Conversely, simplified steady-state models, often purposely developed, are based on empirical and/or experimental mathematical models. In particular, the adoption of simplified methodologies related to several control techniques able to assess the possibilities for increasing energy efficiency in hospitals were presented in Refs. [15, 46]. Here, the tool, which was tested and calibrated at the new emergency hospital located in Novi Sad, Serbia, enables fast analyses by avoiding complex dynamic modelling. Finally, some approaches are based only on on-site measurements [19, 21, 22].

Taking into consideration the energy aspects investigated, it arises that, although a comprehensive analysis of the energy behaviour of hospital buildings should consider all levers affecting energy performance, current scientific literature does not provide worthy studies that explored all the energy related aspects. Čongradac et al. [15] focused on hospital heating and cooling energy consumption, while other works investigated only electricity [19-22, 47, 48], heat consumption for DHW [17], or comfort in healthcare environments [32, 38, 39, 49, 50]. Differently, a wide variety of studies deeply explored the benefits and cost-effectiveness of energy retrofit measures (ERMs) and energy saving measures (ESMs), making a comparative analysis between different strategies [16, 29, 40, 46] or focusing on only one of them and exploring some variations of it [9, 30, 31, 41-43, 51, 52].

A more critical review of the hospital building type and spaces examined in literature shows that these methods were rarely applied to existing and operative hospital structures [15, 40, 42, 43, 46]. Most of the studies were developed considering a reference building representative of the hospital building category. Nevertheless, each reference building was defined on the base of different criteria, like the standards reported by regulations [24, 33-37], statistical data coming from a large number of hospitals [29], hospital templates or reports and datasets providing typical hospital characteristics [24, 33-36], or the parameters dictated by the method employed [32]. Again, several studies took into consideration only single hospital spaces (like a department) [19, 21, 22, 30, 38, 39, 41], or only some buildings representative of the healthcare complex [16-31], due to the difficulties in modelling, calibrating, predicting and interpreting results for all the hospital spaces [16].

In addition, the majority of the aforementioned approaches analysed the hospital (either existing or prototype) at building level, or focused just on some healthcare spaces or departments. Only few works investigated the whole hospital at departmental level [15, 24, 29, 33-37, 46]. Nevertheless, these studies did not refer all the energy related aspects to this space distinction.

Against this background, the Advanced Energy Design Guides (AEDGs) for Large Hospitals [33] and for Small Hospitals and Healthcare Facilities [24] – a product of a collaboration between ASHRAE, AIA, IES, USGBC, and DOE – together with the related Technical Support Documents (TSDs) [34, 36] and a study developed by the University of Washington's Integrated Design Lab (IDL) [37], represent more comprehensive works. These studies thoroughly investigated the energy behaviour of hospital buildings by considering all the energy related aspects at departmental level. The works employed the dynamic thermal simulation approach applied to baseline and low-energy reference buildings in different climate zones. More in detail, the two AEDGs [24, 33] analysed baseline and energy saving parameters regarding the building envelope, vertical fenestration, lighting, HVAC, service water heating (SWH) and plug and process loads (PPLs), then developing specific ESMs. The guides use the macro-level classification of hospital spaces – the same used in scientific literature and regulation [53-57] – distinguishing between Inpatient Units (IPUs), Diagnostic and Treatment Facilities (D&T), and nonclinical spaces, and provide prescriptions regarding daylighting, space layout and lighting power densities (LPDs) in relation to these three macro-areas.

Conversely, the three TSDs [34-36], which integrate the AEDGs, include a more comprehensive analysis of the surface distribution of hospital prototype distinguishing by all the space types. To the space categories identified were referred baseline and energy saving values for ventilation, LPDs, PPLs and SWH loads.

Similarly to the TSDs, the work of the University of Washington's IDL [37] is based on an accurate distinction of the spaces according to their use. However, to this distinction are not referred any of the specifications provided by the work and regarding the building envelope, vertical fenestration, external surface, building and plant systems, electricity and natural gas consumption, etc.

The lack of worthy studies on hospital energy behaviour at departmental level represents a critical knowledge gap in the literature. Indeed, hospitals are known to show a very large variety of area specific energy consumption [58]. Different departments and space types have different morphological characteristics, plant systems, conditioning requirements, occupancy, area, equipment, etc. Therefore, it is different their energy consumption and, what is the most important, the possibility of savings [15, 21, 33]. For this reason, the academic literature has pointed out that hospital energy benchmarks need to be resolved for as specific an area as possible [59-60].

Summarising, the review of the existing studies presented above underlines a series of critical issues regarding hospital energy behaviour assessment and prediction. Firstly, the shortage of works primarily based on measurement data causes a lack of data measured and estimated energy consumptions for hospital buildings. Secondly, a lack of studies exploring hospital energy performance by carefully considering the huge domain of the affecting factors means that the outcomes available in literature are strictly dependent on the investigated loads pattern and cannot be extended to different buildings functions and to different locations [15, 61]. This aspect, together with the absence of studies examining large samples of whole existing operative structures, also hinders the construction of more robust and reliable energy benchmarking. Again, despite increasing research activity in the past decade, it arises that energy analyses are still rarely based on departmental level, thus hospital energy consumption by space type remains largely unexplained [20].

3 Structure of the method of analysis

The aim of the work consists in the development of a numerical model for the annual hospital energy consumption assessment of six hospitals located in the province of Bologna, Italy, in relation to the different departments, medical functions, type of HVAC system, morphological features of the buildings and levels of insulation, ventilation and humidification rates, operating hours, contribution of active and passive energy recovery systems, etc. Although the research has been considering different hospitals within the national context, six hospitals located in the same province have been chosen in order to avoid the climate variables between different regions.

The numerical model was then tested for each healthcare facility through the use of equipment, instruments for the continuous monitoring of technical and physical parameters, and heat meters, which made it possible to monitor the real hospital energy consumption according to the type of management and the climate trends.

The model allows to forecast the energy consumptions related to the refurbishment or modification of existing hospitals, analysing the impact of architectural and functional features, as well as of energy goals.

The main aspect of the work is represented by the methodological framework, which has been based on the identification of the energy needs and consumptions from micro (single space) to macro scale (macro-area). Indeed, the main purpose is to go beyond the existing studies reviewed in section 2, which look at the healthcare structure as a single and unique element of consumption, without a separation between different space types.

Actually, the setup of the whole method of analysis is aimed at addressing the weaknesses of the studies available in literature. Indeed, the exclusive use of measurement data collected from existing and operative hospitals provides a robust and reliable dataset and avoids the inaccuracies that can come from thermal building simulation methods. Furthermore, the model developed takes into consideration all the factors affecting building energy behaviour, providing a comprehensive tool.

The objective of the work, omitting complex dynamic modeling, is also to develop a method as simple as possible, which enables fast obtaining of fairly reliable results, being primarily intended for ordinary engineers, architects, technical staff responsible for the maintenance of healthcare facilities and energy managers.

Each healthcare facility was considered floor by floor and the spaces were distinguished in relation to the single space (micro scale), the functional area (FA) (medium scale), and the macro-area (macro scale) (see Table 1), according to the taxonomy of hospital spaces used in scientific literature and regulation [24, 33, 53-57].

Macro-Area	Functional area	Single space
Inpatient Units (IPUs)	Inpatient units	Patient rooms Examination rooms Medical offices Administrative offices Toilets and dressing rooms Connective spaces Storage rooms Technical spaces and services for patients and visitors*
Diagnostic and Treatment (D&T)	Accident and Emergency (A&E)	A&E specific spaces (observation unit, triages, etc.) Diagnostic/examination rooms Medical offices Administrative offices Toilets and dressing rooms Connective spaces Storage rooms
	Medical offices	Medical offices Toilets and dressing rooms Connective spaces Storage rooms

		Technical spaces and services for patients and visitors*
	Laboratories	Laboratories Medical offices Administrative offices Toilets and dressing rooms Connective spaces Storage rooms Technical spaces and services for patients and visitors*
	Operating theatres	Operating rooms (ORs) and support spaces Toilets and dressing rooms Connective spaces Storage rooms Technical spaces and services for patients and visitors*
	Outpatient department (OPD)	Consulting/examination/ treatment rooms Medical offices Administrative offices Toilets and dressing rooms Connective spaces Storage rooms Technical spaces and services for patients and visitors*
	Diagnostic imaging	Diagnostic/examination rooms Medical offices Administrative offices Toilets and dressing rooms Connective spaces Storage rooms Technical spaces and services for patients and visitors*
General services	Kitchens and canteens	Kitchen and canteen specific spaces Toilets and dressing rooms Connective spaces Storage rooms
	Mortuary	Mortuary and support spaces Toilets and dressing rooms Connective spaces Storage rooms
	Admin. offices	Offices Toilets Connective spaces Storage rooms
	Toilets and dressing rooms	Toilets and dressing rooms
	Connective spaces	Connective spaces
	Storage rooms	Storage rooms
	Technical spaces and services	Technical spaces and services for patients and visitors*

*include mechanical spaces, meeting rooms, cafeteria, lounges, pharmacy, rehabilitation gym and ancillary spaces, chapel, etc.

Table 1. Subdivision of hospital spaces

The research results for each energy related aspect analysed have always been reported both at single space level and at functional area level, like in the following example.

Single space	**A**	**B**	**C**	**D**	**E**	**F**
Patient rooms*						
A&E specific spaces*						
Medical offices*						
Administrative offices*						
Laboratories*						
ORs and support spaces*						
Consulting/Examination rooms*						
Diagnostic/Examination rooms*						
Kitchen and canteen specific spaces*						
Mortuary and support spaces*						
Toilets and dressing rooms						
Connective spaces						
Storage rooms						
Technical spaces and services						
Macro-Areas						
Inpatient units						
Diagnostic and Treatment						
General services						

*as outlined in Table 1, these are single spaces and do not include toilets, connective spaces, storage rooms, technical spaces and services, as well as other support spaces.

Functional area	**A**	**B**	**C**	**D**	**E**	**F**
Inpatient units*						
Accident and Emergency (A&E)*						
Medical offices*						
Administrative offices*						
Laboratories*						
Operating theatres*						
Outpatient department*						
Diagnostic imaging*						
Kitchens and canteens*						
Mortuary*						
Toilets and dressing rooms						
Connective spaces						
Storage rooms						
Technical spaces and services						
Macro-Areas						
Inpatient units						
Diagnostic and Treatment						
General services						

*as outlined in Table 1, these are FAs and include toilets, connective spaces, storage rooms, technical spaces and services, as well as the support spaces specific of each FA.

This distinction by space type was essential also to make a comparative analysis of the research results between the hospital case studies.

In this paper are reported in a parametric form the preliminary results of the work, regarding the morphological aspects of the six hospitals analysed and the distribution of the condition floor area in relation to the type of spaces.

3.1 Case studies

The research analysed six hospitals taken as case studies (Table 2-3) and identified as Hospital A, B, C, D, E and F, which are located in the Emilia Romagna region (Italy), nationally recognized as a best practice in healthcare delivery. All the healthcare structures belong to the LHU of Bologna, the main province of the region.

Data		**A**	**B**	**C**	**D**	**E**		**F**
						orig.	**add.**	
Year of Constr.	1900-1940	✓			✓	✓		
	1940-1980		✓	✓				✓

	1980-2000							
	after 2000						✓	
Conditioned floor area (m²)		3.385	6.033	8.185	13.165	50.786		88.901
S/V*		0,43	0,54	0,43	0,56	0,43		0,34
S/Conditioned floor area		1,36	1,47	1,54	1,51	1,45		1,11

*S = external surface and V = conditioned volume

Table 2. Main characteristics of the hospitals analysed

Departments	**A**	**B**	**C**	**D**	**E**	**F**
Anaesthetics			✓	✓	✓	✓
Breast care				✓	✓	✓
Cardiology				✓	✓	✓
Care of the elderly				✓		✓
Dialysis			✓			
Ear nose and throat (ENT)			✓			✓
Endocrinology				✓	✓	✓
Extensive Rehabilitation			✓		✓	
Accident and Emergency	✓	✓	✓	✓		✓
Functional Rehabilitation		✓				
Gastroenterology		✓	✓	✓	✓	✓
General surgery	✓	✓	✓	✓	✓	✓
Gynaecology		✓	✓			✓
Internal Medicine	✓	✓	✓	✓	✓	✓
Long-term care				✓	✓	✓
Maternity and Gynaecology		✓	✓	✓		✓
Medical laboratory		✓	✓	✓	✓	✓
Neurology					✓	✓
Oncology			✓	✓	✓	
Ophthalmology		✓		✓		✓
Orthopaedics	✓			✓		✓
Pediatrics				✓		✓
Radiology		✓	✓	✓	✓	✓
Rehabilitation Medicine				✓	✓	✓
Specialized Surgery				✓	✓	✓
Urology						✓
Number of hospital beds	34	92	114	211	372	654

Table 3. Hospitals' departments and number of hospital beds

4 Analysis of the healthcare functions

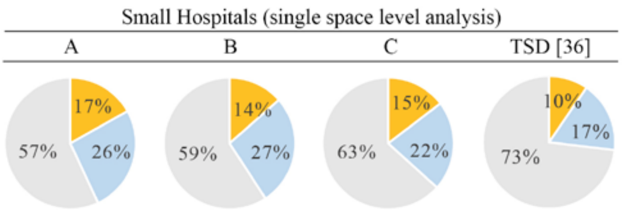
Similarly to the investigation methodology used by Čongradac et al. [15], the entire hospital buildings were created in Excel and defined room by room, to which were referred the measurement data collected.

As reported in Table 4-5 and in Figs. 1-2, the research findings regarding the percentage distribution of the conditioned floor area for the six hospitals were compared to the values reported in Refs. [34-37]. Although the studies exposed in the Refs. used building simulation methods and were based on prototype buildings and not real case studies, they were selected for the comparison since they are the only ones which analysed the hospital building by making a clear and comprehensive distinction of the spaces in relation to their use.

In order to aid a proper interpretation of the first results, it is necessary to underline that the TSD for Small Hospitals and Healthcare Facilities [36] refers to structures with a surface up to about 8.000 m^2, such as hospitals A, B and C, while the TSD for Large Hospital [34-35] regards structures with a surface ranging from about 9.000 to 46.000 m2, a category to which hospitals D, E and F belongs. The study developed by the University of Washington's IDL [37] analyses two types of hospital building form: a traditional and compact form, like hospitals A, C, E and F whose S/V ratio ranges from 0,34 to 0,43, and a more articulated one, like hospitals B and D, having a S/V ratio between 0,54 and 0,56 (see Table 2). In addition, both the TSDs analysed the hospital spaces at single space level, while the work of the IDL distinguished the spaces at department level. For this reason, the analysis of the six hospitals at single space level is compared to the results of the TSDs, while the analysis of the hospitals at functional area level is compared to the values reported by the IDL.

	Conditioned floor area (%)							
	Small hospitals				**Large hospitals**			
Single space	**A**	**B**	**C**	**TSD [36]**	**D**	**E**	**F**	**TSD [35]**
Patient rooms	17	14	15	10	16	10	12	24
A&E specific spaces	2	1	0	1	1	0	0	2
Medical offices	5	7	6	22	6	8	7	21
Administrative offices	6	7	6		7	5	5	
Laboratories	2	5	3	2	4	3	3	3
ORs and support spaces	7	3	2	7	2	3	3	8
Consulting/Examination rooms	8	9	9	6	12	6	6	5
Diagnostic/Examination rooms	2	2	2	2	1	3	2	3
Kitchen/Canteen specific spaces	4	4	3	3	2	2	3	2
Mortuary and support spaces	0	1	1	0	0	0	0	0
Toilets and dressing rooms	9	9	10	5	9	10	9	1
Connective spaces	29	29	32	23	34	36	40	16
Storage rooms	5	3	5	9	1	7	5	10
Technical spaces and services	5	6	5	11	5	7	5	6

Table 4. Distribution of the conditioned floor area in relation to the use of the spaces in small and large hospitals



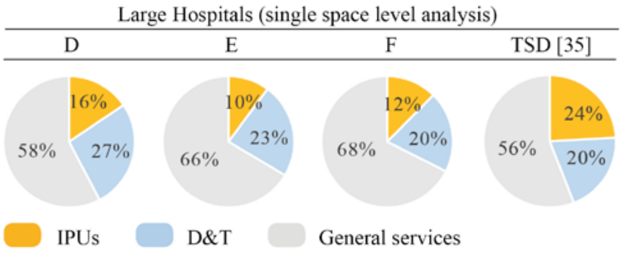


Fig.1 Distribution of the conditioned floor area in relation to the three macro-areas in small and large hospitals

	Conditioned floor area (%)							
	Hosp. with a compact form					Hosp. with an articulated form		
Functional area	**F**	**A**	**C**	**E**	**IDL [37]**	**B**	**D**	**IDL [37]**
Inpatient Units	33	31	27	35	32	26	34	42
A&E	1	3	8	0	4	2	3	4
Medical offices	3	4	5	4	11	5	5	10
Administrative offices	4	3	6	3		6	4	
Laboratories	4	2	3	4	3	7	5	3
Operating theatres	8	10	4	6	9	5	4	9
Outpatient department	8	14	6	9	0	11	18	0
Diagnostic imaging	4	4	4	9	6	4	3	6
Kitchens and canteens	4	6	3	2	2	4	4	2
Mortuary	1	0	1	1	0	1	0	0
Toilets and dressing rooms	3	4	5	4	0	2	4	0
Connective spaces	22	14	20	15	20	16	13	11
Storage rooms	1	1	3	3	3	4	0	3
Technical spaces and services	3	4	5	5	9	6	3	9

Table 5. Distribution of the conditioned floor area in relation to the use of the spaces in hospitals with a compact form and in those with an articulated one

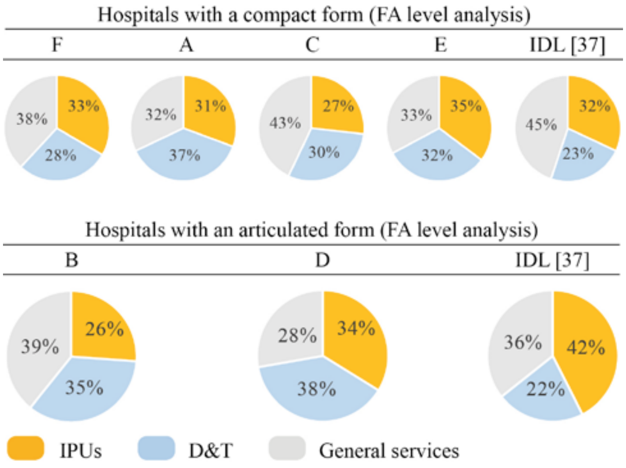


Fig.2 Distribution of the conditioned floor area in relation to the three macro-areas in hospitals with a compact form and in those with an articulated one

Despite healthcare is characterised by the steady shift from inpatient toward outpatient care, the data exposed above show that patient rooms at single space level and IPUs at functional area level are the second and the first space type, respectively, to have an extremely high impact on the distribution of the conditioned floor area, preceded and followed by connective spaces.

However, for a proper interpretation of the data is necessary to underline that half of the hospitals analysed date back to before 1940, while the others were built before 1980. Therefore, considered the difficulties in space flexibility and layout reorganisation typical of outdated structures, the decrease of patient rooms is less visible in the case studies examined. This process is more evident in the analysis of the conditioned floor area at macro-area level, which underlines that general services are the most impacting space category.

Besides patient rooms and Inpatient Units, consulting and examination rooms, at single space level, and operating theatres and outpatient department, at functional area level, have a quite important role in the distribution of the hospital conditioned floor area, due to the advances in medical procedures and the trend from inpatient toward ambulatory care.

5 Conclusions and future developments

The results of the analysis of the six hospitals examined show that the ongoing evolution in clinical and surgical therapy is bringing consistent changings in the organisational and layout features of the interior spaces. Parts of the hospital structure are reorganized to reflect new patterns of treatment.

Spaces previously destined for patient rooms, and IPUs in general, are decreasing in favor of non-clinical spaces and general services, like public connective spaces, patients and visitors specific facilities, administrative and storage areas, etc. The progress of medical techniques and technology and the use of new pain medications and antibiotics are allowing to significantly reduce the patient length of stay. These process, together with the financial and economic crisis and the political pressure to reduce healthcare expenditures, brought to a reduction in hospital beds by about 16% between 2010 and 2015 [62-64]. Against this background, connective spaces are reorganised and increased to ensure the appropriate circulation of patients, staff and medical equipment. Furthermore, hospitals are being redesigned to make them more accessible and familiar, with the introduction of new services and facilities supporting the patients and visitors' experience.

These changings in the architectural features and layout of the healthcare interior spaces are evidence of the increasing complexity of hospital logistics.

For this reason, one of the future development of the work, which is going to be widen to other national and international healthcare facilities, is to analyse a number of intermediate results, always referred to the type of spaces, like the external surface, the heating and cooling energy needs, heat losses due to transmission and ventilation, etc., and investigate examples of inner variations if changing some architectural or functional features.

The aim is to define composite benchmarks for hospitals by taking into account differing energy intensities at a departmental level. Furthermore, being based on larger sample sizes, the work will increase the reliability of the established consumption figures. Such an approach will enable to accommodate the fast-moving changes in healthcare delivery – and their impacts on layout features of hospital interior spaces – as well as the large heterogeneity between hospital buildings. Albeit focussed on hospital buildings, the methodology has a much wider utility as it could be applied to other non-residential building types in temperate climates, even thanks to its ease of use.

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