel abandoning, leading to the imminent energy crisis even though the use of clean energy sources increases [1]. Alongside the expanded and stricter environmental legislation, public consciousness on global warming and climate change has increased [2]. The share of **Renewable Energy Systems (RES)** will be more than 32% by 2030[3], while the overall energy efficiency will increase by 32.5%, and the **Green House Gases emissions (GHGs)** are projected to be reduced by more than 40% [4].Table 1.

The technological transition in recent decades has revolutionised the way people interact, work, move, and live [5]; cities need to move into smart, diverse infrastructure to fulfil people's needs through energy-efficient and sustainable means [6]. Smart Cities are becoming a more popular notion in technology-based enterprises [7]; one of the concept's primary goals is to use new technologies and techniques to achieve long-term economic growth and improve everyday quality of life [8]. Managing energy efficiency in cities lets city councils work on critical energy conservation programs with precise environmental and financial viability facets [9]. Buildings and public lighting are the most energy-demanding activities in cities nowadays [10].

The building sector is critical for energy efficiency in an electricity grid because it accounts for 40% of total energy consumption and 36% CO_2 emissions [11]. Also, buildings play a crucial role in the energy transition, as their corresponding energy efficiency measures can lead to

Abbreviations: AICS, Artificial Intelligent Control System; CF, Carbon Footprint; DALI, Digital Addressable Lighting Interface; DHT, Daylight Harvesting Technique; EMF EU, European Union, Energy Mix Factor; GHGs, Green House Gases; IES, International Electrotechnical Commission; IoT, Internet of Things; nZEP, nearly Zero Energy Port; OCT, Occupancy Control Technique; OHCT, Occupancy Hours Control Technique; RES, Renewable Energy Systems; RLT, Replace Luminaires Technique; POWER, Prediction Of Worldwide Energy Resources; SEMS, Smart Energy Management Systems; SCT, Smart Schedule Control System; SOLCS, Smart Outdoor Lighting Control System.

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Table 1
Notations' list.

Symbol	Meaning
CF_{SOLCS}	Carbon Footprint of the smart outdoor control system
E	Energy demand per quarter-hour
E_{OC}	Energy demand per quarter-hour after the occupational dimming
E_{SLDS}	Total energy needed for the illuminance
EMF	Energy Mix Factor
F_D	Diesel Generator emission factor
i	Luminaire type
j	Timestep
k	Subspace number
Lux	Illuminance
OcF	Occupation Factor
U_o	Light Uniformity
Wr_{min}	Least dimming wattage of each luminaire type

substantial energy savings [12]. Lighting is one of the most energy-intensive systems in a building, especially at night. Several studies have been carried out to investigate energy-saving possibilities for lighting systems in buildings, including the use of sensor-based intelligent lighting systems for future buildings in California [13] and an occupancy-based lighting approach for an open-plan Dutch workplace [14]. The effect of daylight or even glazing has been studied in the past, as well as and the impact of different glazing systems [17]. Also, the control of fluorescent luminaires according to the daylight [15] and the use of daylight for affordable lighting in a house in India [16] have been tested in several past studies.

Control systems taking advantage of daylight have considerable energy savings, especially for indoor applications [18]. Daylight harvesting takes advantage of the ambient light to counterpart artificial lighting from the installed lighting systems to achieve a target illumination level, reducing the electric loads [19]. **Light Emitting Diode (LED)** lighting systems' control, based on the combined use of the occupants' location and daylight distribution, leads to substantial energy savings [20].

Table 2 summarises the literature review findings regarding smart indoor lighting energy-saving systems and techniques. Smart office lighting systems are the future trend, as their energy conservation, cost reduction, improvement of safety, comfort, and easy maintenance, make them an essential tool towards sustainability [21].

It has been deducted that applying the daylight harvesting technique to indoor subspaces can be beneficial and fruitful; the energy demand can be significantly reduced, leading to substantial CO_{2eq} savings. However, can it be beneficial for outdoor subspaces? This question is answered in this research work; this initiative's outcomes encourage outdoor subspaces' lighting.

The amount of outdoor lighting in Europe rises [28], while the urban population increases incredibly; 72% of the EU population live in urban areas extending their activities very often after sunset [29]. More than 90 million streetlights are installed globally. The related energy consumption is more than 114 TWh yearly, resulting in 69 million tns **Carbon Dioxide Equivalent ($CO_{2,\ eq}$)** [30]. The environmental and financial impact of street lighting is expected to increase [31] due to the current urbanisation trends [32]; the number of streetlights is predicted to increase by more than 300% in the upcoming decade [33]. The energy demand of cities' public outdoor lighting and their environmental footprint are inherently connected [34]. Indicatively, lighting accounts for 15% of the global energy demand and 5% of GHGs [35]. Therefore this is not only an economic cost for the local authorities, as it represents 60% of the electricity cost in cities, but it also contributes significantly to the GHGs [36]. Smart outdoor lighting systems can assist in the reduction of GHGs [37].

Three main steps regarding energy-saving and reliability of outdoor lighting are discussed in the available literature. The most important findings are further discussed in this chapter, while Table 3 demonstrates all the literature review's findings of smart outdoor lighting control systems. At first, the most common step towards sustainability on lighting infrastructures is the replacement of the lamps and luminaires [38]; the second step is about the ensuring and regulation of the lighting efficiency [39]; and the last step, and less common, is the automatic control of the lamps according to the conditions of the streets [40].

A new philosophy has begun for turning outdoor lighting into more efficient, sustainable and aesthetic infrastructures [41]. Efficient outdoor lighting provides opportunities for the social use of public spaces at night [42] and can improve road safety and crime prevention [44]. Due to the current climate change challenges, several methods have been examined to make lighting more efficient, eliminating energy wastes [45]. The innovation of LED and the exploitation of RES (through energy harvesters) opened new horizons for outdoor lighting studies, entailing energy and economic prosperity [54]. Street lighting can save more than 50% of energy if LED lamps are installed [46]. Also, if Smart Energy Management Systems (SEMS) are incorporated [47], the energy savings can further increase to more than 33%, according to existing studies [48].

Nevertheless, in April 2017, an EU regulation deals with replacing low energy-efficient lamps with contemporary ones [49]. **Smart outdoor lighting control systems (SOLCS)** lead to substantial energy savings and financial profits [79]. Many schemes that selectively control the outdoor luminaires increasing the energy efficiency have been proposed, but little attention has been paid to the resulting street lighting system's utility [80].

Various studies have revealed that proper street lighting design amplifies the sense of personal protection and safety [43]. An efficient and operational street lighting can diminish crime and traffic-collision cases, encouraging socio-economic activities during night-hours [50]. Substantial energy savings regarding street lighting are achieved by implementing traffic-aware lighting schemes and exploiting suitable predictive models [72].

The obsolete ON/OFF lighting technique is based on astronomical clocks [51], with an annual calendar incorporating a scheduling system that is less efficient than other initiatives with the same purpose [52]. Interestingly, utilising algorithms can be highly beneficial to outdoor lighting control; several studies have been conducted regarding tunnel lights, promising significant energy savings [56]. Besides, Artificial Neural Networks are a valuable tool to control street lights' operation; the employed training algorithm attains significant energy savings compared to other algorithms [61]. Lastly, another interesting approach is to create a complete system of both lighting control systems and RES's implementation to create an **Internet of Things (IoT)** system and achieve the best possible outcome [81].

However, efficiently illuminating an outdoor area, such as a port, and complying with each space's distinct illuminance regulations is a complicated task. Outdoor lighting into ports holds a considerable energy demand share [82], exceeding 70% of a port's total energy needs, in some cases [53]. Ports are characterised by high energy demand due to their complex operations and services; thus, they can be considered communities, villages, or small cities [83]. The primary concern for port authorities towards sustainability is to reduce the port-related GHGs [84]. Superior expertise and experience are necessary to minimise port operations' impact on natural resources depletion and national markets [85].

Most of the current port technologies and techniques are outdated; there is great potential for remarkable energy savings and a significant decrease in ports' environmental footprint [86]. In this context, ports are forced to comply with strict monitoring and social regulations [87]. Nearly Zero Energy Port (nZEP) is a promising initiative towards ports sustainability [88]. In parallel, ports' outdoor lighting is essential for safety matters and comfort [89], improving aesthetics [90].

Table 2
Indoor lighting energy improvement cases in the available literature.

	Area of appliance – Studied case	Type of appliance	Energy Savings	Method[1]	Literature (Ref.)
Indoor Lighting	Institutional building	Experimental	up to 60%	OCT	[22]
	Open-plan office	Simulation	up to 30%	OCT	[14]
	Not specified	Experimental	Higher visual comfort levels	DHT	[18]
	Residential building	Experimental	Higher energy efficiency	DHT	[19]
	Office room	Experimental	up to 60%	OCT	[23]
	Residential building	Simulation	up to 26%	DHT	[16]
	Office room	Experimental	not specified	DHT & OCT	[21]
	Institutional building	Simulation & Experimental	up to 22%	RLT & DHT	[24]
	Healthcare building	Experimental	more than 6.88kWh/m^{2}yr	RLT & OCT	[25]
	Institutional building	Simulation & Experimental	up to 60%	DHT	[15]
	Metro station &Company office	Experimental	up to 36%	DHT & OCT	[26]
	Institutional building	Simulation & Experimental	up to 6%	DHT	[27]

[1] Artificial Intelligent Control System (AICT), Occupancy Control Technique (OCT), Daylight Harvesting Technique (DHT), Replace Luminaires Technique (RLT), Occupancy H Control Technique (OHCT), Schedule Control System (SCT).

Table 3
Outdoor lighting energy improvement cases in the available literature.

	Area of appliance – Studied case	Type of appliance	Energy Savings	Method[1]	Literature (Ref.)
Outdoor Lighting	Laboratory	Experimental	up to 25%	AICT	[47]
	Public Lighting	Simulation	up to 65%	RLT & OHCT	[55]
	Tunnel Lighting	Simulation	up to 35%	DHT & OCT	[56]
	Public Lighting	Simulation	up to 15%	RLT + AICS	[40]
	Campus Lighting	Experimental	up to 50%	AICS + RES	[57]
	Public Lighting	Simulation	up to 47%	RLT	[38]
	Public Lighting	Simulation	not specified	DHT & OCT	[58]
	Campus Lighting	Simulation	up to 33%	DHT & OCT	[59]
	Public Lighting	Experimental	up to 70%	RLT	[60]
	Campus Lighting	Experimental	up to 60%	SCT & OCT & RLT	[20]
	Public Lighting	Experimental	up to 13.5%	RLT & OCT	[61]
	Public Lighting	Simulation	up to 17%	RLT	[62]
	Campus Lighting	Experimental	up to 40%	OCT & AICS	[63]
	Public Lighting	Simulation	up to 72MWh/yr	RLT	[41]
	Campus Lighting	Simulation	up to 70%	RLT & SCT	[64]
	Campus Lighting	Simulation	up to 60%	RLT	[65]
	Public Lighting	Experimental	up to 28%	RLT	[66]
	Public Lighting	Simulation	not specified	RLT & AICS	[67]
	Public Lighting	Simulation	up to 40%	RLT & SCT	[68]
	Public Lighting	Simulation	up to 46%	RLT	[69]
	Public Lighting	Experimental	up to 84%	RLT & RES	[70]
	Parking Lighting	Experimental	up to 41%	DHT	[36]
	Campus Lighting	Experimental	up to 80%	RLT & OCT	[71]
	Metro Lighting	Simulation	up to 36MWh/yr	AICS	[9]
	Public Lighting	Experimental	up to 30%	AICS	[72]
	Public Lighting	Simulation	not specified	RLT	[73]
	Public Lighting	Experimental	up to 10%	OCT & SCT	[74]
	Public Lighting	Simulation & Experimental	up to 20%	AICS	[75]
	Public Lighting	Experimental	up to 10%	RLT	[76]
	Public Lighting	Experimental	up to 30%	AICS	[77]
	Public Lighting	Simulation	not specified	RLT	[78]

[1] Artificial Intelligent Control System (AICS), Occupancy Control Technique (OCT), Daylight Harvesting Technique (DHT), Replace Luminaires Technique (RLT), Occupancy H Control Technique (OHCT), Schedule Control System (SCT).

As a contribution to the literature, this research fills several research gaps and rectifies some of the current open issues in lighting control systems for outdoor spaces. The proposed SOLCS handles every subspace individually[1], considering the different legislative and real-time needs, while the vast majority of the available literature handles a single space (mainly streets or parking areas). The people's comfort is satisfied by enhancing the energy efficiency and improving the illuminance output according to the EU standards; the main light indexes are calculated through the utilised software. In parallel, unlike prior research works, there is no need for multiple illuminance sensors due to the modified algorithms of the suggested tool; one photodetector and twenty-one occupancy sensors are required for the proper tool's operation.

Besides, big and credible historical data and a well replicative test-bed are used, leading to realistic and reliable practical outcomes; only a few studies use quarter-hour input sensors' data to control the luminaires in such short time intervals. The credibility and viability of the proposed tool are examined, quantified, and evaluated through a detailed sustainability assessment[2]; future interested parties can replicate the typology due to its high adaptability, which motivates such

[1] The SOLCS concurrently examines, evaluates, and regulates the lighting conditions of 21 port subspaces, according to their unique characteristics, by ensuring the compliance with the most recent EU legislative standards.

[2] Ultimately, all the three sustainability pillars are considered and equally satisfied, establishing a smart and environmentally-friendly system. The optimization of the energy efficiency and the diminishing of the GHGs by concurrently complying with the legislative standards and enhancing the user's visual comfort is examined for the first time, to the best of the authors' knowledge, helping interested parties to easily comprehend its practicality.

initiatives, making it a generic tool for administrative authorities of every interested party regardless of the sector.

This research's main objective is to present, examine and evaluate a novel typology of resizing a port's lighting infrastructures and efficiently controlling them through a complete SOLCS on a three-stage process. A complete and balanced generic solution/tool is presented for a medium-sized Mediterranean port as a testbed, incorporating three energy-saving measures related to outdoor lighting. The tool is a three-step optimisation typology that can be replicated in other cases. Daylight levels and occupancy indexes are the two input parameters that comprise the two evolutionary algorithms of the proposed tool. These two uncontrollable time-variant input parameters increase the system's complexity due to their unhinged discrepancy throughout the day. According to the daylight illuminance's value and each space's occupancy, the luminaires' dimming levels per space are computed in real-time, without any time delay; the maximum energy savings are achieved.

Section 2 addresses the step-by-step methodology created and followed by the research team to renovate the port's lighting infrastructures and then integrate the smart energy management algorithm to control the system's power demand, according to the actual needs. Section 3 provides the key results of the newly renovated lighting system and the proposed SEMS. Lastly, Section 4 represents the conclusions acquired according to the proposed typology results and future recommendations that might improve the proposed methodology.

2. Methods

The research team picked these two techniques, as the research method, due to their wide use in indoor lighting applications. Also, improving the efficiency of the current control algorithms regarding outdoor spaces, such as motion and daylight ON/OFF sensors, was a decisive factor.

According to the strict EU legislation, ports need to illuminate their spaces on higher and more demanding standards regarding illuminance and light uniformity, especially in dangerous spaces; adequately and efficiently illuminating a whole port's area is complex.

The suggested typology is comprised of three major stages (Fig. 1):

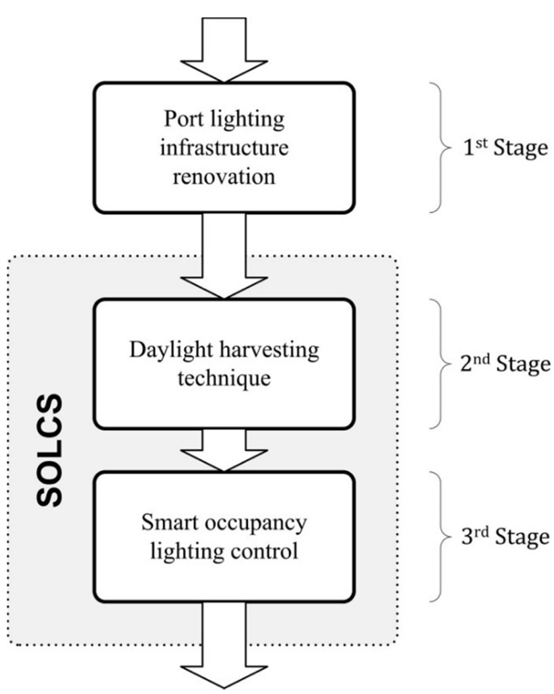

Fig. 1. General flowchart of the proposed methodology.

(a) the total renovation of the existing obsolete lighting equipment;
(b) the daylight-harvesting technique, modified for outdoor spaces, and
(c) the newly-established occupational dimming technique.

A SOLCS is developed and explained in stages (b) and (c). The tool can be applied in any case, either indoor or outdoor, by properly modifying the control algorithms. The input of enough data for the lighting infrastructures and the outdoor/indoor spaces' illuminance regulation standards is a prerequisite for providing reliable and efficient outcomes. The medium-sized Mediterranean Port of Rethymno (Crete, Greece) is selected as the most favourable testbed for this study because of the access to actual data and due to the sustainable vision of the port authorities. Its high outdoor lighting-related energy saving potential and the complex nature of its outdoor lighting infrastructures are a decisive factor. The suggested SOLCS can be applied in any other port outdoor lighting system due to hundreds of similar ports worldwide and its high applicability. There are hundreds of similar-sized ports worldwide, making the proposed SOLCS a highly reproducible tool. Any interested port authority may use the methodology to apply the best combination of techniques based on the case-specific facts; input-data ambiguity is avoided.

The vast majority of ports are characterised by higher energy demand during night-hours due to their outdoor lighting. As long as the system is built for a complicated case, it may easily be adapted to a simpler one. The examined techniques are the most mature among the available options, further strengthening the multiplication potential and the replicability for each possible case. The further evolution of the current techniques leads to even more accurate and energy-efficient results.

The actual historical input data were obtained in collaboration with the port authorities and personnel visiting and reviewing the current lighting infrastructures. The majority of the outdoor luminaires are equipped with low energy-efficient compact fluorescent lamps. The current lighting outcome is insufficient, in terms of uniformity, according to the latest EU regulations. The port is divided into 21 subspaces[3] that serve different operations (Table A.1.) for the needs of this study and to enhance the tool's efficiency; primarily, the EU illumination and uniformity standards are different per subspace and operations.

The port is mainly operating to (a) serve the needs of a transportation vessel twice a week during summertime, (b) serve the needs of fishing boats and smaller vessels, (c) facilitate two spacious parking areas with more than 100 parking lots available, and (d) facilitate the maritime authorities' buildings.

Although several works have examined the efficiency of the two techniques, no one combines them towards a complete SOLCS. Also, the studies regarding the ports' outdoor lighting are inadequate; there is an urgent need for relevant works in port areas, as outdoor lighting is among their most energy-demanding operations.

The daylight harvesting technique is chosen as the already examined systems were based on the scheduled ON/OFF technique; when the illuminance sensor measures illuminance levels above a threshold, the luminaires are turned off. When the sensor measures illuminance values below another predefined threshold, the luminaires are turned on. To the best of the authors' knowledge, only a few researchers measure daylight in real-time and use it to dim the lamps' power appropriately. It is the first time an outdoor daylight system dims the lamps' power on a 15-min time step; only a few studies measure the hourly illuminance levels and control the luminaires to provide the required illuminance.

[3] The research team divided the port area into subspaces to ensure optimal lighting control per subspace. For instance, the inner part is used for only two days per week, which means that the access is strictly restricted for the rest of five days; there is no need to provide that much illuminance as the legislative values indicate.

The occupancy control technique has been used widely for street appliances in the available literature as a power on/off control strategy; the lights are turned on with the presence of a car/person and then turned off after a predefined threshold of time without any presence. The proposed algorithm of occupational dimming is an evolutionary version of the occupancy control technique, which dynamically dims the luminaires' power according to the number of people in each space with particular regard to the required safety standards; the illuminance in each space is not decreased below 40% to ensure the safety even if there is no presence. The 15-min occupancy dimming algorithm leads to more accurate and efficient outcomes and thus to higher energy savings.

2.1. Total port's lighting infrastructure renovation – 1st stage

First, the existing lighting infrastructures are modelled, simulated and evaluated using the DIALux software; the existing luminaires and their current location need redimensioning. Thus, the lighting infrastructures were redesigned, incorporating a new, contemporary lighting system following the most recent EU legislation, concurrently guaranteeing end-users safety and visual comfort (Fig. 2).

The DIALux software, commonly used in lighting applications, ensured that the lighting model's outcomes would be as accurate and reliable as possible for the baseline and the optimised scenarios. A baseline case is created according to the current lighting routines. The baseline scenario constitutes a reliable benchmark with which the optimised scenario is compared. The operational actions are kept constant, were not monitored, and cannot be predicted. The baseline scenario's simulations were validated by measuring the actual illuminance in the port areas and comparing it with the simulated model's outcomes; the illuminance deviations were less than 5%.

The selection of the new poles and luminaires is based on specific inclusion and exclusion criteria; the poles should be resistant to extreme conditions, increased salinity on the air particles, and high wind gusts. Also, the luminaires should be capable of being dimmed; the luminaires feature the Digital Addressable Lighting Interface (DALI), an industry-standard universal protocol specified in the International Electrotechnical Commission (IEC) 62386, industrialised for digital, bi-directional communication among all the components of a lighting control system. The comparison of the two scenarios' outcomes is presented in Fig. 3. The port's subspaces description can be found in Table A.1 (Appendix).

2.2. Control algorithm 1 – Daylight harvesting – 2nd stage

A smart control algorithm is created at the second step to substitute the conventional port lighting schedules, which are currently widely applied worldwide. The current lighting control's typical schedule is based on a simple time-based power on/off strategy; the administration preschedules the luminaires' operation. The luminaires are powered on at full load, neglecting the daylight levels during the port's operation hours.

This research attempts to take advantage of the usable per-quarter daylight amount by dimming the luminaires' output power to provide the additional required illuminance. Precisely, the sun's illuminance during the day-hours is calculated by multiplying the solar irradiance with the appropriate empirical factor. The current sun irradiance data are acquired employing an existing sensor in Rethymno and are indicative for the whole town. The data are validated by comparing them with NASA's Prediction of Worldwide Energy Resources (POWER) and the ones from the National Observatory of Athens [91]. Consequently, the first decision variable of the system is the ambient sunlight's illuminance.

The time-series of the port area's illuminance data are created using a developed algorithm involving actual hourly data for Rethymno and random distribution. The sunrise and sunset time of the day were set according to their empirical daily values for Rethymno. The illuminance measured values are modified by a smart sub-procedure, developing a per-quarter hour illuminance time series. An assumption has been made for the actual illuminance data; the actual illuminance at the sensor's location is the same as the port subspaces' hypothetical one.

A smart procedure was developed considering the daylight's illuminance during the day, inspired by the gaussian distribution, to calculate the per quarter-hour fluctuation of the illuminance. According to this procedure, the first and last hour per day is identified when sunrise and sunset occur. The differences between the per quarter-hour illuminance values in these hours' intervals are higher than those during the midday hours. This procedure handles all these differences, extracting a 15-min time step time-series from the hourly data, involving randomness and ensuring that the newly-created time series is realistic and accurate.

Mathematical models quantify the impact of daylight's illuminance on the actual illuminance demand for outdoor subspaces. Thus, the actual value of incident lux is calculated according to the geometry and the light's desired uniformity, using the DIALux software's outcomes. At the next step, the actual sun's illuminance is being subtracted from the total lux demand for each subspace, as shown in Fig. 4; the calculated difference is the lux demand from the artificial light sources, supplementary to the available lux value from the sunlight, indicating the real lighting needs per subspace during each timestep.

Subsequently, the improved daylight harvesting algorithm searches for the actual minimum wattage per subspace's available luminaires that could provide the required quarter-hour illuminance and correspondingly dims the luminaires wattage. Each luminaire's illuminance contribution is calculated from the DIALux outcomes to eliminate any possible deviation of each subspace's lighting uniformity.

Fig. 4 shows the actual application of the daylight harvesting technique. The baseline system's operation is presented on the figure's left part; the luminaires provide all the required illuminance to meet the required levels regardless of the available amount of daylight. The system under the daylight harvesting technique on the figure's right part shows that the amount of daylight plays a crucial role in the dimming of the luminaires; the luminaires' wattage is set after the calculation of the sunlight's illuminance, as mentioned before.

The actual energy demand per timestep is calculated by using equation (1), which is taking into consideration the type of luminaires used in each space (i, the five types of luminaires), the actual timestep number (j, 35,040 per-quarter timesteps for a year), and the number of the subspace (k, 21 different subspaces in the port's area).

$$E_{SLDS} = \sum_{i=1}^{i=5} \sum_{j=1}^{j=35040} \sum_{k=1}^{k=21} W_{rmin} \tag{1}$$

E_{SLDS} = the total energy needed for the smart lux dimming system

W_{rmin} = the least available dimming wattage of each lamp capable of providing the required lumens

2.3. Control algorithm 2 – Occupational dimming – 3rd stage

An enhanced occupancy-based control system is proposed at the third stage to increase the SOLCS's efficiency further. At the moment, each subspace's occupancy is disregarded, leading to energy wastes for spaces that are not used during night-hours. This research comes to propose a lighting control algorithm incorporating the subspaces' occupational data. The information about each subspace's occupancy is acquired by asking relevant questions to the port's administration and staff. An empirical, per quarter-hour time-series of the occupancy (%) was then created using MATLAB; unexpected events were also considered by implementing a random number generation in the algorithm.

The occupational dimming algorithm considers every subspace's occupancy for the non-operation hours to properly dim the luminaires' power level.

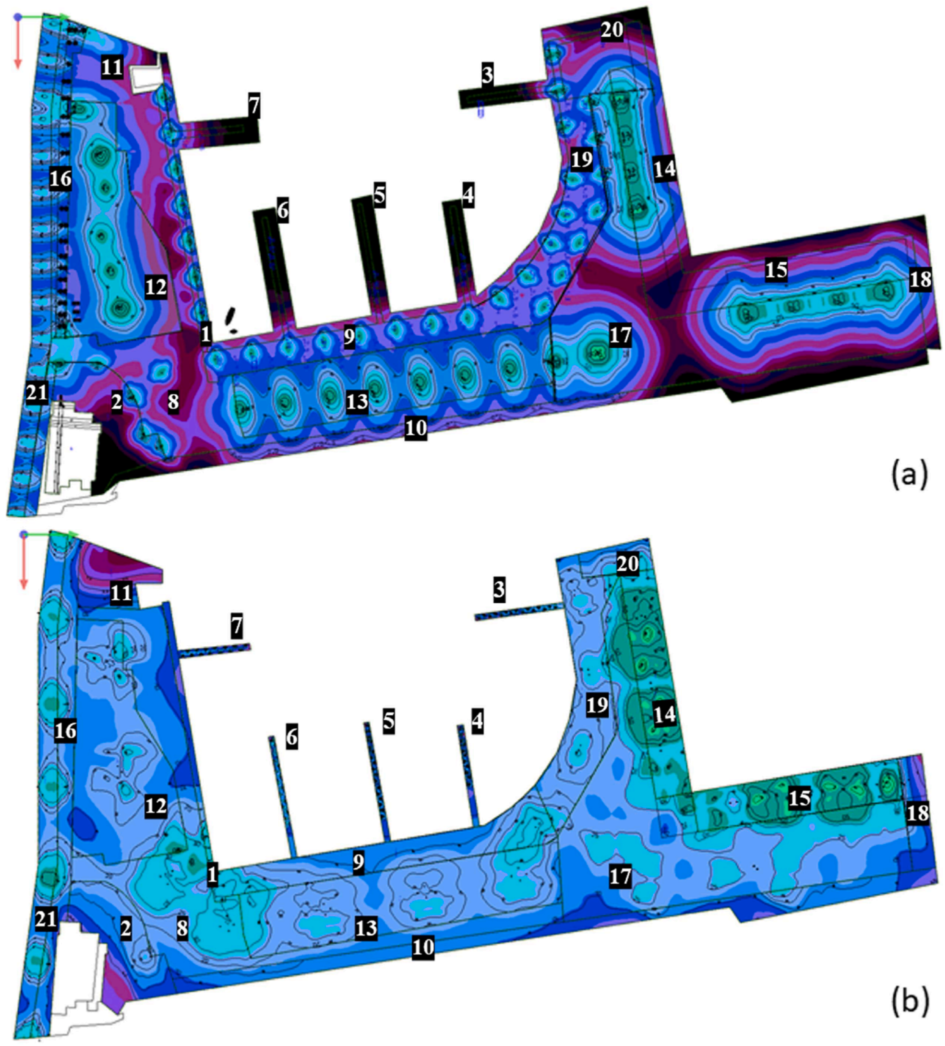

Fig. 2. Comparison of the port's subspaces' illuminance (top view) for the baseline (a) and the proposed case (b).

Specifically, an algorithm that calculates the occupancy (%) per subspace is created based on the acquired information from the port's personnel. The basis of the per quarter-hour occupancy is the experience of the port's personnel and some empirical measurements that were made through the observations' method. Expressly, the staff indicated specific lower and upper practical limits of each subspace's occupancy for the different periods of the day. Indicatively, during the operating hours (06:00–18:00), the per quarter-hour occupancy (in the span 0–10) is considered as 10 (100%); during the night hours right after the operation hours (till 00.00), the per quarter-hour occupancy is between 3 and 10, while after 00.00 the per quarter-hour occupancy is between 0 and 6. Also, some data from the port's parking area were utilised to estimate each port's per-quarter occupancy.

The research team tried to eliminate the possibility of creating a biased occupancy time-series by using a newly-created advanced algorithm based on the specified lower and upper occupancy bounds, motivating the port's stakeholders to adopt similar techniques. The occupancy factors are calculated using a properly developed algorithm, picking random values between the lower and upper limits. The random number generator ensures that the outcomes are not biased. The research team decided not to power off any of the subspaces' lighting but to set lower boundaries for safety reasons; even if there are no people at the port's subspaces, the luminaires will never be dimmed below 40% of their rated power, ensuring adequate illuminance during all night-hours for any possible unexpected event (Fig. 5). The total energy demand from the implementation of this technique is calculated by equation (2), similar to Equation (1).

$$E_{oc} = \sum_{i=1}^{i=5} \sum_{j=1}^{j=35040} \sum_{k=1}^{k=21} [(0.6 \times E \times OcF) + (O.4 \times E)] \tag{2}$$

E_{OC} = the per quarter-hour energy demand from the implementation of the occupational dimming algorithm

E = the per quarter-hour energy demand

OcF = the occupation factors

This technique can be used alongside the daylight harvesting technique mentioned above, converting equation (2) to equation (3).

$$E_{oc} = \sum_{i=1}^{i=5} \sum_{j=1}^{j=35040} \sum_{k=1}^{k=21} [(0.6 \times E_{SLDS} \times OcF) + (0.4 \times E_{SLDS})] \tag{3}$$

E_{SLDS} = *the total energy needed for the smart lux dimming system*

E_{SLDS} = *the total energy needed for the smart lux dimming system*

OcF = *the occupation factors*

2.4. Control algorithm 3 – Combination of 2nd and 3rd stage

The optimal results can be achieved by combining the control mentioned above to create a complete SOLCS.

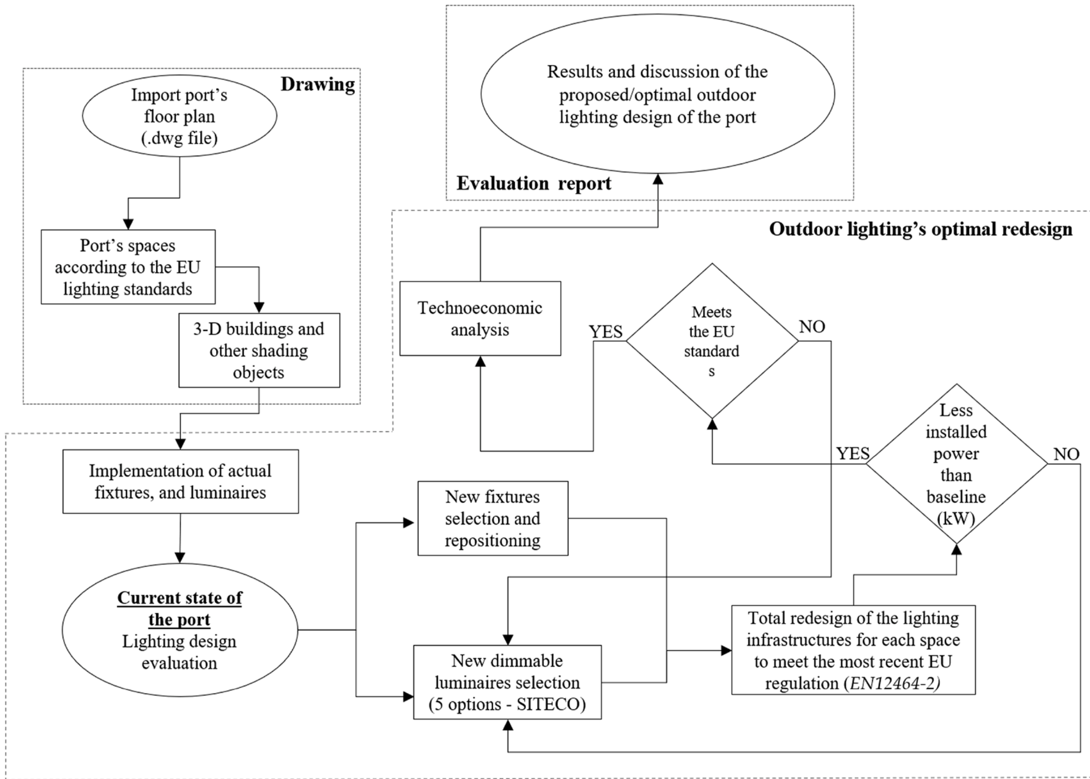

Fig. 3. The 1st stage of the adopted methodology; the marina's lighting equipment total renovation.

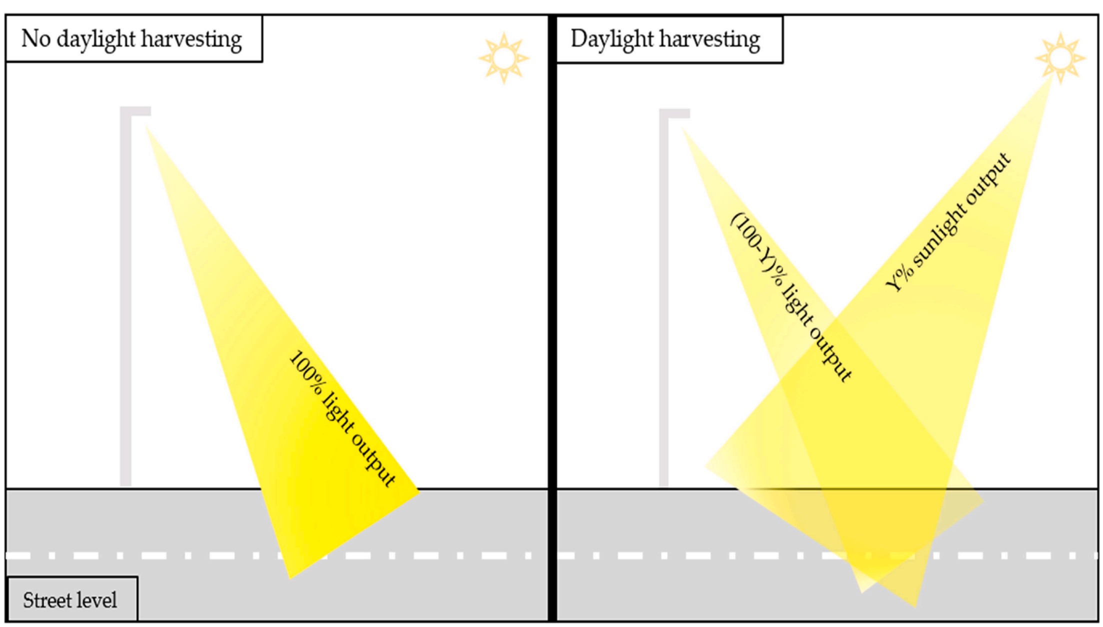

Fig. 4. Daylight harvesting technique for the hour before the sunrise and the sunset.

The first step is to provide the required input data through four different ".csv" data files. These files include the data needed for (a) the hourly daylight, (b) the per quarter-hour operation and occupation factors, (c) the unique characteristics of each subspace, and (d) the unique specifications of each out of five suggested DALI luminaires. The hourly daylight data is converted to per quarter-hour, applying a smart algorithm explicitly described above.

Next, the smart system checks for the operation factors and sets the per quarter-hour energy demand to the baseline case. The next step is to investigate the ambient daylight illuminance and each subspace's actual lux demand. The actual illuminance per subspace is calculated using DIALux, considering its geometry and unique characteristics. Then, the optimal wattage of each luminaire (local minimum) is set by the smart algorithm; if there is more than one type of luminaires in the same subspace, the actual proportion of their lumens output is taken into account to avoid possible losses and interruptions on light uniformity.

The last step of this methodology is the human presence's calculation in each subspace, and the corresponding luminaires' dimming level,

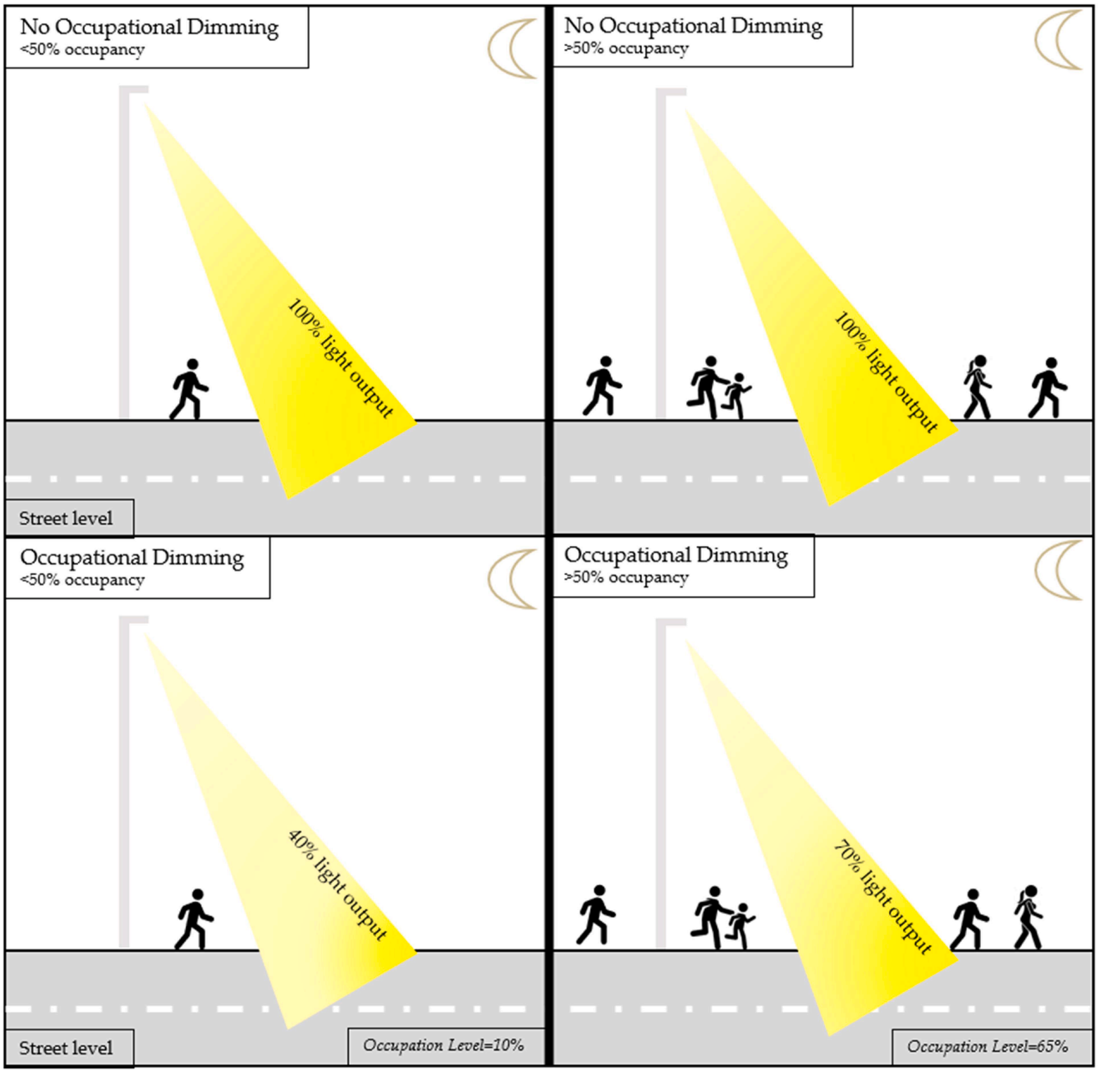

Fig. 5. Occupational Dimming technique for the night hours.

based on the predefined values, i.e., the lowest possible value is 40% of the rated power.

The overall operation of the suggested SOLCS-tool, per subtask, is presented in Fig. 6.

2.5. Assumptions

Several assumptions have been made for the needs of this study. First, the port's outdoor lighting infrastructures are assumed to be divided into 21 unique spaces, and the electricity billing scheme (energy cost) is assumed to equal 16c€/kWh. Since all subspaces are open outdoor spaces (almost) no shadings, the daylight's illuminance level is set the same for each subspace. The existing poles are assumed that can be reallocated and can house the newly-picked luminaires. Also, the costs of the equipment are acquired from the manufacturer company's personnel.

For the baseline case, it is assumed that the existing luminaires operate for 10 to 11 h daily, depending on the season. Moreover, for the daylight harvesting technique, it is assumed that the examined luminaires have a zero-response time and unlimited times to be dimmed, as the manufacturer company indicated. For the occupancy dimming technique, it is supposed that the luminaires are not allowed to be dimmed below 40% of their total power and that fewer people visit the port areas during the late-night hours, according to the port's personnel. Lastly, the hypothetical sensors for the daylight and the occupancy are assumed to operate uninterruptedly and measure the input data every 15-min.

The Carbon Footprint (CF) is measured in $kgCO_{2,\,eq}$, and is calculated by multiplying the total energy demand with the Energy Mix Factor (EMF) [92]. The $CO_{2,\,eq}$ per kWh for the Crete's electricity grid equals 0.989 $kgCO_{2,\,eq}$/kWh and the CF of the SOLCS is calculated by equation 4 [93].

$$CF_{SOLCS} = F_D x EMF = 0.989x0.785 = 0.776kg\frac{CO_{2eq}}{kWh} \tag{4}$$

3. Results

Ports have a fishing village's or town's characteristics; roads, pavements, green areas, administrative buildings, and docks. Specific subspaces need to be more illuminated than others due to the current legislative limits. Some specific subspaces in ports, such as docks or passenger areas, have limited safety to handle their operations under low illuminance. These areas are more energy-demanding than others, in terms of lighting, for safety reasons. Due to the different legislative limits and variations of various subspaces' illuminance levels, they can be considered building zones. Smart systems created for ports feature high versatility as they can be replicated in other lighting applications.

The current lighting infrastructures consume more energy (96,190

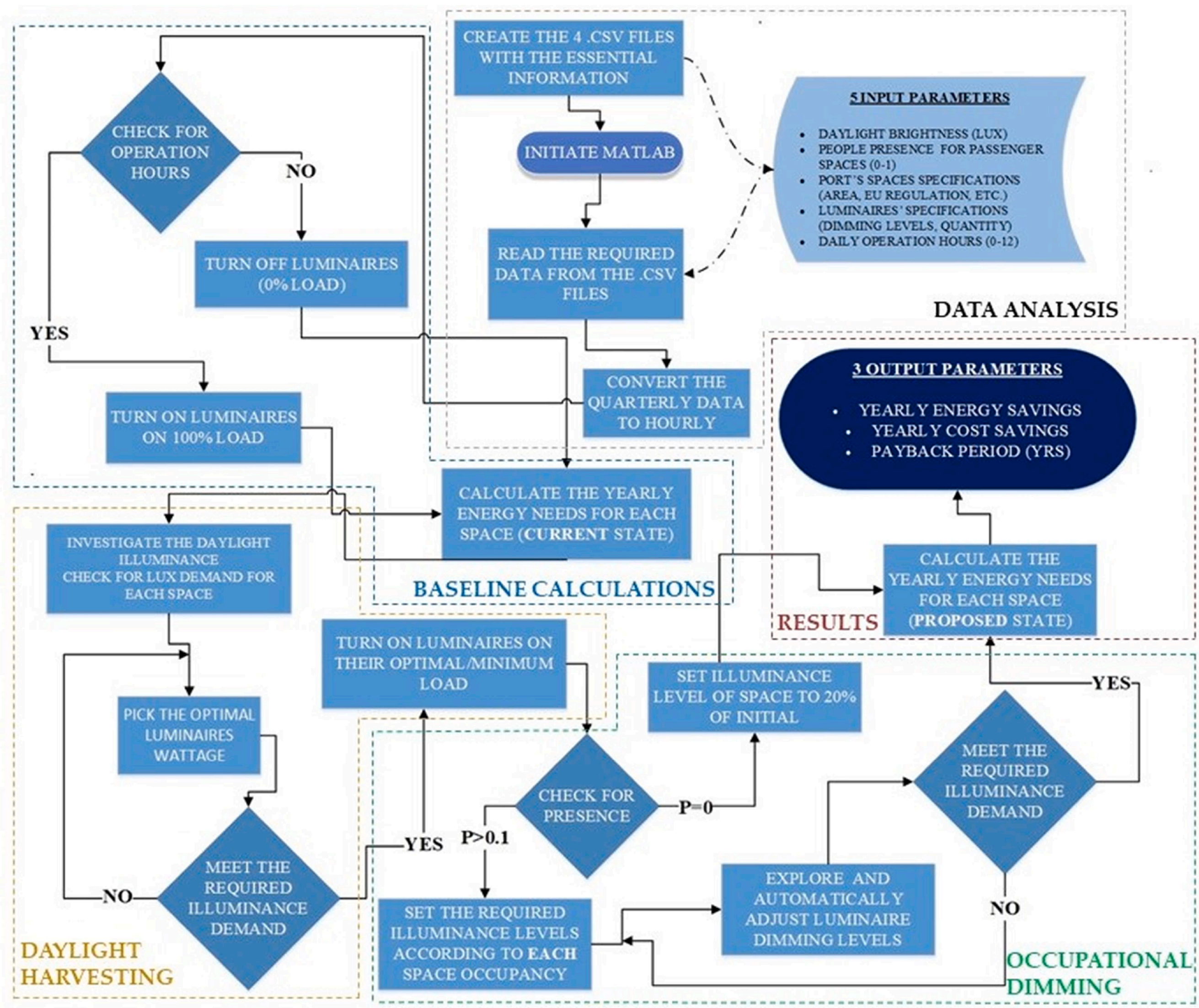

Fig. 6. Flowchart of the smart outdoor lighting control system.

kWh/yr) than the optimal because of their old-fashioned technology; thus, the need for replacement and renovation is urgent. As for the 1st stage, the new lighting system is much more effective than the baseline (Fig. 7); the total yearly energy demand is reduced from 96.2 to 76.7 MWh (21.3%), which corresponds to 15.1 $tnCO_{2,\ eq}$[4] savings. Similar past initiatives have shown that even higher savings can be achieved while the possible energy savings are related to the existing luminaires' technology and output power. Fig. 7 depicts the daily energy and $CO_{2,\ eq}$ savings during the 1st stage of the SOLCSs.

The energy consumption is reduced to 50.3 kWh from 76.7 kWh (34.4%), further decreased by 13.7% from the 1st stage. Fig. 8 and Fig. 9 depict the hourly energy decrease attributed to daylight harvesting in four different subspaces during the shortest (21st of December) and the longest (21st of June) day of the year, respectively. The dark blue colour line gives the baseline case, the green line is for the 1st stage, and the yellow line is for the 2nd stage. Regarding the 2nd stage, the energy consumption is lower during the first (sunrise) and the last (sunset) day-hours. This is different among the various subspaces because of the legislative standards; streets and subspaces with low illuminance requirements present the most significant percentage decrease. The proper tool's operation is validated as there is strong fluctuation among the results per day and subspace (Fig. 8).

There are subspaces for which the 1st stage is much more effective and efficient than the two smart control systems. For instance, in subspace 21, concerning the main street outside the port, the total installed luminaires power is reduced by 1.45 kW, resulting in substantial energy savings (more than 70% of the initial energy consumption). This corresponds to 20kWh/day savings; almost 2.2$tnCO_{2,\ eq}$ can be saved annually.

Meanwhile, for the subspaces with higher lighting installed power, the percentage decrease achieved by the 1st stage is lower; regarding subspace 14, where the passenger boarding occurs, the lighting requirements are the highest; an 8.0% decrease is achieved, corresponding to 12kWh/day and 0.74$tnCO_{2,\ eq}$.

Fig. 9 illustrates the overall lighting's energy demand on June 21st regarding all stages for (a) the three previously-picked subspaces and (b) the whole port area. As this day is the longest of the year, the outdoor lighting demands are the lowest. Based on the corresponding figures, the total hourly energy consumption is lower during June than December; the overall energy savings are higher during the winter months because

[4] For the $CO_{2,\ eq}$ calculations, the energy mix of the island of Crete was taken into account, as mentioned before. The island's electricity grid is being supplied 21.47% from RES and the rest 78.53% from fossil fuels combustion. The $CO_{2,\ eq}$ coefficient is equal to 0.989 $kgCO_{2,\ eq}$/kWh.

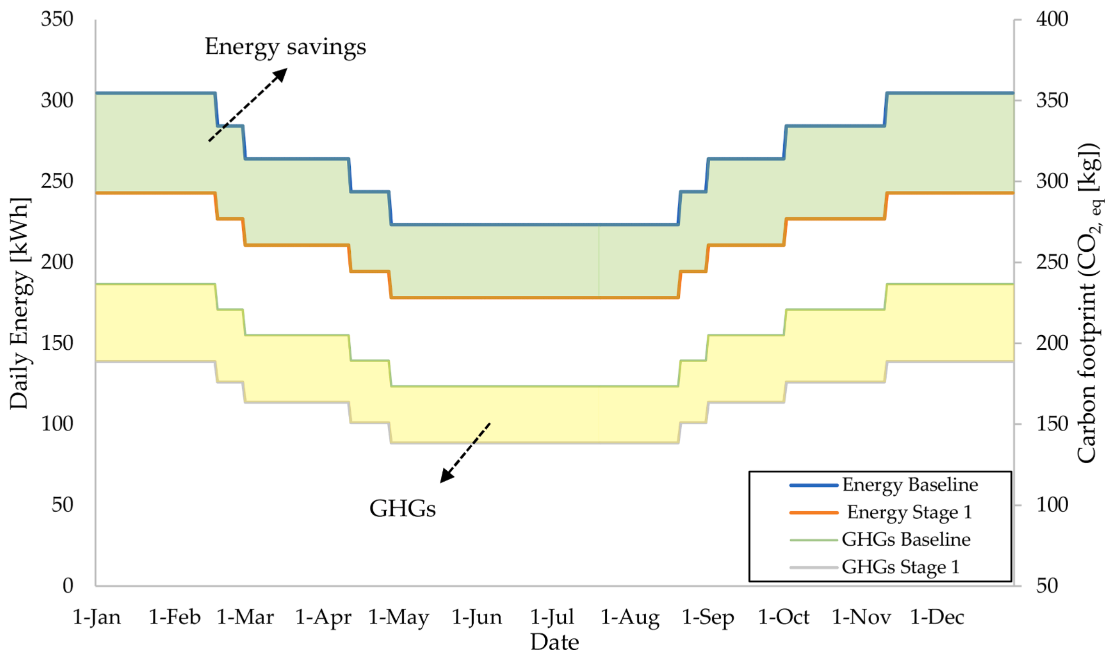

Fig. 7. Daily energy and GHG savings for the 1st stage of the methodology.

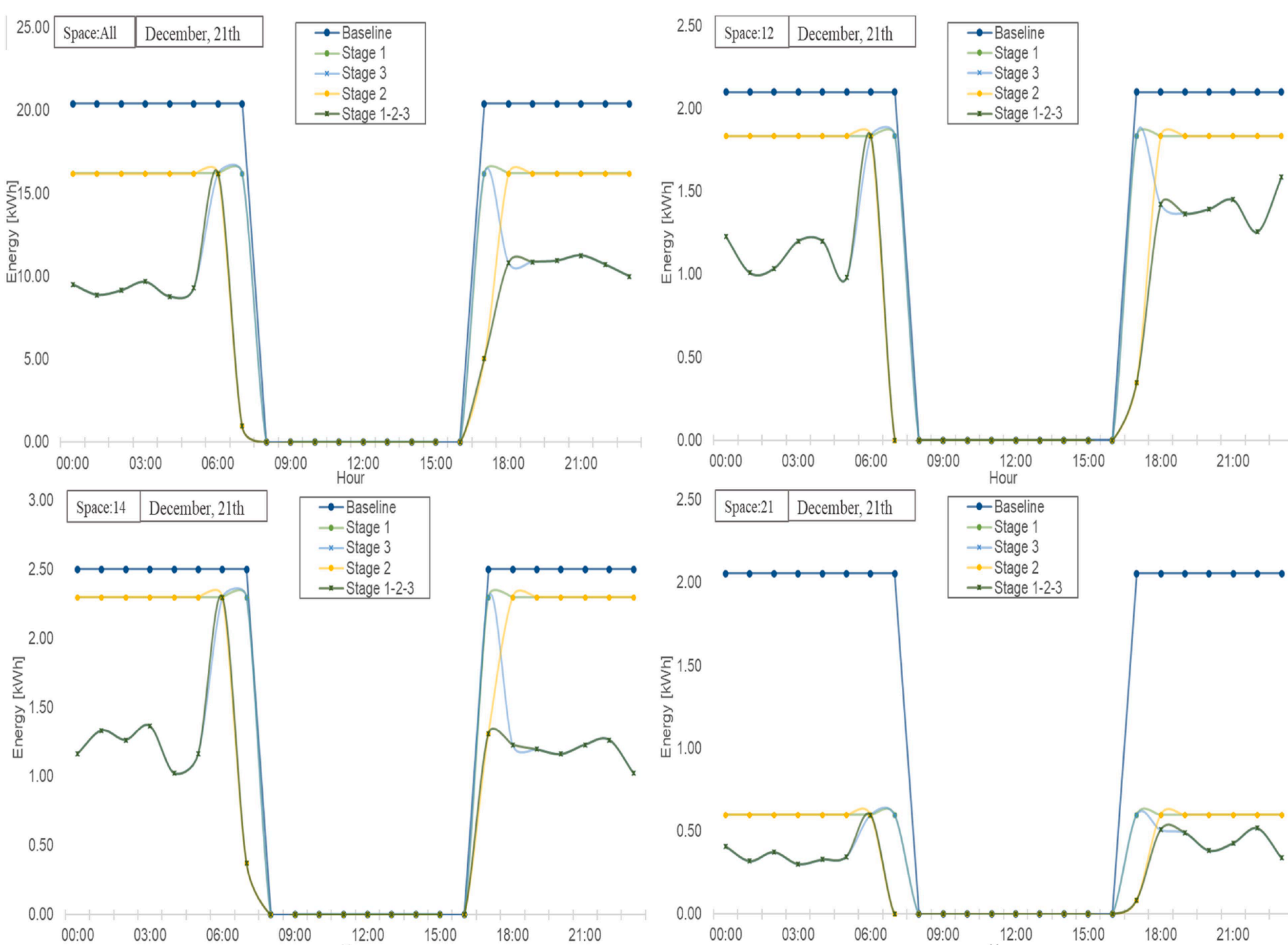

Fig. 8. Hourly energy demand per stage of the methodology for four spaces' cases for the 21st of December.

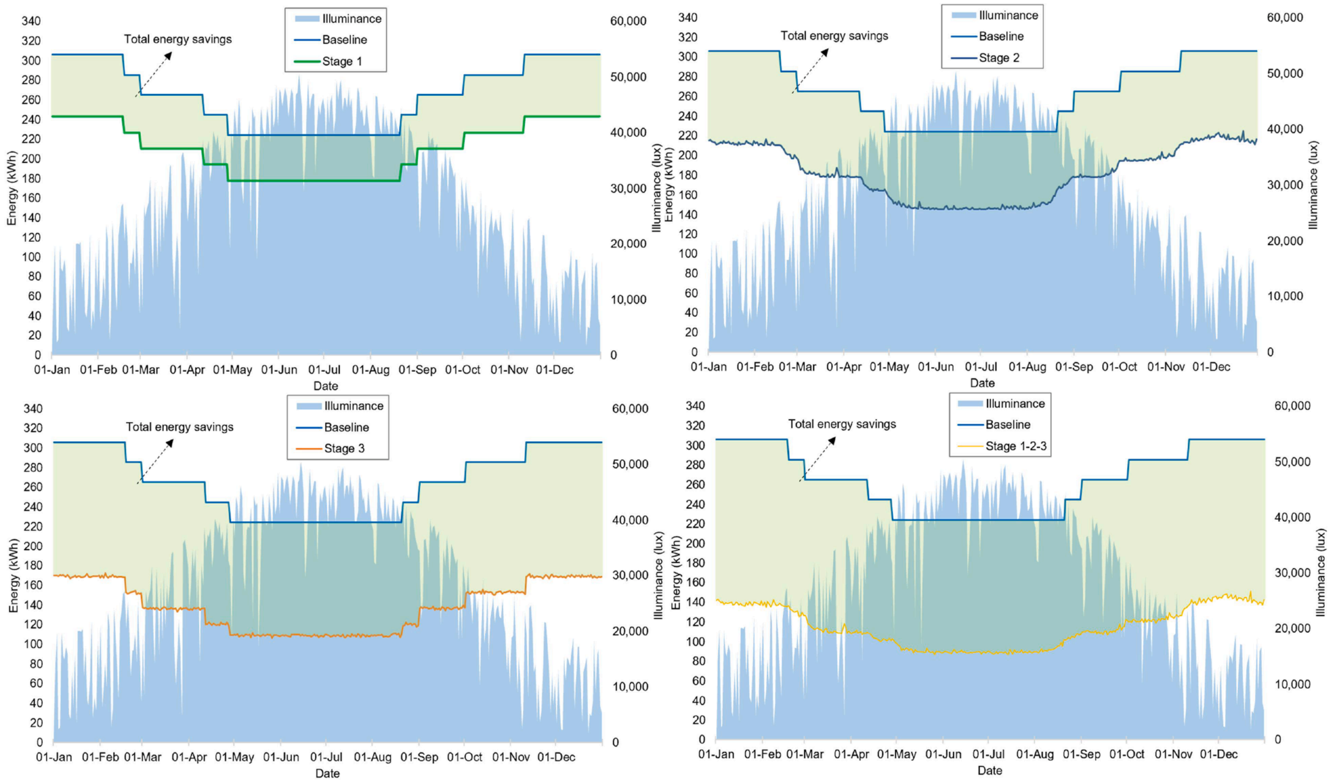

Fig. 9. Hourly energy demand per stage of the methodology for four spaces' cases for the 21st of June.

of the higher lighting energy demands.

Similarly, as in December, the total energy savings are considerable for all the methodology stages. The occupancy factors are different for these two specific days, attributed to the visitors' high seasonality on the port's subspaces. Subspaces 12 and 14 present lower energy savings after the 1st stage procedure (replacement and reallocation of the luminaires), attributed to the high legislative EU standards. Moreover, due to the high currently installed power for lighting, stages 2 and 3 are

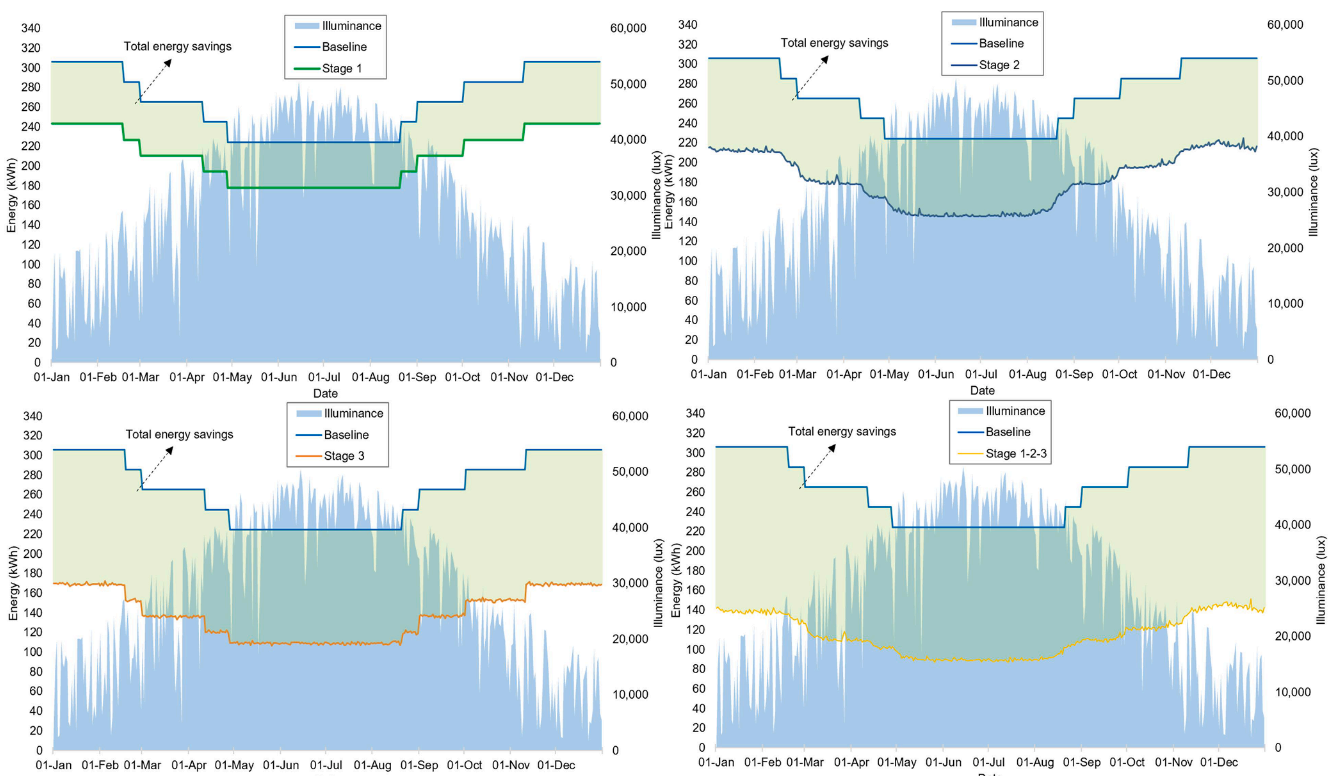

Fig. 10. Total daily energy demand, daylight illuminance, and energy savings for the three stages of the suggested typology for all the subspaces.

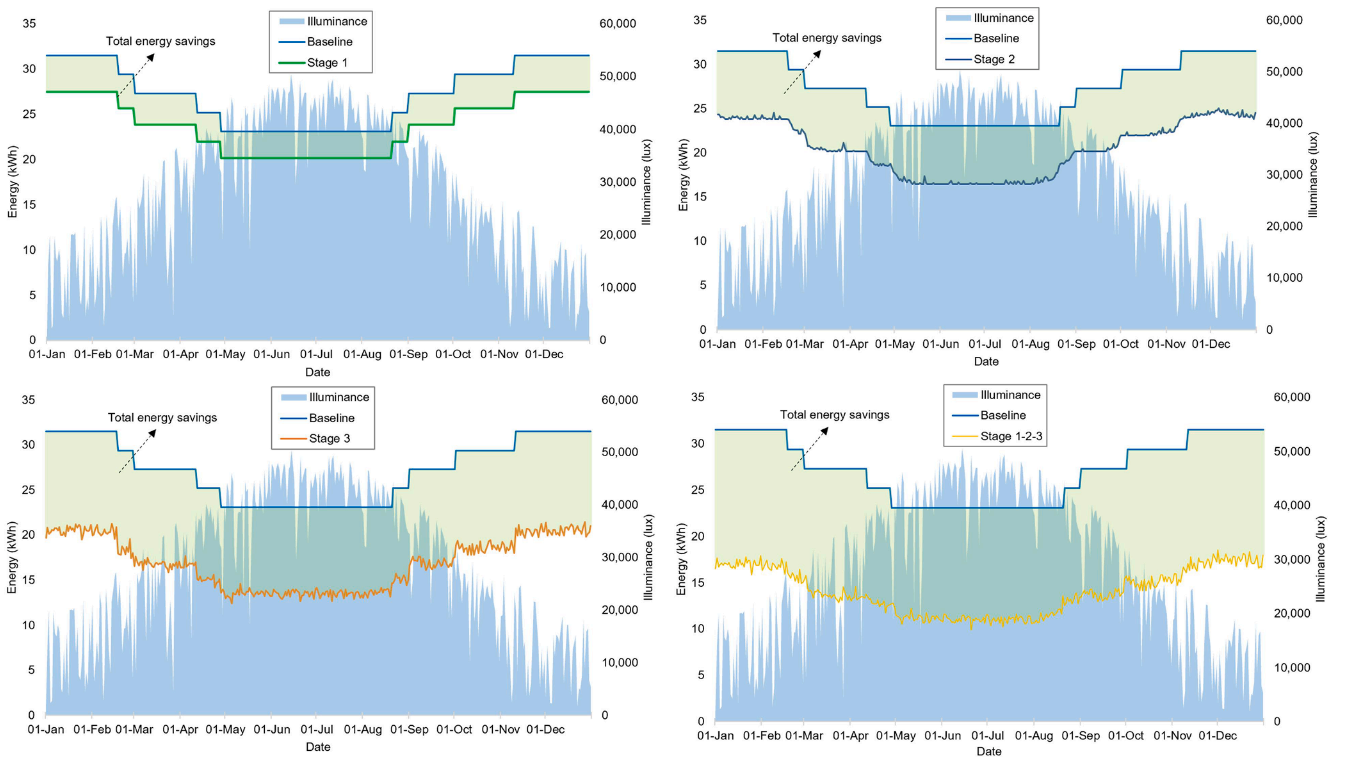

Fig. 11. Daily energy demand, daylight illuminance, and energy savings for the three stages of the suggested typology for subspace 12 (Parking area 1).

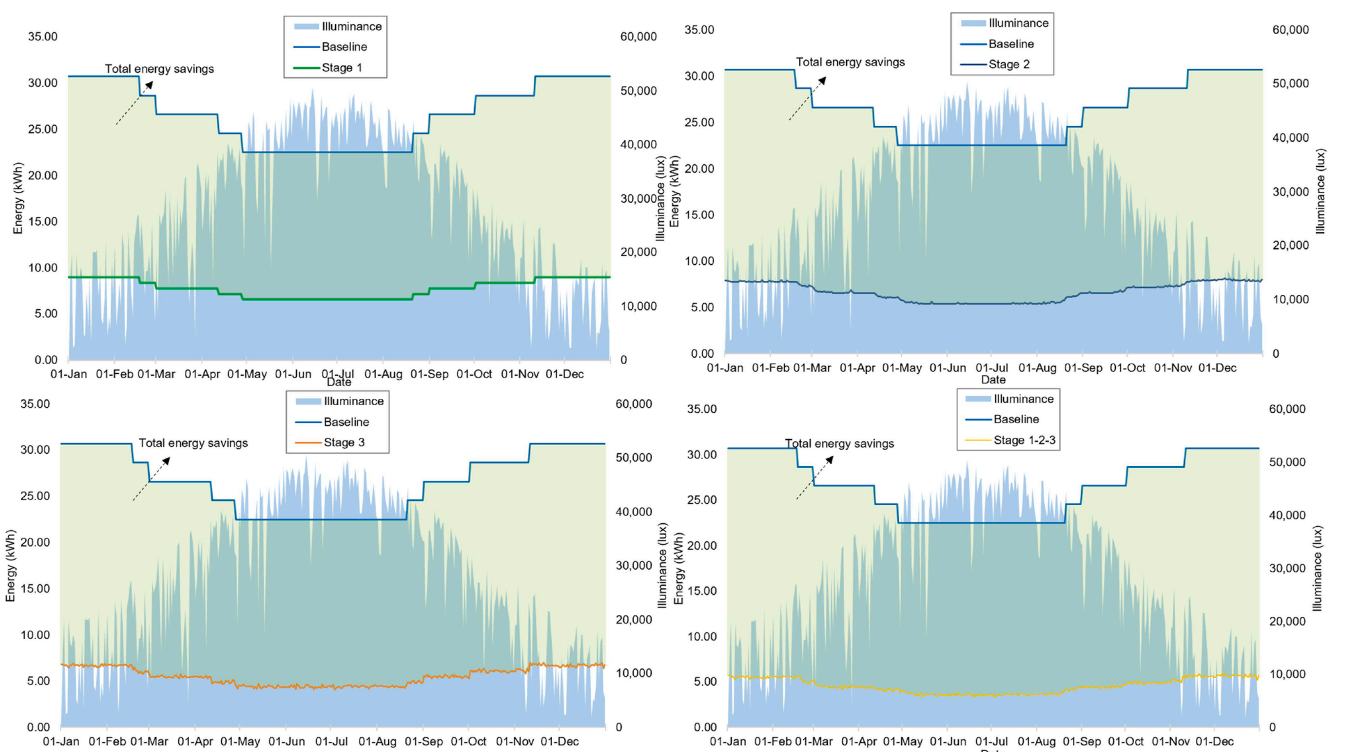

Fig. 12. Daily energy demand, daylight illuminance, and energy savings for the three stages of the suggested typology for subspace 21 (Venizelou street).

beneficial, leading to very high energy savings.

Figs. 10, 11, and 12 depict the energy savings and the daily illuminance among the methodology's different stages. The energy consumption for the lighting operations of the marina subspaces 12 and 21 are presented, respectively. The energy savings regarding the 1st stage are satisfactory for the port area and Parking 1 (subspace 12). Additionally, the energy savings on subspace 21 (Venizelou Street) are outstanding for the 1st stage. On the other side, the more beneficial the 1st stage of the methodology is, the less beneficial the net two stages are. This can be easily explained as the total energy savings are higher when the installed lighting power is higher due to the increased energy savings potential. Besides, even if the energy savings at some stages are not so significant, the total energy decrease is high because of the measures' efficiency. Consequently, since the stages are inherently connected, the results are optimal, according to the most recent EU legislative standards.

The overall energy savings are remarkable for every subspace when all three stages are implemented. Each stage's drawbacks are counterbalanced by another stage's benefits, resulting in a well-established end-product.

Considering subspace 12 (Fig. 11), where one of the two parking areas is located, the 3rd stage is the most influential; the occupancy factors appeared to be the most effective control strategy.

The highest energy consumption reduction for the 1st stage is observed on subspace 21 (Venizelou street). The installed energy is decreased to 0.60 kWp (greater than70%) while the energy savings potential is reduced dramatically for the following two stages (Fig. 12).

Fig. 13 shows the actual energy consumption's shift among all the stages. Considering the stages by order, the 1st stage's results are substantial. Indicatively, there is a 20.6% decrease in energy consumption compared to the current state. This decrease reaches 31.4% when the 2nd stage is applied, while the total energy savings can rocket up to 56.8% compared to the baseline case.

If the 3rd stage is compared to the baseline, skipping the 2nd stage, the energy savings are about 48%. This implies that the occupancy control smart algorithm's importance to such situations due to its high applicability, replicability, and efficiency alongside its significant low implementation, operation, and maintenance cost.

Also, to further evaluate each stage's efficiency, the total annual energy demands between the consecutive stages are compared. There is a 20.6% energy consumption decrease from the baseline when applying the 1st stage, a 13.6% decrease between the 1st and the 2nd stage, and a 24.1% decrease from the 2nd to the 3rd stage. The findings, as mentioned above, do enhance the conclusion that the occupancy control system (3rd stage) has the highest potential in similar cases.

Lastly, Fig. 14 depicts the monthly fluctuation of the total energy demand for the port. The daylight's illuminance is limited during the winter months. Consequently, the luminaires themselves must provide much more illumination, consuming more energy. Fig. 14 also shows the actual monthly savings due to the implementation of each stage, as the energy expenses are proportionally connected to the energy consumption due to the fixed energy cost.

The proposed SOLCS achieves the highest energy savings during the late-night hours, as expected (Table 4). After midnight, there is a restriction to access some port's subspaces; there are energy wastes during these hours. The problem is solved by employing the proposed system; almost equal amounts of energy are consumed during the early-night hours (before 00:00) and the late-night hours (after 00:00). Indicatively, the energy savings can reach up to 68%, leading to significant GHGs savings (Table 4).

Although the overall energy savings are significant, the highest savings are between May and July due to the more efficient use of the daylight's illuminance. The highest amounts of energy are saved during August and November for the post-midnight time period, while the lowest amounts of energy are saved during these months for the period before midnight. Indicatively, the total energy savings for November are 3.83MWh; 1.58MWh are saved before midnight, while the rest 2.25MWh are saved after midnight. The overall cost of the system is estimated to be almost 200,000€ due to the high investment cost for replacing the luminaires and some of their poles.

The initial investment will be paid back in 15 to 20 years, considering the total energy savings. If the proposed SOLCS is included in the port's authorities' sustainability plan, the investment will be much more feasible and practical; the energy demand will be substantially diminished compared to the current state. The payback period of this holistic framework could be reduced to seven or even five years; the initiative is now considered fruitful, viable, and reliable.

This tool is critical to support port management authorities towards nZEP. This research work aids the port management authorities on a multidimensional level as it offers a wide variety of useful capabilities regarding their most energy-intensive operation. The proposed SOLCS embeds critical features that have overcome the limitations of past researches and have filled some of the research gaps.

At the outset, the proposed SOLCS provides a remote-control tool

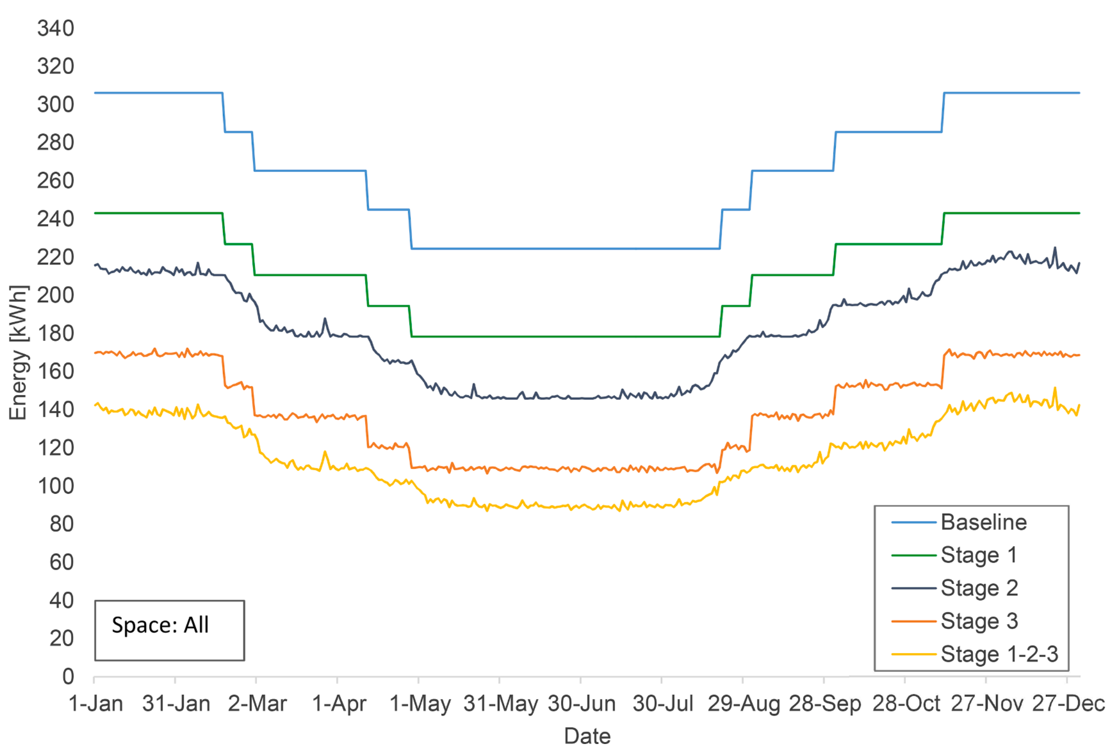

Fig. 13. Total energy consumption for all the port's subspaces during all the three stages of the proposed typology.

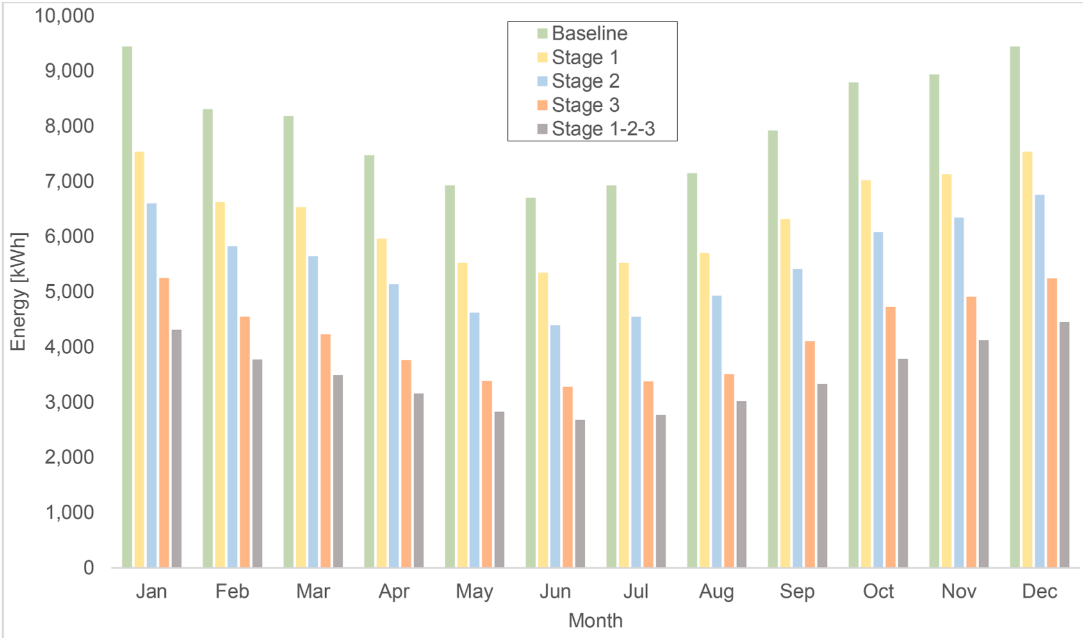

Fig. 14. Total monthly energy demand for the whole port area for all the three stages of the suggested typology.

that can be embedded in any current outdoor case if the current infrastructures can house it by properly modifying the appropriate calculation parameters. Also, the establishment of the control algorithms minimises the error possibility by providing accurate control setpoints to the luminaries, eliminating the energy wastes. The energy savings are more than 50% for the whole port area, while the savings can reach even higher percentages for some of the port spaces. Thus, the energy costs are proportionally decreased for the port authorities leading to significant capital savings in a reasonable initial investment cost. If combined with the implementation of RES and energy harvesters, the investment's significance is rocketed up.

Besides, the environmental footprint of the port operations is meaningfully decreased as the energy efficiency is enhanced. The corresponding $CO_{2,\ eq}$ is eliminated; more than 40 $tnCO_{2,\ eq}$ are saved yearly. The newly installed lighting infrastructures provide higher energy efficiency and visual comfort, as the strict EU regulations are adequately satisfied. The proposed SOLCS can be a decisive tool for the accomplishment of the climate-neutral EU by 2050.

Lastly, based on those mentioned above, it is well-known that GHGs penalties are projected to be applied in the immediate future to motivate stakeholders to move towards sustainability into their infrastructures. As a critical node to global transportation, Ports must move towards sustainability to provide a green and sustainable logistics and transportation chain. Thus, the avoidance of these penalties due to the ports' outdoor lighting infrastructures would be highly beneficial to the related authorities and stakeholders; this capital could be possibly invested into other sustainable measures, such as the implementations of RES and SEMS for other port activities (cranes, cold-ironing, etc.).

4. Discussion and conclusions

A SOLCS specially designed for ports is being presented in this research work. The proposed SOLCS incorporates three major steps, which include: (a) the renovation of the current port lighting infrastructures, (b) the implementation of the Daylight Harvesting and the Occupational Dimming techniques, and (c) a combination of the above to wholly evaluate the tool. The main novelty of this research work is that it effectively combines and improves three common energy-saving techniques for outdoor lighting, creating a highly replicable SOLCS. The suggested tool is universal as it can be easily implemented in other outdoor or even indoor cases if the appropriate data are available and the control parameters are appropriately modified; the tool can also be tested and evaluated in actual conditions by simply installing the required sensors in any possible testbed. Also, the suggested SOLCS utilises actual historical data about the input parameters, leading to realistic simulations' outcomes and reliable conclusions. The immediate tool's response to sudden changes of the control parameters is an asset that was missing from the existing literature's systems, while the division of the port's area to 21 subspaces, individually handling each subspace, is presented for the first time in the literature, to the best of the authors' knowledge. Delving deeply into the algorithm's novelty, the improved occupational dimming and daylight harvesting techniques lead to substantial energy savings while, at the same time, improving the end-users visual comfort.

As an overall outcome, energy wastes during the first, the last, and the late-night hours are diminished, leading to substantial benefits due to the two implemented control techniques. The tool leads to an average 56.8% decrease in the port's lighting operations' annual energy consumption, which can be compared to similar past research works; the available literature indicates that energy decreases up to 70%, confirming this research's findings. For several months and some other spaces, the energy savings can be higher than 90%. The main differences to the past studies are that this tool uses a combination of three lighting-related energy-saving techniques in a port area for the first time, on which 21 unique subspaces are handled and optimised individually. Also, the simulation period is a whole year with 15-min interval time-steps; most of the past works are about small-scale projects for a single space, and the test periods are short/medium-term. Lastly, compared to the past literature's tools, there are no prediction schemes or motives that may lead to inaccurate outcomes.

The future of smart lighting approaches is a multi-disciplinary research field. Consequently, the existing smart lighting systems need to be thoughtfully re-built to create a brighter future for lighting, inspired by the current research. The proposed tool yielded intriguing and unique data that may be beneficial when approaching a port's outdoor lighting design, paving the way towards sustainable development in terms of energy, economics, and social factors.

According to the available literature, past studies have faced various

Table 4
Energy and GHGs savings for (a) The overall system, (b) the period before 00:00, and (c) the period after 00:00.

	All					Before 00:00					After 00:00				
	Baseline[1]	SOLCS[1]	Energy saved[1]	% of saved energy	CO_2 saved[2]	Baseline[1]	SOLCS[1]	Energy saved[1]	% of saved energy	CO_2 saved[2]	Baseline[1]	SOLCS[1]	Energy saved[1]	% of saved energy	CO_2 saved[2]
Month															
Jan	9.49	4.31	5.17	54.5%	4.02	4.43	2.09	2.34	52.9%	1.82	5.06	2.23	2.83	56%	2.20
Feb	8.57	3.77	4.79	55.9%	3.72	4.00	1.80	2.20	55.1%	1.71	4.57	1.98	2.59	57%	2.01
Mar	8.22	3.49	4.73	57.5%	3.67	3.79	1.72	2.08	54.7%	1.61	4.43	1.77	2.65	60%	2.06
Apr	7.96	3.16	4.80	60.3%	3.73	3.67	1.65	2.02	55.0%	1.57	4.28	1.50	2.78	65%	2.16
May	8.22	2.82	5.40	65.7%	4.19	3.79	1.42	2.38	62.7%	1.85	4.43	1.41	3.02	68%	2.35
Jun	6.73	2.68	4.05	60.2%	3.15	3.06	1.33	1.73	56.7%	1.35	3.67	1.36	2.32	63%	1.80
Jul	6.96	2.77	4.19	60.2%	3.25	3.16	1.37	1.80	56.8%	1.40	3.79	1.40	2.39	63%	1.86
Aug	6.96	3.02	3.94	56.6%	3.06	3.16	1.54	1.62	51.3%	1.26	3.79	1.48	2.32	61%	1.80
Sep	7.96	3.33	4.63	58.2%	3.59	3.67	1.70	1.98	53.8%	1.53	4.28	1.63	2.65	62%	2.06
Oct	8.22	3.79	4.44	54.0%	3.45	3.79	2.06	1.74	45.8%	1.35	4.43	1.73	2.7	61%	2.10
Nov	7.96	4.12	3.83	48.2%	2.98	3.67	2.09	1.58	43.1%	1.23	4.28	2.03	2.25	53%	1.75
Dec	9.49	4.46	5.03	53.0%	3.91	4.43	2.24	2.19	49.4%	1.70	5.06	2.22	2.84	56%	2.21
Total **96.74**	**41.72**	**55.00**	**56.87%**	**42.72**	**44.62**	**21.01**	**23.66**	**53.11%**	**18.38**	**52.07**	**20.74**	**31.34**	**60.17%**	**24.36**	

[1] The total energy is measured in MWh.
[2] The GHGs are measured in $tnCO_{2eq}$.

Table A1
Description of port's subspaces.

a/a	Subspace	Lux demand	Area	Short Description
1	Bottom Dock Area	10	488.7	Only for pedestrians
2	Building Yard	5	2,167.1	The yard outside the port's personnel's building
3	Dock 1	10	157.9	Boats and vessels bunkering point
4	Dock 2	10	194.1	Boats and vessels bunkering point
5	Dock 3	10	196.2	Boats and vessels bunkering point
6	Dock 4	10	200.0	Boats and vessels bunkering point
7	Dock 5	10	150.0	Boats and vessels bunkering point
8	Main Street 1	20	7,527.6	The main port's street, nearby the parking areas, leading to the passenger areas
9	Mid Dock Area	20	3,224.4	Only for pedestrians
10	Right port's side	5	3,310.5	Only for pedestrians
11	Left Port's side	5	1,164.8	Only for pedestrians
12	Parking 1	20	5,731.9	Port's parking place
13	Parking 2	20	6,040.5	Port's parking place
14	Passenger Area 1 - Inland Ships	50	2,394.1	Inland ships bunkering point
15	Passenger Area 2 - Cruise Ships	50	2,538.7	Cruise ships bunkering point
16	Road's side road walk	20	2,389.8	The road walk outside the port
17	Street 2	20	11,198.8	The secondary port's street, nearby the passenger areas
18	Upper Commercial Port	10	815.7	The upper side of the port; it's used only during daylight hours by the port's personnel
19	Upper Dock Area	20	3,224.4	Only for pedestrians
20	Upper Left Side	10	597.4	Only for pedestrians
21	Venizelou St.	20	2,800.3	The main street leading to the port's entrance

limitations such as the input data uncertainties due to the lack of actual data and the forecasts errors; even with a small error, the optimal solution is irrelevant from the financial and environmental perspective, which highlights the importance of the utilisation of actual historical input data. Likewise, to most of the past researches, this study faces the problem that outdoor lighting systems produce various consequences related to various factors extending the problem to a multi-objective issue. Lastly, all the available studies have faced the limited available initial capital issue.

On the other hand, this research study had several restrictions, such as the unavailability of quarter-hour illuminance data for the port area, the lack of indoor spaces' data to examine the effectiveness of this smart system, and the lack of market data for other luminaires.

Concluding, the proposed SOLCS is a complete well-established tool necessitating implementation in actual conditions, utilising in-situ installed sensors to validate its high effectiveness. Besides, some more actions can be taken from port authorities to enhance its effectiveness, such as installing illuminance and occupancy sensors to various port's spaces to acquire more precise input data for the control parameters. Also, applying this methodology to other infrastructures, such as university campuses, villages, streets, etc., or even into indoor spaces to compare its effectiveness with other similar systems would be highly beneficial. Lastly, more luminaires' types could be examined during the first stage of the proposed tool.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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