Article

Data-Driven Methodology for Coliving Spaces and Space Profiling Based on Post-Occupancy Evaluation through Digital Trail of Users

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Abstract: Sustainable spaces are those that are optimized, accessible, promote user experience and aim to reduce CO_2 emissions while enhancing users' well-being and comfort. The purpose of this paper is to present a methodology that was developed during the COVID-19 pandemic to understand and improve the use of coliving spaces based on remote Post-Occupancy Evaluation (POE) analysis of the digital trail generated by the users. Applying the POE methodology based on data collection from IT infrastructure enabled to identify opportunities to improve the future design of human-centered spaces. The residential market, design-wise traditional for centuries, is now facing a high-speed adaptation to the changing needs, accelerated by the COVID-19 crisis. New ways of living and shared spaces like Coliving are escalating. Technology is both an enabler of this shift in housing and the solution to operating and managing these new buildings. This paper demonstrates, through the case study of a Coliving space located in Madrid, Spain, the benefits of implementing data analysis of the digital trail collected from in-built IT systems such as smart locks, Wi-Fi networks and electric consumption devices. The conclusion is that analysing the available data from the digital infrastructure of coliving buildings can enable practitioners to improve the future design of residential spaces.

Keywords: coliving; COVID-19; digital trail; human-centered design; Post-Occupancy Evaluation; space profiling; sustainability; user experience

1. Introduction

Designing the perfect home for its resident has been architects' ambition for centuries, aesthetic perfection, functionality, which responds to the consumer's market. Today, the residential sector is experiencing a paradigm shift due to the changes in needs of its inhabitants: the incorporation of technology in spaces [1], remote working trends [2,3], workforce intercity and intercountry relocation and fluidity. Additionally, an unaffordable urban housing market [4] that makes houses non-accessible for part of the population and an increase in loneliness [5–7] are factors that are driving people towards diverse rental typologies with more shared spaces and innovative plug-and-play solutions, like coliving [8]. This is a trend that has been accelerated by the COVID-19 pandemic [9,10].

Before COVID-19, Europeans spent around 55%–66% of their time at home—home indoors—[11]; these ratios have increased during the pandemic, when we spent a considerably larger amount of time at home due to restrictions. In 2021, a new normality has brought new routines and evolving requirements for residential spaces.

COVID-19 has led to a redefinition of the way we live, how we use our residential spaces, our behavior and home responsibilities [12]. Loneliness, once said to be the

illness of the XXI century, has risen exponentially, partly due to the regulations imposed by governments in response to pandemic [5,6,13]. According to the United Nations, community actions to reinforce social cohesion and reduce loneliness are needed to reduce the mental health consequences of the pandemic [14].

Coliving is an emerging residential typology, a "top down, modern form of housing where residents share spaces, activities, values, and/or intentions" [1,8]. These shared living solutions have shown ways of fostering human relationships and close networks that improve daily lifestyle, without imposing sharing behavior or patterns, simply by enabling users to choose what spaces to occupy and the levels of camaraderie they want to engage with. Monitoring and evaluating the use of these spaces has become essential to improving the future of spaces and promoting sustainable housing, tracking the factors of environmental, social, and financial sustainability [15,16]. Post-COVID-19 housing resiliency is related to flexibility, adaptability, reducing risk infection and ensuring user well-being [17,18], and has turned even more human-centered.

HCD defines a design based on human needs and experience [1]. HCD puts the end-users, humans, at the center of the design [19]; psychology and technology are implicit in its initial planning [1,20,21]—the human factor of buildings. Research that connected architectural design and behavioral patterns [18] has grown exponentially thanks to smart technologies and sensors [22].

The level of digitalization of buildings is also growing exponentially [23]; as buildings become smarter and more connected, the Architects, Engineers and Constructors (AEC) industry must adapt [1]. Smart buildings are living entities capable of adapting to the changing needs of the users and reporting to practitioners to improve the future design of spaces.

This research aimed to generate a methodology of spatial analysis using Post-Occupancy Evaluation (POE) of the spaces' performance and user behavior patterns based on the available technology infrastructure.

There were two primary objectives: the first was to identify the data provided from existing data sources that will offer valuable information for HCD spaces, and the second was to generate data-driven Space Profiles (SP) based on the methodology generated that can help AEC experts improve the design of future coliving spaces based on data-driven techniques.

The innovation of the current research also relied on the methodology fully performed remotely due to COVID-19, in real time and relying on the existing IT infrastructure of Coliving without adding other sensors.

1.1. Coliving

The residential sector is transforming quickly, accelerated by the COVID-19 crisis. Factors such as densification of cities, population growth, affordability, housing supply, demand dichotomy, rising prices [24] and lack of regulations [25] have impacted house prices and facilitated the evolution of new housing typologies. Coliving offers a more flexible leasing structure and increased engagement with the household to form more meaningful connections with housemates and the general community—regardless of the duration of stay [26].

Coliving operators, property managers and real estate investors have highlighted that their formula of success relies on providing the creation of fluid communities and neo-tribes [27], which are related to a state of mind and a lifestyle more than a membership or lineage [28,29]. Coliving also provides a variety of shared spaces mutualized by the whole community otherwise unavailable and unaffordable in a traditional way of living. Characteristics that made them have grown exponentially across Europe and other areas (Figure 1). For the new creative class, home means also an ideal place of work: it is mobile and social [30] with the communal spaces being key for the users [27]; additionally, the need for exterior and communal spaces, core spaces of coliving buildings, has also multiplied due to the COVID-19 crisis [18,31].
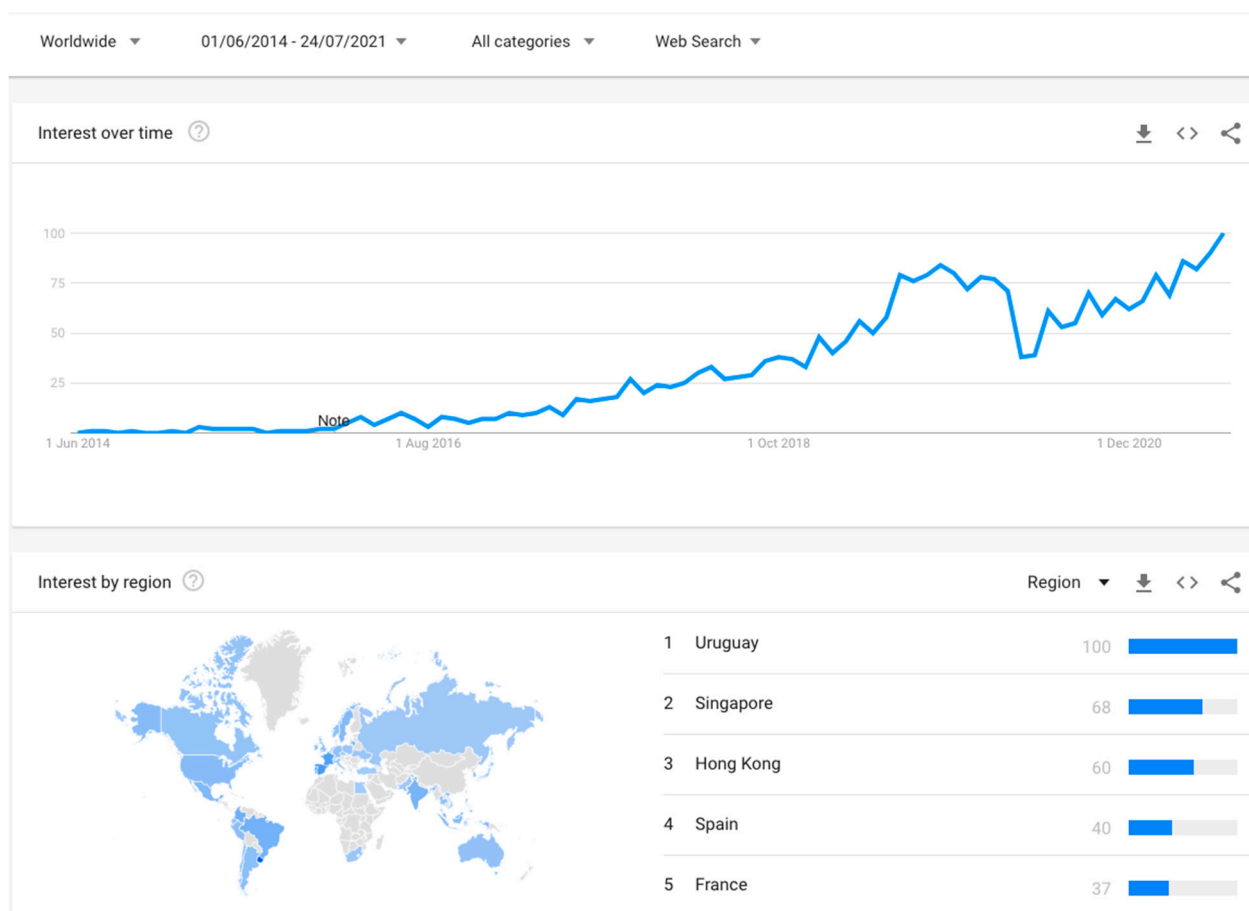
Figure 1. Evolution trend for the term 'coliving' Worldwide in the past 7 years 2014–2021 [32].

The rise in searches for the term 'coliving' in 2015 was likely due to an increase of these facilities in New York City and companies beginning to expand this typology outside of the tech world [33]. Spain is now the country with the fourth highest interest globally, according to Google, and the first in Europe. The current research was performed at Urban Campus, a coliving operator in Spain and France with several assets being operated under coliving and coworking and with a strong strategy for monitoring and optimizing buildings performance and user wellbeing.

One of the spatial strategies to encourage community is incrementing the shared amenities [34,35] and sharing these spaces with the whole community. The incidence of these spaces outside of the private room has promoted informal interactions, which in turn enhanced familiarity among residents and community [36].

Nevertheless, little architectural or interior design research is available to describe this emerging typology and scattered best-practices or guiding principles are appearing to aid designers in making informed decisions when designing or evaluating coliving spaces [8]. There has also been limited exploration into the houses to understand HCD approaches and climate adaptability of smart housing to meet user needs [1,37].

1.2. State of the Art Data-Driven Design through Post-Occupancy Evaluation (POE)

Using data for building design is not new ([38–40]). But incorporating qualitative and quantitative data in decision-making processes is a practice that has been recently incorporated into spatial design [41,42]. Post-Occupancy Evaluation (POE) is the methodology of obtaining feedback on the use of spaces in a building and its performance for the users [43,44].

Within this changing paradigm, a need for more advanced, digital methods to understand the use of space and improve its design has risen [45,46]; POE and other methods [47,48] are becoming essential to analyzing the current use of spaces, predict performance and ensure housing resiliency [17,49–53]. Recent studies have shown how POE could improve electricity performance predicted during the design of non-residential spaces [54]; a similar method has been applied for coliving residential spaces.

The POE is generally carried out a minimum of one year after the building is fully occupied [55] and includes several methodologies to perform holistic research of the building. The research studied a method of integrating technology and Internet of Things (IOT) data analysis as an added real-time assessment of end-users' electricity consumption patterns [56]. Remote comfort and well-being tracking systems and sensors enabled to collect and analyze data with little human intervention [28,57].

Innovation and new technologies facilitate a faster and more accurate understanding of the occupancy of and interaction with space [58,59]. IOT integrated entities of the physical world by making them addressable through the Internet and making the Internet accessible through physical objects. [60]. New ways of monitoring and data analysis have already provided real-time feedback as shown in different spaces like workplaces [46,61,62]. This paper reflects how residential spaces like coliving can undergo a similar transformation by incorporating in-built technology infrastructure POE data analysis to assess use of space.

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2. Materials and Methods

The study relied on available digital infrastructure designed for Urban Campus Colivings (smart locks, Wi-Fi, and electricity consumption devices) as data sources for operating coliving, defined as Post-Occupancy Evaluation (POE). The coliving spatial assessment evaluation framework in Table 1 sets a basis to understanding behavioral performance of spaces and to making informed decisions towards future sustainable and Human-Centered Design (HCD) of spaces. Behavioral patterns in space, experience, environmental consumption, and well-being were assessed.

In Figure 2, the 4 methodological stages were mapped based on the available IT infrastructure piloted in the study: (A) Electricity analysis, (B) Access analysis, (C) Network crosscheck, (D) Spaces profiling study. The mixing methods theory [76,77] was used to combine quantitative and qualitative inputs and was implemented during phase (D) to generate the SPs.

The data sample of the coliving spaces were collected during a 31-day period (1 May 2021–1 June 2021). Additional data were collected retroactively for the Electricity analysis for 1 year (1 June 2020–1 June 2021) in order to demonstrate the applicability of the methodology to explore and compare the use of spaces across different times and seasons. The data were extracted, cleaned, processed, and represented the data through PowerBI—a business analytics platform from Microsoft enabling user friendly visualization and interactions for behavioral analysis and sustainability decision making.

The subject group of study included the 72 residents of the coliving space with an age range of 25–40 years and coming from multiple nationalities including local Spanish colivers. For the current study, full authorization was granted by the residents and the data were treated in full compliance with the EU General Data Protection Regulation, (GDPR), being aggregated and anonymized accordingly to regulations. The analysis was performed in accordance with the principles outlined in the Declaration of Helsinki.

2.1. Spatial Definition

The current study analyzed a 3000 m^2 coliving residence in Madrid. The building has been operated as a Coliving by Urban Campus since 2019; the methodology that enabled the carrying out of remote research developed was fully compliant with regulations and COVID-19 restrictions in place in May 2021. Four different typologies of spaces in the Coliving were categorized into Table 2. There were three cluster spaces; a cluster is a shared flat consisting of individual or double studios with a private bathroom and a shared space with a shared kitchen and living room. Both the entrance door to the cluster and the door that separates the common cluster spaces from the private studio had a digital smart lock that managed entry permissions (see Figure 3). The shared kitchens and living rooms of all the clusters were open to the entire community from 07:00–23:59 and remain accessible only to cluster inhabitants during the night.
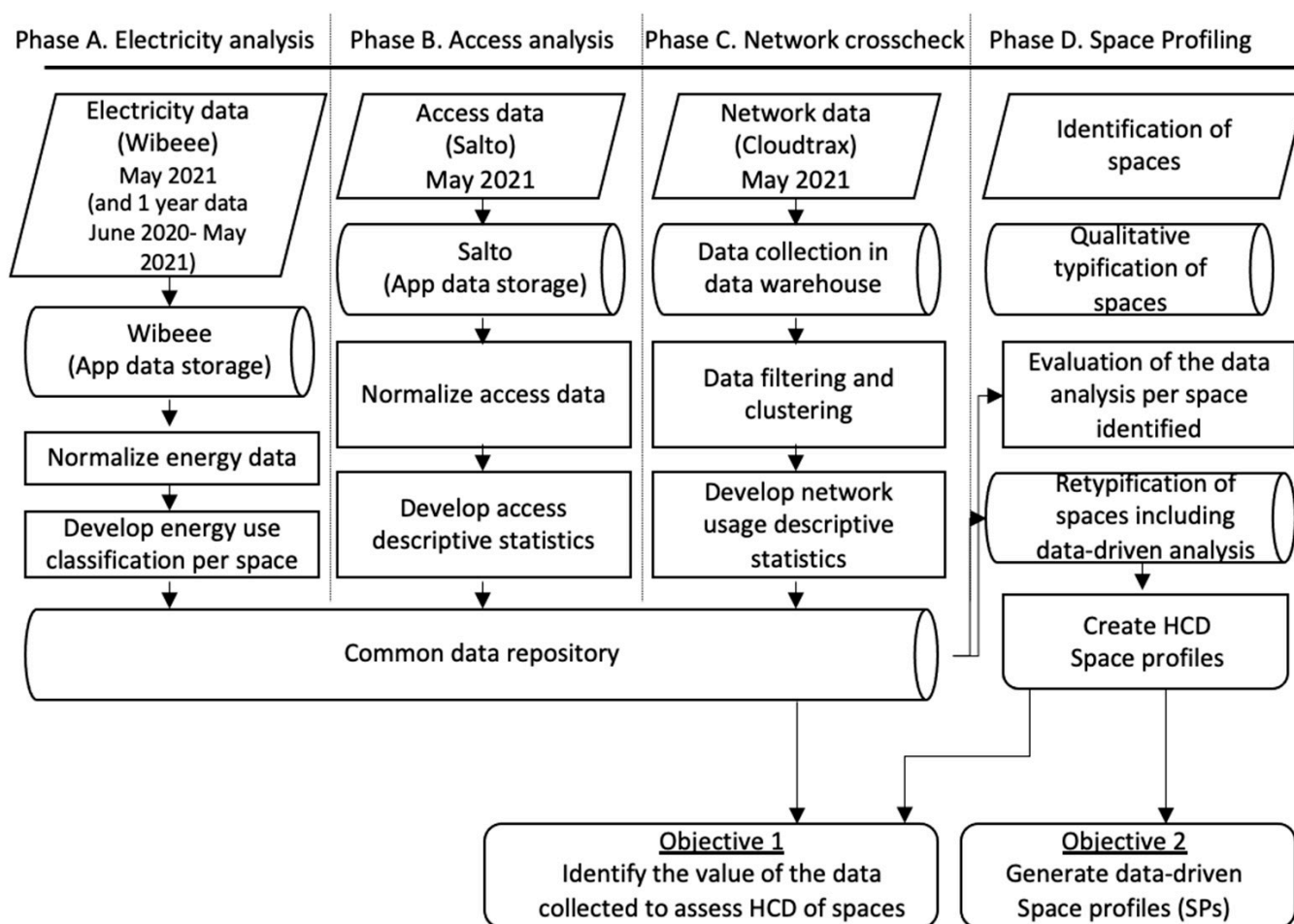

Figure 2. Flow chart describing methodology and the objectives of the study.

Table 1. POE coliving spatial assessment evaluation framework. The variable name is an acronym of the "Description" and a subindex that identifies the phase(s). (1C, 2D, 2I, 6C and 0I are the units of spaces analyzed through the current research).

Variable	Description	Unit	Evaluation	Device	Sustainability Indicator	Spaces Assessed in the Coliving	Literature
VE	Entries per coliver	# Entries per occupant	Ordinal, low, medium, high	Smart lock	Social	1C, 2D, 2I,	[63–66]
VH	Entry hours	in or out	Ordinal, out of hours	Smart lock	Social	1C, 2D, 2I, 0I, 6C	
PB	Presence (lights)	Hours	On/Off	SEM (Smart Electricity Meter)	Environmental Financial	6C	[67]
ECA	Electricity consumption	Hours	Activity time and appliances	SEM	Environmental Financial	1C, 2D, 2I, 0I, 6C	[68–71]
RWB	Computing laptop/data	Hours	Activity time	Wi-Fi	Social	1C, 2D, 2I, 0I, 6C	[22,72–75]
EB	Cooking/events home appliances	Hours	Activity time, appliances	Wi-Fi Smart-locks	Social	1C, 2D, 2I, 0I, 6C	[22,72–75]
Tc	Level of trust	% Open private spaces/Total private spaces	Open/closed	Smart-locks	Social	1C, 2D, 2I	[68–71]
AA	After-hours activity	Hours	Presence & use of appliances/devices	Smart locks-SEM	Social	1C, 2D, 2I, 0I, 6C	[68–71]
WABC	Week vs. weekend	Hours	Ordinal, not ordinal	All	Social	1C, 2D, 2I, 0I, 6C	All the previous

Note: # stands for "number of", % measures the percentage of private spaces left open against the total number of spaces.
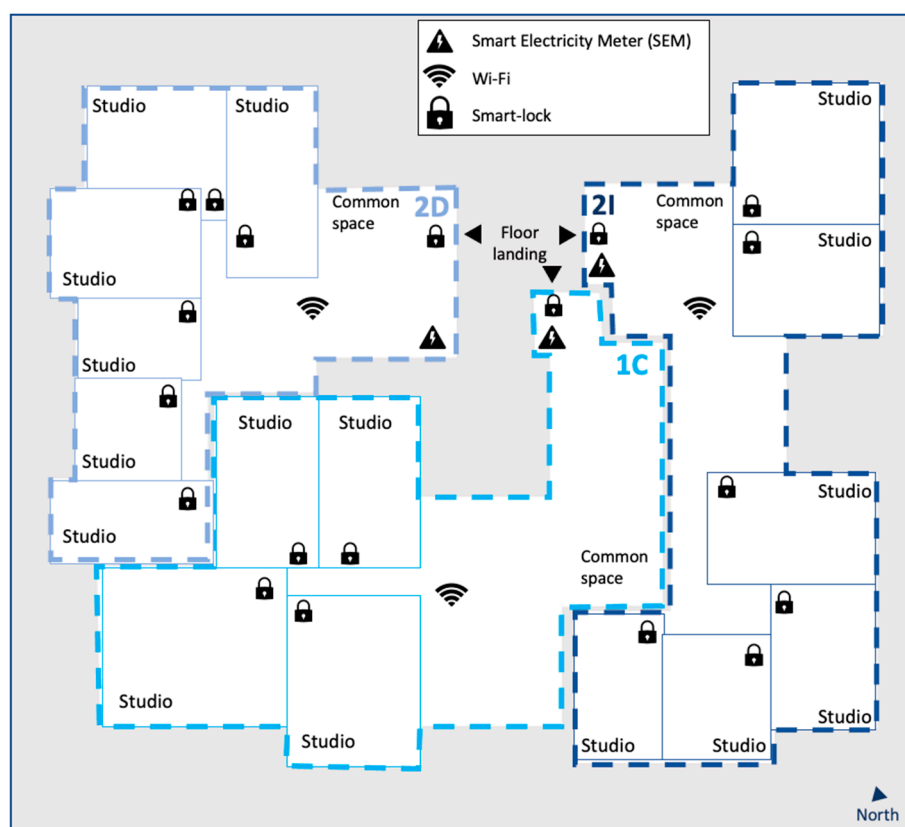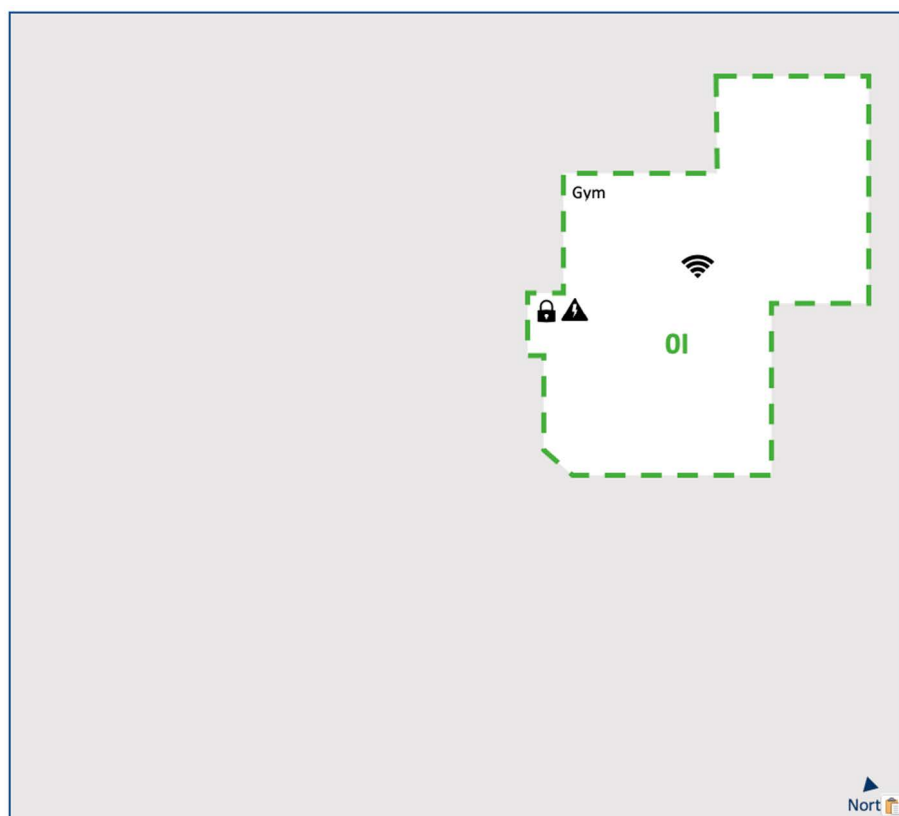
(**a**)
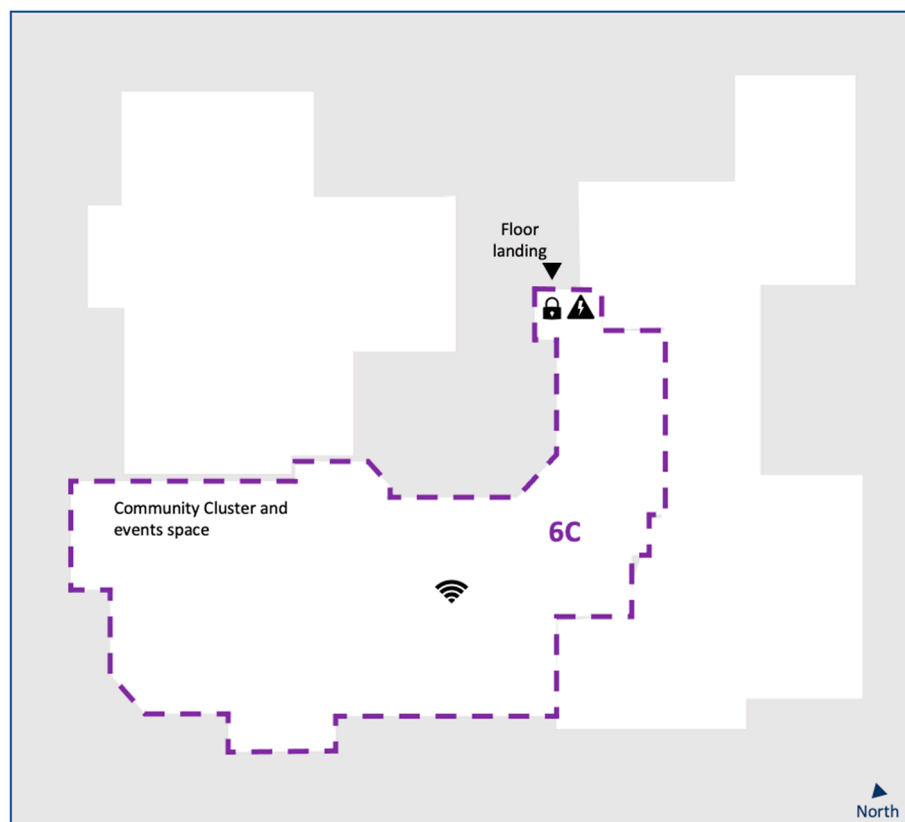
(**b**)

Figure 3. *Cont.*

(**c**)

Figure 3. Schemes of the different spaces studied: (**a**) Cluster apartments with studio subdivision 1C, 2I, 2D (**b**) Community Coworking space 6C; (**c**) Gym (0I).

Table 2. Physical classification of analyzed spaces. (Size in Net Usable Area NUA). The central cluster is the shared units that correspond to the central apartments in each floor of the building. The lateral cluster corresponds to the apartments situated at the left and right of the central apartment of each floor of the building.

Space	Typology	Residents	Uses	Access to All Colivers	Size of the Common Space
2I	Lateral Cluster	6	6 studios + kitchen/living-space	07:00–23:59 floor residents	22.88 m^2
2D	Lateral Cluster	6	6 studios + kitchen/living-space	07:00–23:59 floor residents	21.15 m^2
1C	Central Cluster	4	4 studios + Large kitchen/living-space	07:00–23:59 all residents	62.05 m^2
6C, 0I	Community Space	0	Coworking, social area, gym, terraces	07:00–23:59 all residents	6C = 156 m^2 0I = 60 m^2

2.2. Phase A: Electricity Analysis

Smart Electricity Meters (SEM), clamp-connected devices that measure the electricity consumption per apartment (cluster) and smartly classify the data of different appliances [56], were an essential adoption to guiding the transition towards sustainable use of resources such as water, electricity, and gas in residential spaces [78]. The innovation of the current research is that the information was collected to understand behavioral patterns and use of space, not only consumption dynamics. The data were then stored in a cloud

platform designed for the visualization of the electricity consumption in almost real time. For the study, the data were extracted from the platforms and filtered by days and clusters selected to the study (I, C, D), community spaces and gym (0I).

Afterwards, the SEM were trained by the Urban Campus and IT teams to identify the different domestic appliances according to the SEM patterns for identifying appliances (Air-Conditioning (AC), home appliances, lights and plugs). The isolated use of each device and electricity consumption was collected in real time and transmitted through the Application Programming Interface (API) during the night.

2.3. Phase B: Access Analysis

The smart locks (from Salto) were connected to the digital network through Wi-Fi enabling remote opening of doors and transferring information of door status (open vs. closed) and entry times in real time and retroactively from the Salto platform. The research analyzed the patterns of aggregated users' digital trails and visiting of spaces in the building. The various doors—building main entrance, access to cluster doors and common spaces doors and individual doors to private studios—were configured with different accessibility permissions depending on the use of space and privacy. Central apartments were accessible to all residents (ex: tenant living in 1I has access to 1C, 2C, 3C, . . .), while side apartments were accessible to all residents living on a floor (tenant living in 1C has access to 1I, 1C and 1D but not 2I or 2D). Table 3 shows the 3 types of locks and the credentials according to the space works as follows.

Table 3. Categorization of locks according to the typology, location, and access permits.

Typology	Location	Position	Access Permits
Building access lock (password and digital key)	Building main entrance	Open-Locked	Everyone
Cluster Cylinder	Cluster access I-C-D/R all Coliving	Open-Locked	Cluster members 24 h Others 07:00–23:59
Private studio Gateway	Studio access I-C-D studios	Open-Locked-Unlocked	Individual

The data were downloaded from the Salto platform. The data were presented in charts that assess the use of space routines; the access analysis method enabled understanding of the use and entries but not occupancy as it does not provide information on different members accessing a space at the same time or exit time.

2.4. Phase C: Network Cross-Check

The Wi-Fi network connection structure was built using Cloudtrax software. There was one network, "Service Set Identifier" (SSID) with 1 or 2 Access Point (AP) per cluster space and per Community space—a total of 20 SSIDs in the building. Data from 5 SSIDs were analyzed (two Lateral Cluster spaces 2I and 2D, one Central Cluster space 1C and 2 Community Spaces: 1 Community Coworking (6C) and Gym (0I). The location of the APs in this study relied on original infrastructure and networks available and the places located.

The Wi-Fi network worked as a digital trail of any device that is present in the spaces and is identified by the APs without the need to be connected to the Wi-Fi. The current method implied identification of the members of the coliving space and association to the digital devices they own; each coliver has on average 2–3 devices and is then anonymized and aggregated according to GDPR laws. Analysis of any device that was not assigned to a person and mobile in space was eliminated, keeping laptops, tablets, smartphones, and smartwatches. Other devices like Chromecast and SEM were dismissed. The data collected enabled to identify patterns of use based on traffic data, number of devices connected and routines that served also as a cross-check for Phase A and Phase B.

2.5. Phase D: Space Profiling (SP)

Once the Electricity, Access, and Network analysis were concluded, the Space Profiles (SPs) were developed. An SP is a dynamic flashcard that integrates the description of spaces together with inputs from real time use of this space and users' behavior obtained through users' digital trails collected from the existing built-in IT infrastructure. The process relied on the mixing methods theory extracted from Phases A, B and C learning to conform the assessment. For the current paper, 4 SPs were developed: (A) Cluster Central (B) Cluster Lateral and (C) Community Space profiles. Assigning features and characteristics to the 3 profiles developed based on the previous phases enabled to understand how Coliving spaces worked. The potential of the SP was to understand the identity of spaces as an active space, that responds in different ways depending the user's needs and its specific design features. This methodology was tailored to the different spaces and local needs to be able to reproduce the best experience for colivers, for example reducing electricity consumption and therefore optimizing cost [79].

According to Williams [80], interaction between physical, personal and social factors has an impact on behavior, that can be used to evaluate the physical profile of shared housing facilities. The characteristics he identified include size, density, proximity, surveillance, ratio of private to communal spaces and affordances within each, and non-spatial factors such as formal and informal social factors.

The SPs were the HCD interpretation of space, adding the analyzed digital trail features to the traditional spatial space definition and working as an interface between users and spaces. For example, it is broadly understood that modifying the size of the bed or the capacity of a wardrobe changes the experience of a space; likewise, interfering with the digital network, access permissions or AC parameters also alters the experience and behavior of a coliver. Residential spaces have become something other than a bed and a kitchen; the digital dimension and how it shapes users' performance must be considered when defining spaces taxonomy.

Following Williams [80], the interaction between users and spaces Table 1 is needed to evaluate different typologies of spaces (Table 4) in order to have a complete assessment of experience in the space and be able to design future spaces. The SPs represented the standards to replicate conditions for future spaces; they are also an example of interaction with real studies to test how modifications or interfering with these spaces modifies behavior and likewise interfering with behavior affects the way we use spaces. Studying these conditions helped to better understand the community. The definition of SPs for coliving and studying evolutions was essential to improving sustainable design in the present and future of coliving spaces.

Table 4. Spaces classification according to William's parameters (Physical parameters). * Studios are private spaces, 1 per Coliving each cluster is connected to 3–6 studios (In Italic to differentiate from the common spaces that will be measured).

Space	Space Typology	Size (m²)	% of the Total Building	Proximity (Distance to Studio)	Ratio (m²/person)	Privacy Level	Equipment
Lateral Cluster (2I, 2D)	Cluster	18–22	11%	Same apartment (<1 min)	2.38	Semipublic (Open 07 h-00 h)	Kitchen + small living space
Central Cluster (1C)	Cluster	55–65	16%	Same apartment (<1 min)	3.57	Semipublic (Open 07 h-00 h)	Living room + Large kitchen
Gym (0I)	Community	75	4%	Ground-floor (<5 min)	0.89	Public	Fitness and exercise room
Community Coworking (6C)	Community	135	7%	Sixth floor (<5 min)	1.61	Public	Coworking, events, coffee corner sofa area, terrace
*Studio**	*Studio*	*8–18*	*59%*	*N/A*	*14.76*	*Private*	*Bedroom + Bathroom*

3. Results

3.1. Phase A: Electricity Analysis

Four spaces with a total count of 1,047,498 inputs were assessed: 1C (central cluster), 2I, 2D (lateral clusters) and 6C (community space, coworking and social life). Figure 4 shows the average electricity consumption per space: a clear difference in trends is highlighted for the cluster spaces (1C, 2D, 2I). The double peak linear trend showed an increase of the intensity during lunch and dinner times, particularly high in 1C. The Cluster Central was associated with having larger common spaces accessible to the whole community; colivers used this space for shared dinners with other colivers. Instead, the study identified that Community Coworking 6C showed a very different trend, with a single smooth one-lump shape with a peak at 6 pm that corresponded to a different use of this space. Figure 5 focused on 6C during the complete year: the electricity consumption shows a sensible increase from 9:00 to 23:00 in a plateau shape due to moderate electricity consumption related to use of laptops and lighting during autumn, winter, and spring seasons. During the summer season, the plateau shape stressed to a peak shape during the afternoons impacted by the use of air-conditioning (AC) because of the western orientation of the space that increased the temperature.
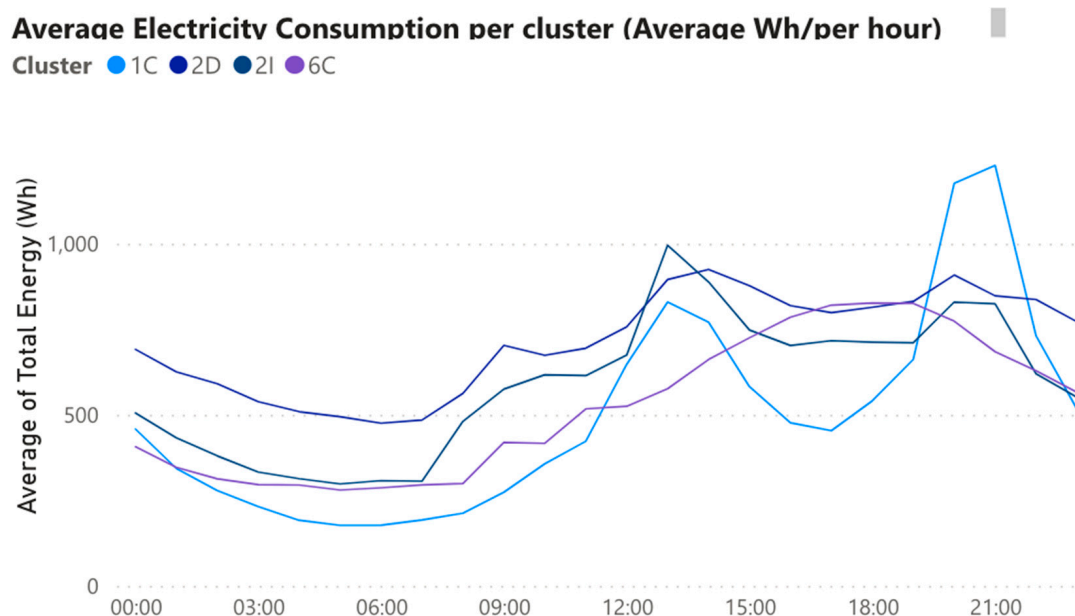
Average Electricity Consumption per cluster (Average Wh/per hour)

Cluster ● 1C ● 2D ● 2I ● 6C

Figure 4. Average yearly electricity consumption per cluster (Average Wh/per hour) data records from 1 June 2020 to 1 June 2021. Visualization with PowerBI.

Figure 6 compares weekdays to weekend days. Cluster kitchens were being used more during weekdays than during weekends, especially dinners (Friday, Saturday, Sunday). Lateral clusters 2D and 2I and the Community Coworking 6C showed the only trend of a later start in activities from 9 h during the weekdays, up to 13 h during Saturday and Sunday.

3.2. Phase B: Access Analysis

In total, 75 different doors of the building (75 smart locks) were monitored; the spaces had different levels of access depending on the time of day (Table 2). The data respond to the different spaces: 1C Central Cluster with common kitchen, 2D & 2I Lateral Cluster with small kitchen, 6C Community Coworking and the other community spaces were also considered for this filtering.

Data for 6C (community space for a coworking) were missing for Mondays, Tuesdays and Wednesday; this is a sample of colivers' interaction with space as they decided to leave that door open during the day for its constant use as a coworking and meeting space.

Each coliver visits an average of 3.58 shared spaces (excluding private studios) from the coliving space, apart from their own studio, with a range that goes from one to eight shared spaces (median of 3) per coliver. Table 5 shows that among all their favorite spaces, the most visited is the Gym(0I), being used by 68% of the inhabitants. After the gym, the central apartments (1C) are the most popular, despite hosting 25% of the private studios and colivers, visited by 67% members. These central apartments with larger kitchens and commons spaces act as a catalyst of communal activities such as dinners, reinforced in the electricity consumption records.

Table 5. Percentage of colivers visiting the different shared spaces per weekday, "S" is the % of colivers that visited a space at least once during the sample period. Entrance corresponds to the main gate of the building, therefore 100% of colivers transit it. Visualization from PowerBI. (The numbers are the ordinal representation of the weekdays 1 = Monday, 2 Tuesday . . .). 1 May 2021 to 1 June 2021.

Spaces	1	2	3	4	5	6	7	S
1C	16.7%	26.4%	22.2%	27.8%	25.0%	22.2%	16.7%	43.1%
2D	5.6%	4.2%	5.6%	6.9%	5.6%	6.9%	4.2%	11.1%
2I	%	6.9%	6.9%	6.9%	6.9%	6.9%	6.9%	8.3%
6C	-	-	-	1.4%	4.2%%	16.7%	18.1%	27.8%
Entrance	93.1%	93.1%	91.7%	94.4%	90.3%	90.3%	93.1%	100.0%
Gym	40.3%	44.4%	41.7%	44.4%	47.2%	19.4%	27.8%	79.2%
Any space	94.4%	95.8%	94.4%	95.8%	93.1%	91.7%	94.4%	100%

Table 6 shows the entries to the spaces. The number of colivers that share one cluster varies from 3 to 6. The most popular clusters visited were the central clusters "C" with the larger kitchens and living spaces. 1C was the most popular space with up to 31 colivers, 43% of the sample community visiting the space at least once—the average number of colivers that visit common spaces is 23% (1C, 2D, 2I). Figure 7 shows the habits and patterns of the visits, when and what are the most visited spaces and the comparison between weekdays when mobility increases within the Coliving from 8 to 9 am and at 8 pm and especially at the gym(0I) and weekends when the overall activity decreases and is concentrated opposingly during night hours and late morning.

a) 6C Average Electricity Consumption per month (Average Wh/per hour)

Figure 5. *Cont.*

b) 1C Average Electricity Consumption per month (Average Wh/per hour)

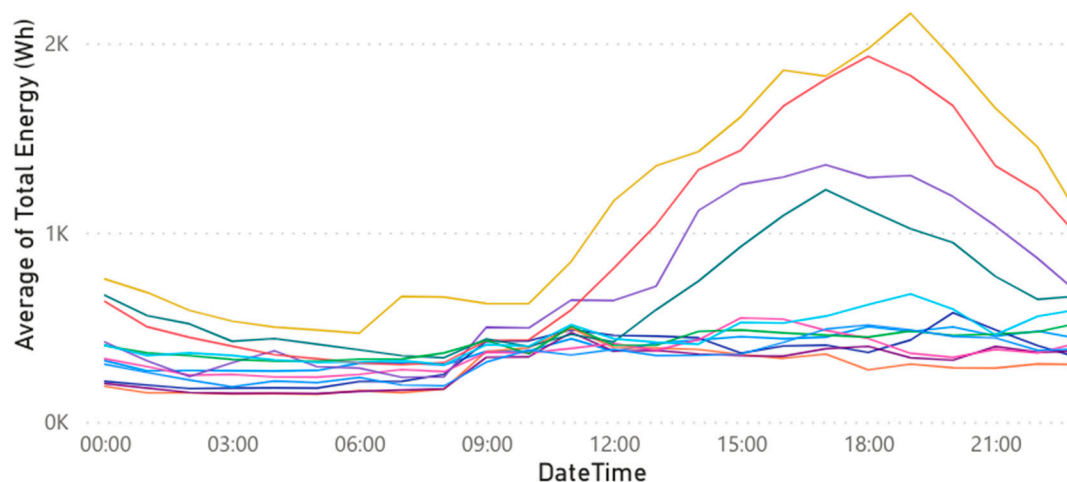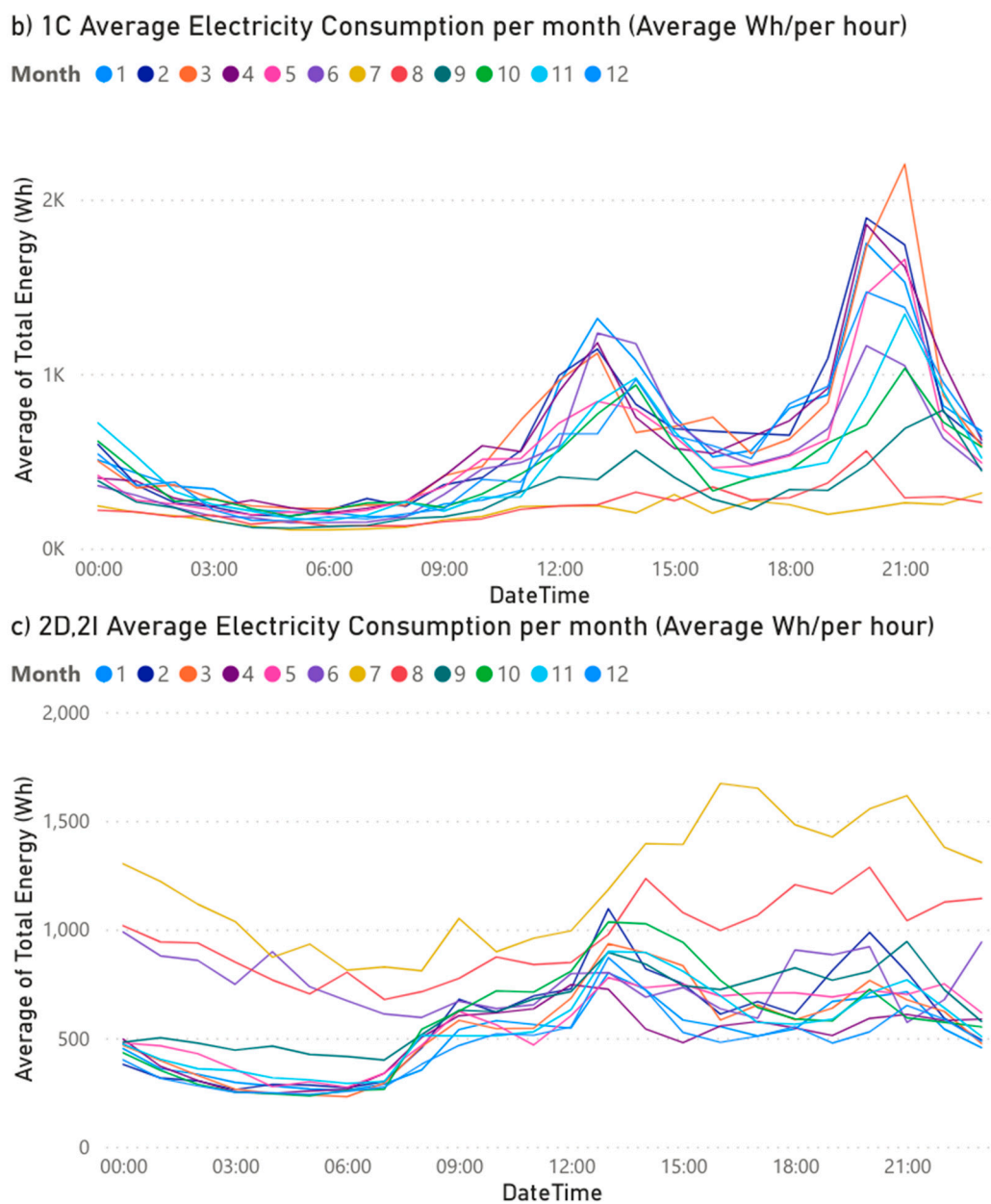### c) 2D,2I Average Electricity Consumption per month (Average Wh/per hour)

Figure 5. Seasonal electricity consumption. Electricity consumption per month (**a**) Community Coworking 6C (**b**) 1C Cluster Central Space (**c**) 2D, 2I Cluster lateral spaces in Community Space 6C (Average Wh/per hour) data records from 1 June 2020 to 1 June 2021. Visualization with PowerBI.

Table 6. Number of colivers visiting each space from 1 May 2021 to 1 June 2021. Visualization from PowerBI.

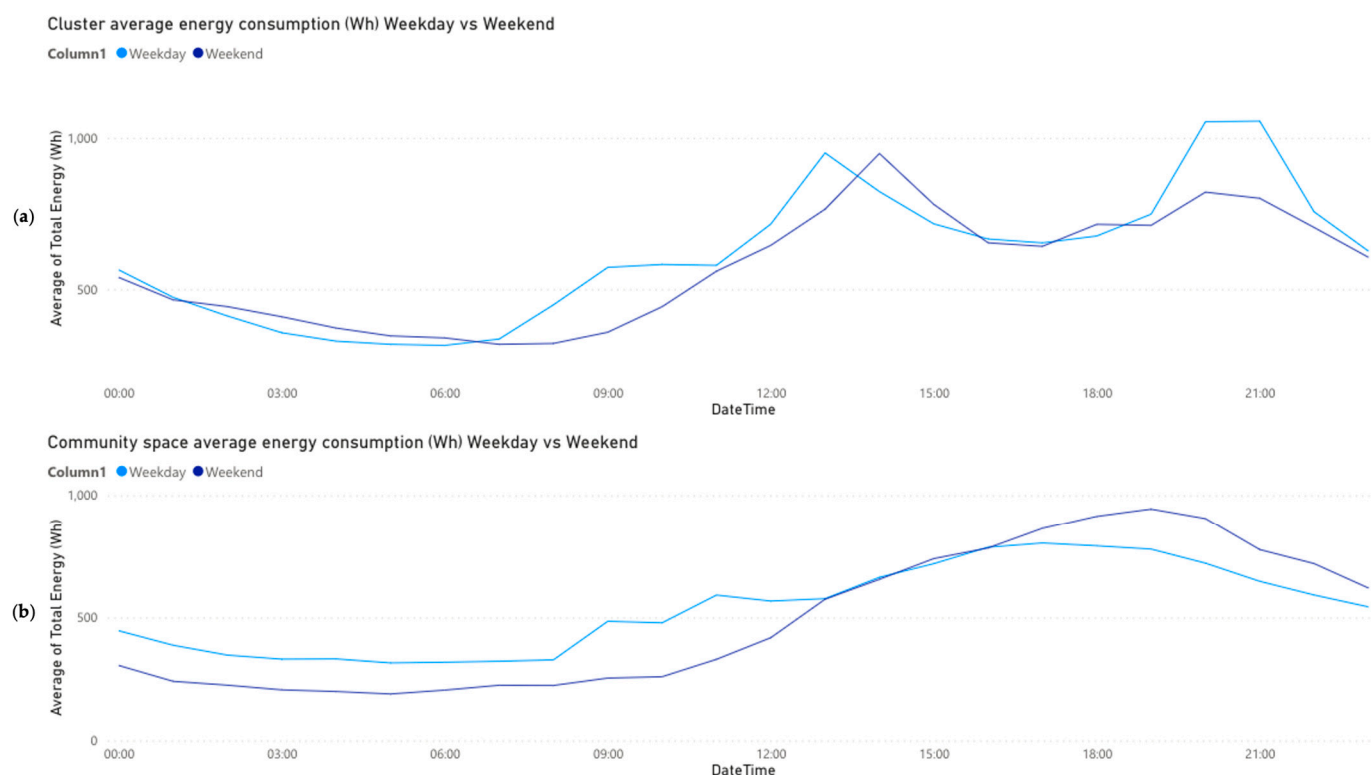| Space	Gym	1C	4C	5C	3C	6C	4D	1D	2C	3D	2D	1I	6I	2I	3I	6D	Average
Visitor count	57	31	25	21	20	20	12	10	10	9	8	7	7	6	5	3	16.6
(%) from total	79	43	35	29	28	28	17	14	14	13	11	10	10	8	7	4	23

Figure 6. Average yearly electricity consumption per weekday (Average Wh/per hour) data records from 1 June 2020 to 1 June 2021. Visualization with PowerBI. (**a**) 1C Central Cluster with common kitchen, (**b**) 2D & 2I Lateral Cluster with small kitchen, (**c**) 6C Community Coworking space.
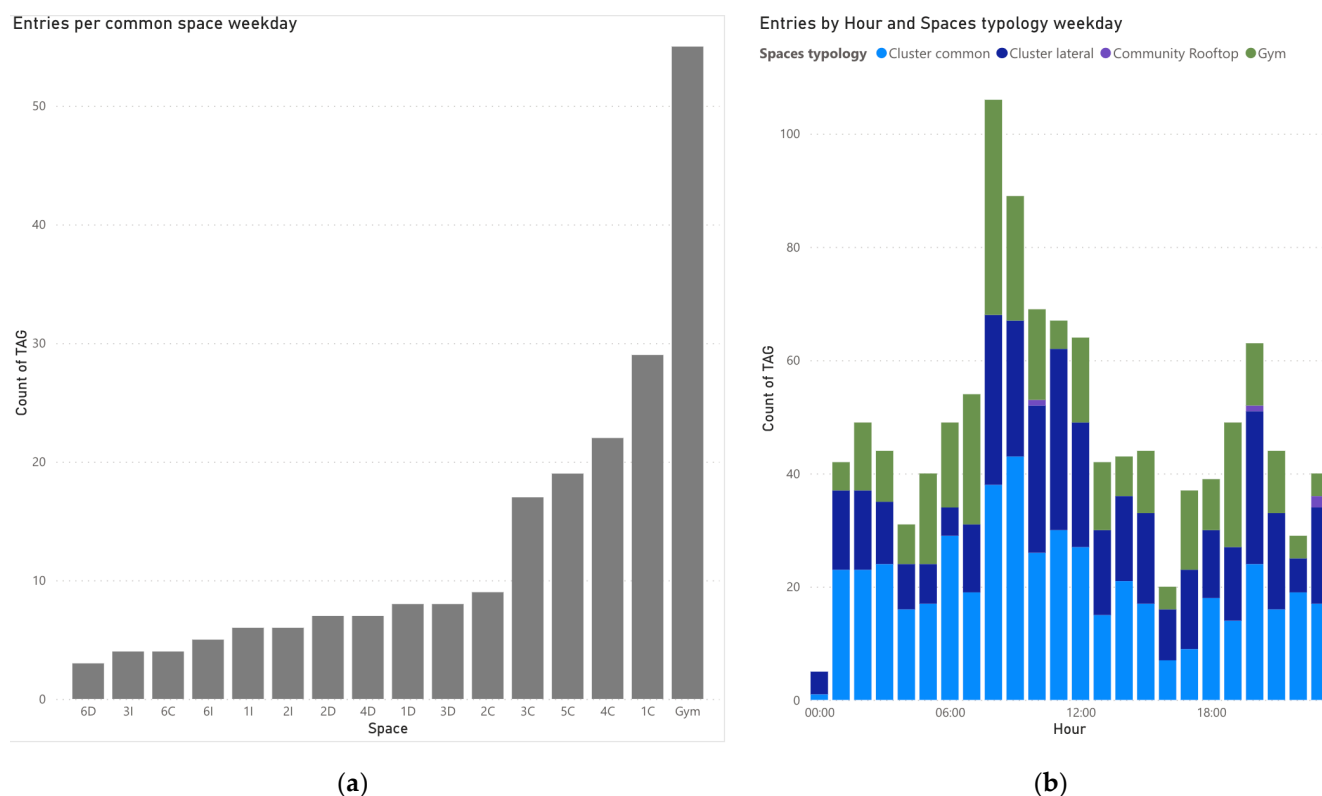

(**a**)

(**b**)

Figure 7. *Cont.*

Entries per common space weekend

(**c**)

Entries by Hour and Spaces typology weekend

(**d**)

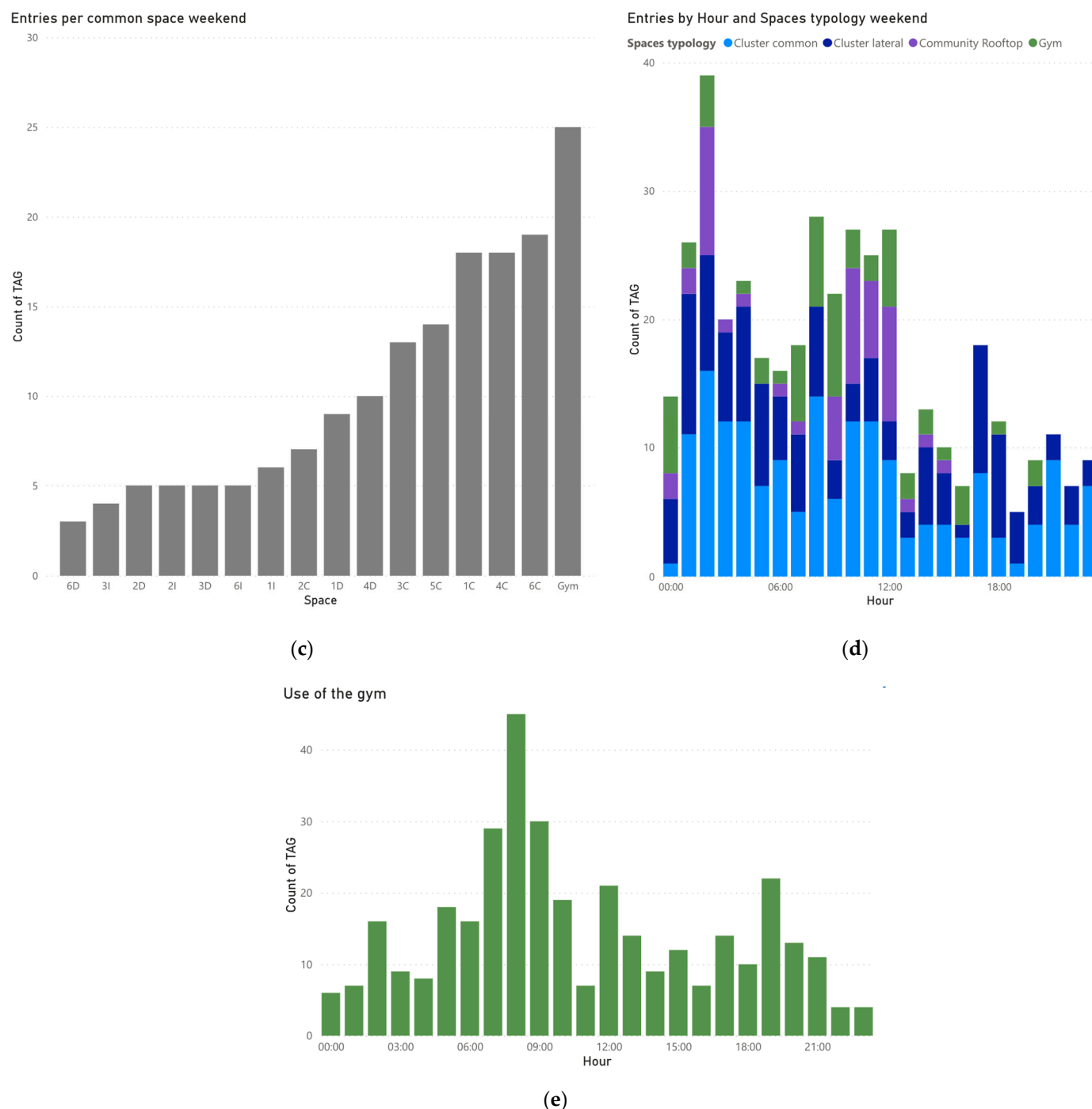**Use of the gym**

(**e**)

Figure 7. (**a**) Number of visitors per common space weekdays. (**b**) Visiting routines weekdays. (**c**) Number of visitors per common space weekends (**d**) Visiting routines weekends. (**e**) Visiting routines of the gym. (TAG is every entry by a coliver) from 1 May 2021 to 1 June 2021. Visualization from PowerBI.

3.3. Phase C: Network Cross-Check

The Wi-Fi had the advantage of seamlessly capturing data visualization of the co-livers mobile devices (laptop, mobile phone, tablet, watch) in each space, enabling the identification of different behavioral routines depending on the space. Figure 8 represents the devices seen per space and per hour as a daily average of the month. (a) shows the profile of all the spaces analyzed, (b) focused on the gym, with peak on activity at 1 pm and another peak the afternoon and evening during the weekdays (the night connections were also linked to the use of the common spaces next to the gym that had the Gym SSID

as the closest network, highlighted by colivers, and cross-checked by the Access Analysis). (c) the Community Coworking area and events show a distributed activity starting at 12 pm until night in office working areas and dinner time more frequent during weekdays, but both charts were very different to (d) Cluster spaces 2I, 2D and 2I that all perform at low intensity during the day but peak between 9 pm and 11 pm during the weekdays, dinner and after dinner time, when colivers that are regularly active in their private spaces or common cluster spaces—this input is essential for the spaces profiling as it identifies the spaces clearly by the behavior within them. During the weekends, similarly to the access controls, there was considerably less use of internet and movement within the areas; 50% of connections in the coworking space 6C and even less in the Gym and surroundings and in the private spaces.
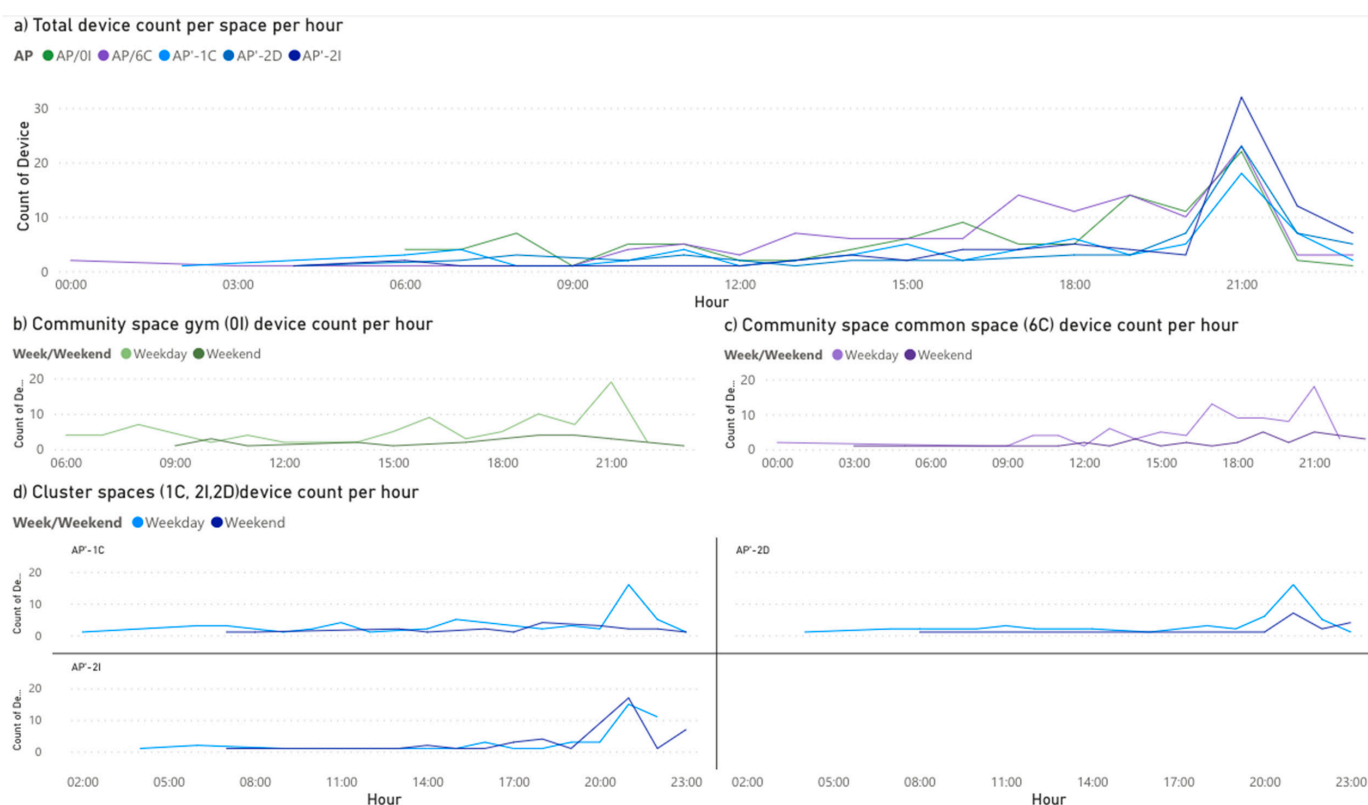

Figure 8. The graphs represent the daily average total devices seen by the APs per hour in the different spaces. (**a**) Average daily total devices seen per AP. (**b**) Total devices seen at the gym (0I) per hour, (**c**) Total devices seen at the Community space Coworking and events (6C) per hour, (**d**) Total devices seen in the different cluster spaces (2D, 2I, 2I) per hour, Count of De . . . (Count of Device). From 1 May 2021 to 1 June 2021.Visualization developed with Power BI.

3.4. Phase D: Space Profiling

After concluding Phases A, B and C, the indicators of Table 1 were crosschecked with the space classification Table 4 and synthetized it to develop the SPs. The corresponding author developed the first SP and the co-authors, technology, head of local operations, IT expert, Chief of Operations and Head of Innovation reviewed and complemented the information. It was an iterative process complemented by adding details and helped understanding of the profiling Figure 9.

A) Central Cluster (1C)

Spatial characteristics: Shared spaces with large kitchen and living space.

Frequency: 1 per floor

Studios: 4 studios

Functionality: Living use with private studios and shared spaces

Network: Active use of network during the evenings by members of the cluster

Access and privacy: Gathering space visited by 43% of the community during the month.

Visiting times, Weekends, more emphasized in the mornings

Electricity consumption: Increased consumption during lunchtime and dinners, particularly due to kitchen appliances, showing a pattern of shared dinners among the inhabitants of the same cluster and other clusters

Considerations for optimization:
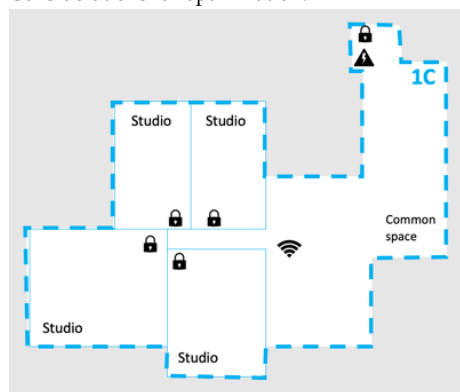
The Central Cluster spaces are essential for fostering informal communication and community gatherings across clusters, promoting their use for shared lunches and dinners by providing appropriate furniture and appliances. As they are the most used among the colivers, electricity saving appliances must be included and have the electricity power contracted to a variable rate adjusted to the consumption patterns//Provide good acoustic insulation between shared cluster space and studios in this cluster due to frequent social gatherings//Advice colivers the central clusters are more social and active, preferably for active users likely to engage in social gatherings.

B) Lateral Cluster (2D,2I)

Spatial characteristics: Shared spaces with small kitchen.

Frequency: 2 lateral cluster per floor
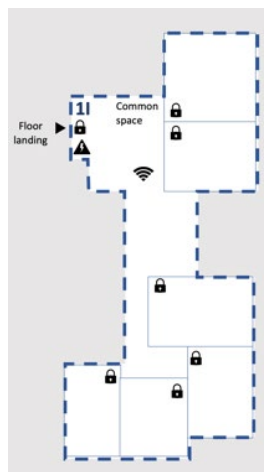
Studios: 3–6 studios

Functionality: Living use with private studios and floor shared spaces

Network: Active use of network during the evenings by members of the cluster

Access and privacy: Gathering spaces visited by 8.33% (2I)–11.11% (2D) of the community. Across the day weekends and mainly during the mornings during the week.

Electricity consumption: Increased consumption during lunchtime and dinners, particularly due to kitchen appliances.

Considerations for optimization:

The Lateral Cluster spaces are more optimized for supplying support space for private studios. Basic kitchen for quick and efficient breakfast lunch and dinner and discrete and silent spaces for colivers that want to live in independent spaces and chose when to gather with the rest of the community visiting other spaces//Appropriated for independent colivers less likely to look for frequent community gatherings.

Figure 9. *Cont.*
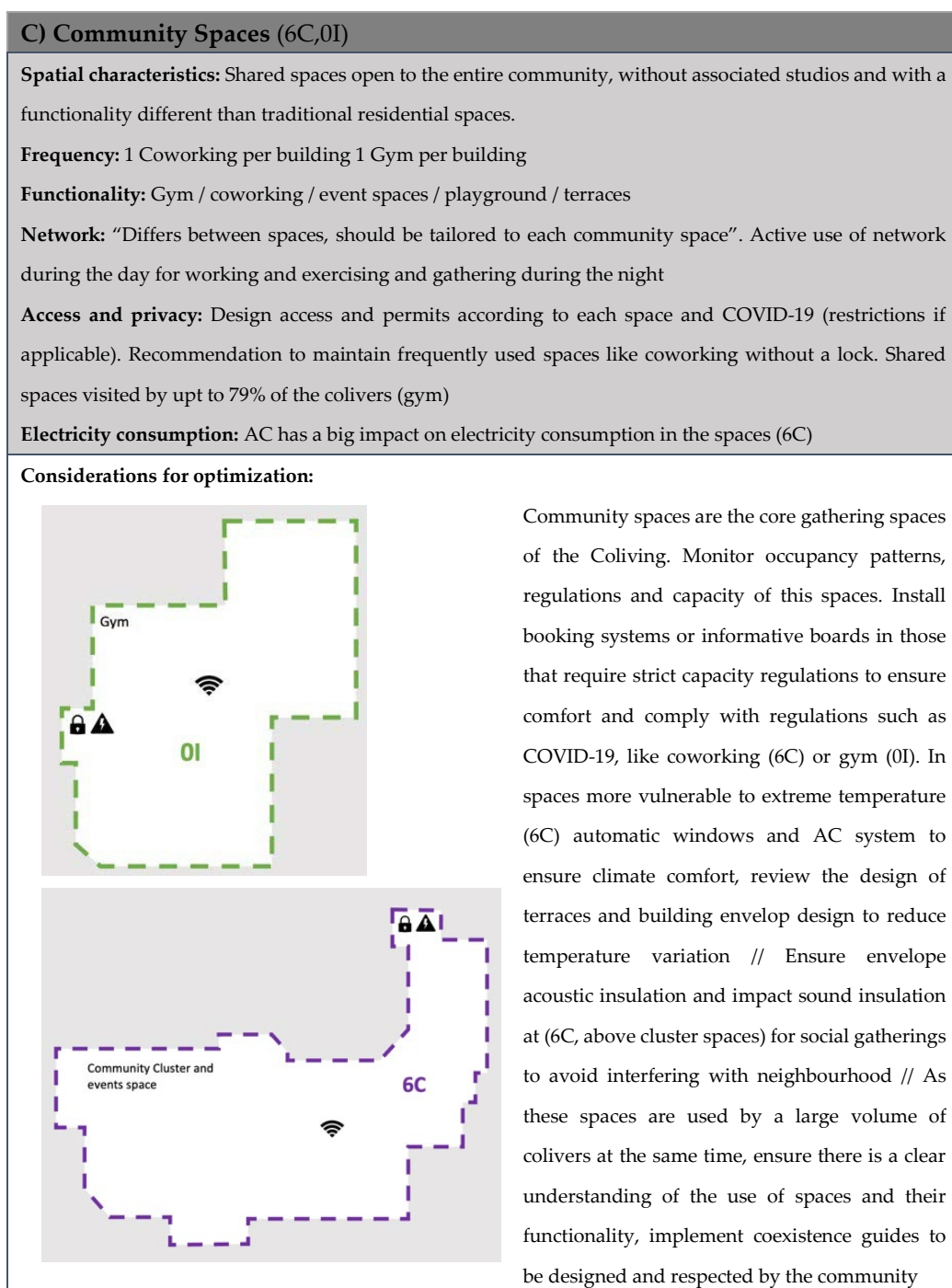
C) Community Spaces (6C,0I)

Spatial characteristics: Shared spaces open to the entire community, without associated studios and with a functionality different than traditional residential spaces.

Frequency: 1 Coworking per building 1 Gym per building

Functionality: Gym / coworking / event spaces / playground / terraces

Network: "Differs between spaces, should be tailored to each community space". Active use of network during the day for working and exercising and gathering during the night

Access and privacy: Design access and permits according to each space and COVID-19 (restrictions if applicable). Recommendation to maintain frequently used spaces like coworking without a lock. Shared spaces visited by upt to 79% of the colivers (gym)

Electricity consumption: AC has a big impact on electricity consumption in the spaces (6C)

Considerations for optimization:

Community spaces are the core gathering spaces of the Coliving. Monitor occupancy patterns, regulations and capacity of this spaces. Install booking systems or informative boards in those that require strict capacity regulations to ensure comfort and comply with regulations such as COVID-19, like coworking (6C) or gym (0I). In spaces more vulnerable to extreme temperature (6C) automatic windows and AC system to ensure climate comfort, review the design of terraces and building envelop design to reduce temperature variation // Ensure envelope acoustic insulation and impact sound insulation at (6C, above cluster spaces) for social gatherings to avoid interfering with neighbourhood // As these spaces are used by a large volume of colivers at the same time, ensure there is a clear understanding of the use of spaces and their functionality, implement coexistence guides to be designed and respected by the community

Figure 9. Space profiles (SPs). (**A**) Central Cluster (1C). (**B**) Lateral Cluster (2D, 2I). (**C**) Community Spaces (6C, 0I).

4. Discussion

As buildings are made smarter, AEC practitioners must integrate the latest technologies to adapt to a rapidly changing society and respond to sustainable HCD spaces [1]. The seamless Post-Occupancy Framework enabled to create a methodology to monitor and adapt the space to user needs over time. It is important to note that the SPs were not an objective itself, but a dynamic, interactive flashcard that provided inputs from the use of spaces. They are a means of dialogue between users and AEC practitioners to improve space design, iterate, modify physical characteristics of space, and analyze how it affected to colivers routines and the use of spaces through the digital trail of the users.

The SPs are therefore scalable and can be implemented globally, adapting to different buildings, locations and taking into consideration the different restrictions or regulations such as the COVID-19 restrictions in place during the time of study. The SPs are a powerful iterative, spatial tool to interact with residents use of space, and behavioral patterns to improve future design, optimize spaces and assess comfort and wellbeing.

Central Cluster spaces are visited by 14%–43%, an average of 29.7% (21.2 colivers), and the largest electricity consumption and visits are within weekdays at lunch and dinner hours, whereas the Lateral Clusters are visited by only 4%–17% of the community which meant an average of 10.3% (7.4 visitors from other clusters) and has a high consumption of internet at 21:00 h, mostly individual connections inside the private studios. Community Spaces like the gym had a visitor rate of up to 79% and coworking was preferred to be open without restricted access during the day.

Cluster spaces had a higher electricity consumption rate during lunchtime and dinner time mainly due to intensive use of appliances; community spaces like coworking spaces intensified electricity consumption gradually during the afternoon due to AC during the summer months—the rest of the months they encountered a plateau-shaped stable consumption trend. Central Cluster spaces acted as catalyzers of community, colivers visited an average of three to four common spaces, Central Clusters being frequented more by external visitors.

Our consultations with colivers were also essential to complementing and understanding their choices as key to HCD. Interviews and codesign to improve SPs is always recommended as a future line of research. For example, after identifying the electricity patterns and consumption habits of users, the results of the current research recommended modifying the electricity contract to be adjusted to match the peak hours of consumption of the Coliving in order to match their habits. In addition, other measures were suggested to improve wellbeing and use of spaces. Feedback also showed that colivers had a significant interest in the following: understanding building and performance, environmental sustainability, knowing how to improve performance and suggested visualization measures to reduce environmental impact. This interaction helped not only to improve the performance of current spaces but also to collaborate for a more conscious future society.

The use of space routine also differs depending on the day of the week: at weekends, the number of in-house common dinners was significantly reduced and mobility within the Coliving decreased and shifted towards late mornings and night-time rather than during the week when it is distributed more evenly along the day.

Colivers also showed different habits and patterns of use of space: more social colivers visit up to eight spaces apart from their private studios on average, others just one or two. After the study the Central Cluster spaces were recommended to colivers more interested in networking and community interaction and Lateral Clusters to others looking for more independence.

Future Lines of Research

In future lines of research, the researchers would complement and enhance the research by repeating the process in other buildings with a different typologies and other available data sources to be processed, such as open databases to track interaction with the city and sociodemographic data.

Including surveys to the colivers to enlightening colivers motivations for choosing coliving and their perception of the different spaces would be an additional value-added study for future research.

A post COVID-19 assessment of the building will also be performed to add additional feedback on the building and comparison of data during and post-COVID-19 crisis.

5. Limitations

Several limitations were encountered during the study: the first was to implement the study in a single building and geographic location in Madrid. Although colivers

had an international background, the outputs and the SPs were therefore linked to the geographical context, target users and COVID-19 regulations. The methodology was designed to be iterated, replicated, and scaled to any kind of building and location, enabling the repetition of the process, the updating of the digital trail with the available data sources and replicating the SPs for other locations, users, and conditions.

At the beginning developing this methodology during the COVID-19 was a limitation due to difficulties to visit the space for data collection. This was transformed into an opportunity to take a step forward to POE analysis and adapt it to restrictions to develop a system that could be implemented fully remotely, which meant the process could be exported and scalated to other geographies, globally, without the need for geographic relocation; in addition, this methodology helped to understand the evolution of the use of spaces during and after the pandemic.

6. Conclusions

The current research demonstrated how POE techniques based on the digital trail can be employed to design a methodology for sustainable HCD Coliving spaces.

The infrastructure available in highly digitalized IOT-based buildings, like colivings, has proven to be a valuable resource to assess performance of spaces and behavioral patterns based on the already existing IT devices, without the need to install additional sensors, regarding the expected learnings.

The three SPs showed major differences in the use of spaces and enabled a comparative analysis of the use of spaces. The different data sources provided inputs to enable identification of the level of occupancy of the different spaces, average number of visitors and overall popularity of the spaces, differentiating between most occupied spaces and less occupied.

Data sources also provided insights into energy consumption and activities implemented in each space according to data consumption patterns.

A home is not a roof—walls and doors are physical divisions of space. This paper proved buildings go beyond the physical skeleton and shell, and strongly rely on digital networks and experience. The developed methodology and the use of SPs was essential for sustainable HCD interpretation of buildings to assess not only the behavioral patterns of the users but also the interaction of the building with the environment.

Abbreviations

The following abbreviations are used in this manuscript:

AC   Air-conditioning
AEC   Architecture, engineering construction professionals
AP   Access Point
API   Application Programming Interface
HCD   Human-centered design
MDPI   Multidisciplinary Digital Publishing Institute
NUA   Net Usable Area
POE   Post-Occupancy Evaluation
SEM   Smart Electricity Meter
SP   Space Profiles
SSID   Service Set Identifier
TAG   Input entry by Coliver

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