Govern complex systems in the design of an innovative, safe and sustainable hospital

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Abstract. The hospital is essential for managing the health of citizens with a high degree of complexity. The hospital system is very energy-intensive, presents rapid technological obsolescence and often requires specific and multidisciplinary skills to also manage new clinical-health organizational models for the dynamic change of functional needs and the management of emergencies (e.g. Covid 19 pandemic). The proposed methodology envisages the pervasive use of renewable energy and the modeling of the digital twin of the building with system solutions specifically designed to increase the comfort of the users of the structure and optimize the maintainability of the systems. These systems, thanks to artificial intelligence software, after an initial period of "learning" the behavior of the building, are able to dynamically simulate different ways of operating the systems in order to pursue the model capable of maximizing the energy saving of the building. The advanced energy monitoring system (BEMS - Building Energy Management System) allows to guarantee the monitoring of the pre-established performance indicators with undoubted advantages from the point of view of the reduction of the primary energy necessary for the functioning of the structure, the study of consumption for cost, air quality and resource consumption.

1 Introduction

The hospital is the healthcare facility with the greatest complexity and with the highest number of operational and management functions. In Italy there are 1382 public and private hospitals in 2022 [1]. Most of these structures are old and obsolete and require expensive maintenance and renovation. The construction of new hospitals involves long and complex processes from design to construction, testing and accreditation. In this context, it is essential to represent that the design of a public work of such importance cannot fail to take into account that the structure will have to be planned, programmed and designed with a vision of an innovative, safe and sustainable hospital that fits and integrates into the urban and social fabric of smart cities. A smart and sustainable city combines the quality of life in a context of one health with the correct and economical use of natural resources for the present and the future. Given the breadth and relevance of the complex systems to be governed, in the face

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of the ambitious objectives of efficiency, effectiveness, appropriateness and sustainability to be achieved, a new strategy is needed to govern the design process of such an important public work with great managerial-organizational value and a high impact on the social, productive and economic fabric. The proposed methodology aims to facilitate the management of complexity for the design of a high-intensity and high-risk public system. It is based on strategic planning, Knowledge Management by applying Building Modelling Information (BIM) [2-6] and Digital Twin techniques [7] to Cyber Physical Systems. At the moment there is no specific literature on the subject but some articles on the design phases applied to non-hospital works

2 Baseline Scenario

The main drivers of changing the design criteria for a hospital are digital transformation and ecological transition. The digital transition is taking place progressively and dynamically in the various countries and is being implemented at different speeds [8]. In the various countries, the digital transformation is closely linked to the different investments in information, multimedia and infrastructure technologies, as well as investments in training and a culture of change at different social and economic levels [9]. In Europe, the European Commission plays a key role in the digital transition of the various countries by stimulating actions and investments in different public, private and social sectors with a propulsive action towards the organizational change of complex management systems [10]. In particular, health systems that have different models in different European countries have been incentivised through important funding policies with the resources of the European budget to implement a significant digital transition. The analysis of the information collected also revealed numerous critical issues that are barriers to change [11].

Specifically, the study of the evolution of the Italian National Health System and regional health systems has shown the need to overcome the bureaucratization of management processes that hinders the change to digital models. The response of regional health systems to the Covid 19 pandemic has also highlighted the critical issues inherent in the lack of integration of information between databases and the need for a reorganization of health systems and related structures to respond effectively and reactively to emergency situations dictated by the pandemic [12].

An important turning point for organizational and managerial change was then given by the PNRR, which addressed and stimulated digital health with conspicuous interventions [13]. In particular, the hospital-territory dualism has been overcome with the introduction of a complex network organizational system that starts from patient care at every level to the management of acute and chronic care [14,15].

The design of an innovative, safe and sustainable hospital is also part of a new global and European strategy defined by the "2030 Agenda for Sustainable Development"[16], drawn up in 2015 by the United Nations General Assembly, in which a concrete list of things to do for people and the planet was decided through the identification of 17 strategic goals for sustainable development (SDGs, Sustainable Development Goals). The SDGs, together with the Paris Agreement on climate change, constitute the roadmap to improve the living conditions of the planet within a global framework of international cooperation on sustainable development and its economic, social, environmental and governance dimensions. The innovative, safe and sustainable hospital is part of SDG 3 (ensure well-being for all at all ages) and SDG 11 (make cities and human settlements inclusive, safe, resilient and sustainable) (Fig. 1).

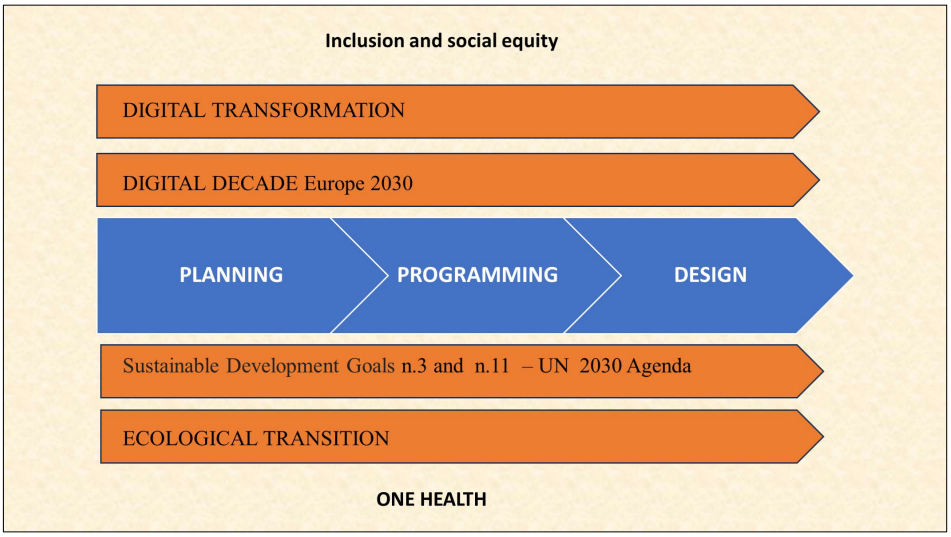

Fig. 1. The Framework of Innovation.

With Decree no. 77/2022 of the Ministry of Health [15], a new organizational model of the health system was introduced, which indicates a new model of territorial health management, creating a network system with new reference structures to overcome the dual hospital-territory logic through a network organization in synergy with the new hospital of the future (smart hospital). The decree was born on the experience gained during the management of the Covid-19 pandemic, which has demonstrated several weaknesses of the health organization in the face of the management of highly complex problems related to the emergency urgency and the taking charge of the patient and has also taken into account the technological and infrastructural innovations generated by digital health (e-health) and the changes in the management of clinical-care processes due to the introduction of ICT technologies. In particular, digital transformation has led to a new health management strategy that has telematic infrastructures and the increasingly pervasive use of Telemedicine as the main lever of change. The new organizational structure of public health provides: Community Houses (CHouse); Community Hospitals (CH), Territorial Operations Centres (COT) and Hospitals, the latter increasingly with a view to Smart Hospitals, i.e. innovative but also safe and sustainable hospitals. As shown in the framework of figure 2, the new organizational model is part of the innovative strategy for health indicated by the digital agenda and with a systematic and integrated review of the connection and communication infrastructures (NUE 116117, NUE 112, 118).

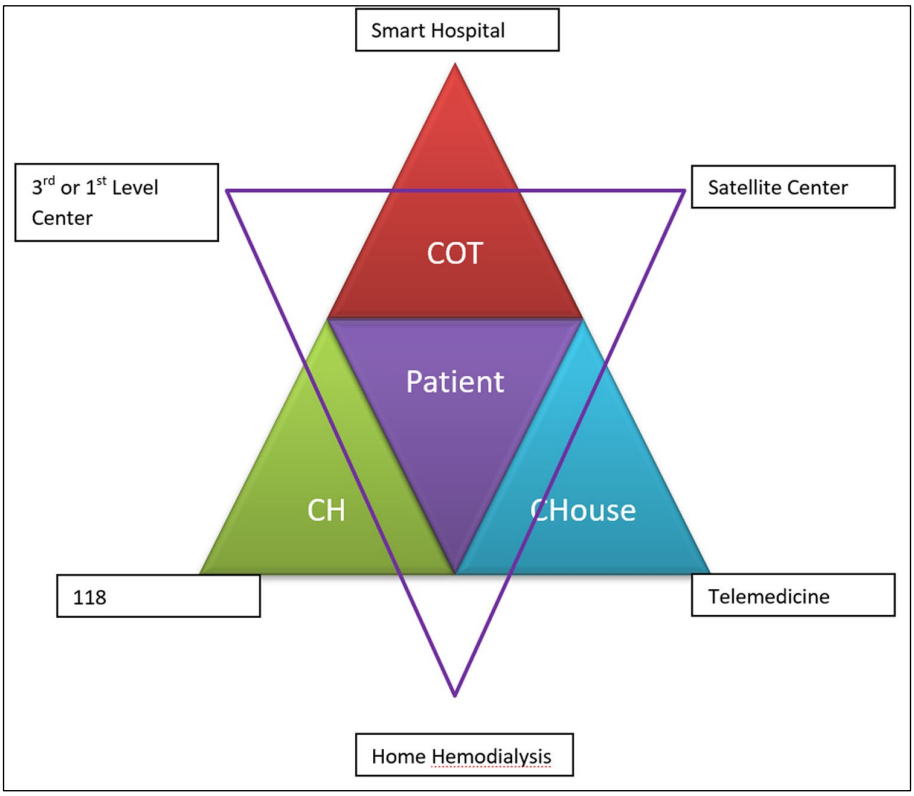

Fig. 2. The new organizational model of Italian Public Health.

Currently, given the importance of the Hospital and in order to further improve what has been determined with the new organizational model, the ministerial table for the revision of hospital-territory standards hs been established (Ministry of Health, July 2023) with the aim of harmonizing management processes and eliminating any critical issues.

2.1 Modern hospital and Telemedicine

The design of a modern hospital cannot be separated from the knowledge and monitoring of the progressive and constant evolution of Telemedicine in the context of clinical care processes [17]. Telemedicine, a fundamental factor of digital transformation in healthcare, can be defined as the way of providing healthcare services, through the use of innovative technologies, in particular Information and Communication Technologies (ICT), in situations where the health professional and the patient (or two professionals) are not in the same location. Telemedicine involves the secure transmission of medical information and data in the form of text, sound, images or other forms necessary for the prevention, diagnosis, treatment and subsequent monitoring of patients. In addition, the Ministry of Health has ordered that Telemedicine services must be assimilated to any diagnostic/therapeutic health service. The knowledge of the evolutionary processes of telemedicine is fundamental in the Vision of a new innovative, safe, sustainable hospital as it is used not only for chronic situations but also for the management of urgent emergency situations (connection and interaction between the structures and 118, second opinion function in specialist

teleconsultation, timeliness in the management of critically ill patients and in situations with fragile patients in the case of monitored rare diseases in hospitals). In the following figure 3 there is the conceptual framework of telemedicine (teledialysis) with the classification, the scopes and the relationship with patients.

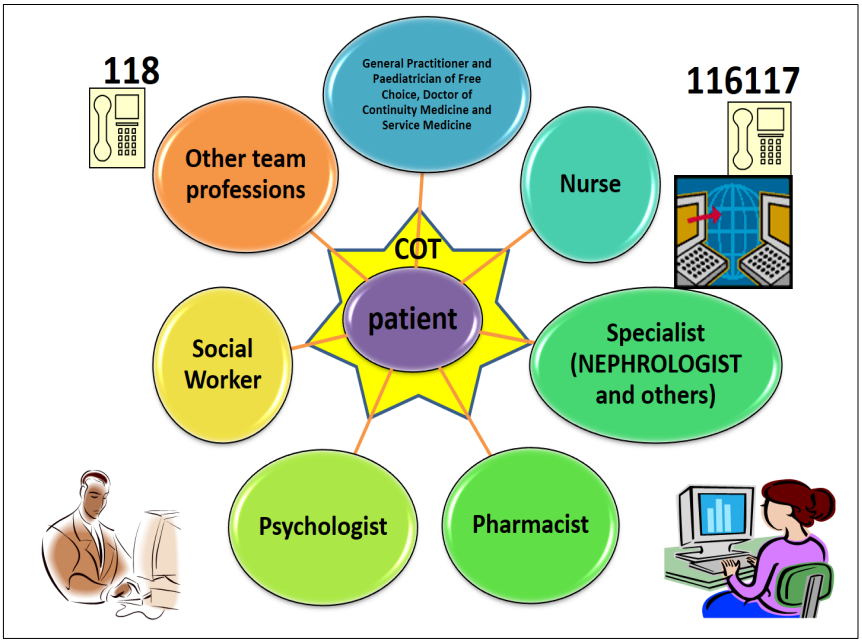

Fig. 3. The framework of Teledialysis in new organizational model.

Among the various areas of technological innovation affecting healthcare (Augmented Reality, Artificial Intelligence, IoT, Big Data, Machine Learning, Robotics, etc.), Telemedicine and the creation of digital infrastructures and smart buildings are strategic factors of change, these synergistic and interconnected elements are fundamental for the new healthcare management paradigm of the future. [18]

3 From strategic planning to design – governance of complex systems in hospital design

The strategy for the design of an innovative, safe and sustainable hospital must be framed in the smart city context in relation to the processes of creating public value in economic, social and organizational terms with the ultimate aim of pursuing the well-being of citizens and raising the quality of life. In particular, the innovation and sustainability of the hospital system that is intended to be created must be evaluated in its three fundamental aspects: Economic sustainability; Social sustainability and environmental sustainability. These dimensions of sustainability presuppose the following actions as show in figure 4.

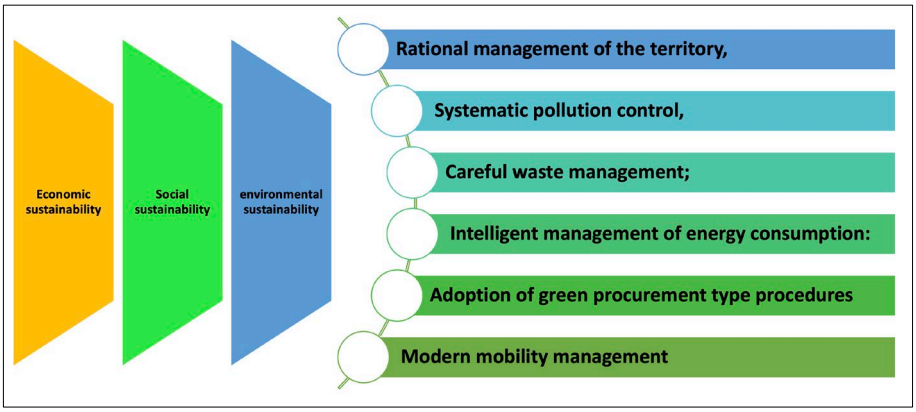

Fig. 4. Dimensions of sustainability and actions to govern complex system in design of smart and sustainable hospital.

Therefore, the coherent strategy to pursue sustainable development must be characterized by the following intrinsic characteristics: resilience capacity, organizational quality, social orientation, attention to economic and environmental aspects, propensity to apply digital innovations.

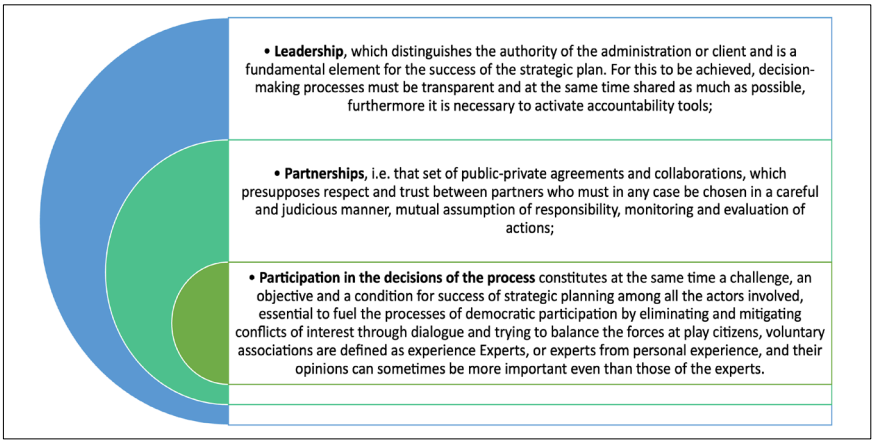

Fig. 5. Three elements characterizing the strategic planning process to govern complex system.

Sustainability is therefore an essential character of the modern hospital and is based on four pillars or strategic elements: Economic capital, Natural capital, Human and social capital, Governance. Sustainability has therefore become an essential requirement in the development of hospital design and this implies the need to activate a strategy that takes into account the economic and social environmental issues that are the basis of good governance. Therefore, since the modern hospital system is characterized by a multiplicity of complex systems with a fragmentation of institutional and non-involved actors, the strategic planning method is the best as a reference model for the process of experimenting with new forms of governance of the complex -I know the design process. In other words, it represents the most suitable tool to guarantee the sustainability of the governance choices of the complex systems that make up a hospital. Before embarking on the strategic planning process, the objectives and conditions of effectiveness, after having identified the composition of the actors involved in the plan, it is necessary to start a careful analysis of the territory in which the hospital

structure will be located, for example, analysis of the context, the useful tools of which can be interviews, interviews, questionnaires to analyse the urban context and the positioning of the structure, for example with respect to other settlements, all the resources available are therefore taken into consideration [19]. Natural assets of the geographical area in which you are operating, in fact the so-called SWOT analysis is initiated, i.e. the identification of strengths and weaknesses, opportunities and threats [20,21]. Once the analysis phase has been completed, we move on to define the Vision, a sort of prefeasibility study enriched by the different solutions that can be undertaken to achieve the design objectives in the medium to long term [22].

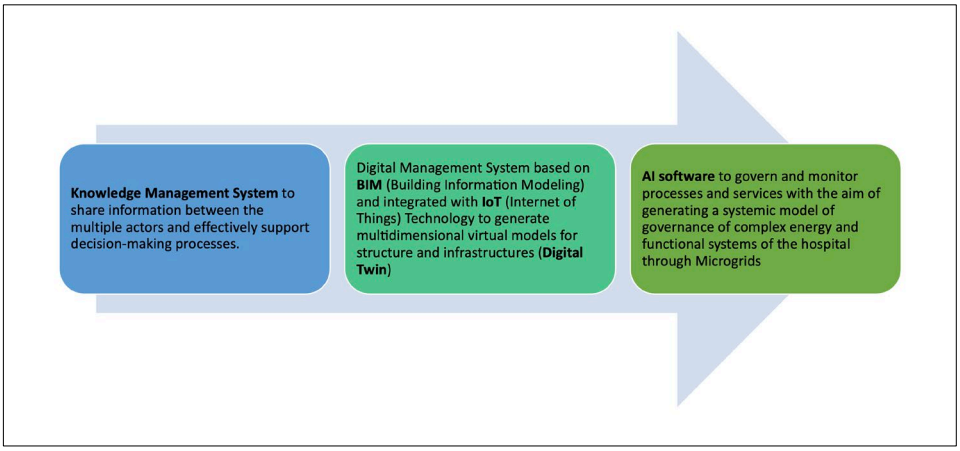

Fig. 6. Key elements in the strategic planning process to govern complex system design.

The systemic process to govern the complexity of the design of a modern hospital therefore starts with the definition of the strategic idea and a swot analysis, then the following steps are carried out:

1. Planning with analysis of the current strategic positioning of the structure to be built; formulate a long-term vision and outline the mission; select the areas of intervention; develop an organizational strategy consistent with the intervention to be carried out; define, select the project ideas and investments to be implemented; a communication strategy; define a methodology for monitoring and evaluation;
2. Project and investment development; general select and organize project ideas to achieve objectives; acquire the resources to support the development of projects; implement projects;
3. Communication;
4. Monitoring, evaluation and accountability; monitor activities, evaluate results, and initiate an adjustment and modification process

In relation to the considerations set out so far, the following framework has been created for the governance of complex systems in the design of an innovative, safe and sustainable hospital.

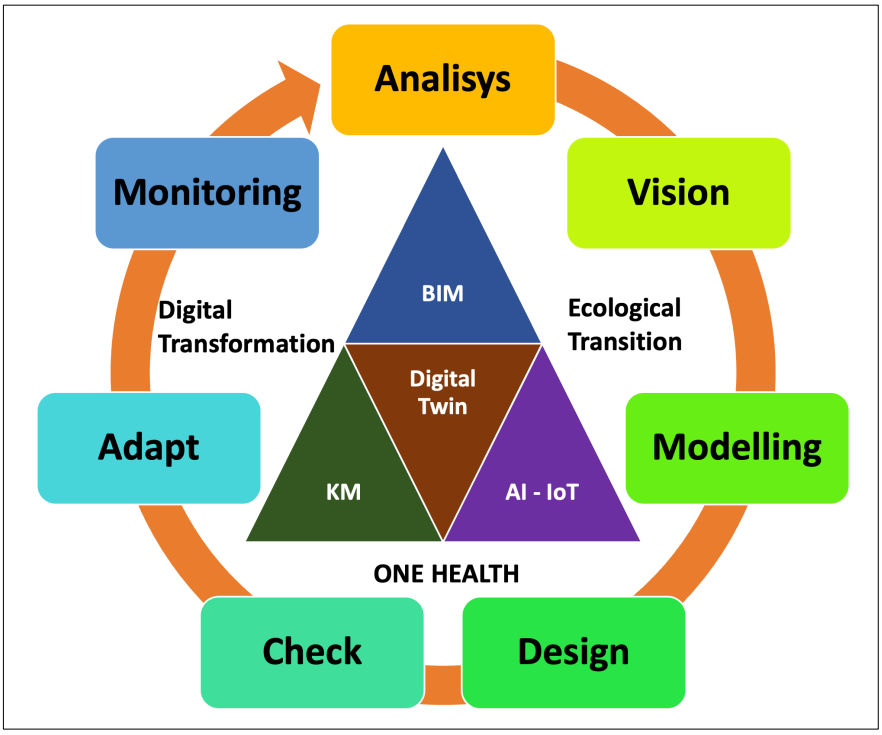

Fig. 7. Framework for governance of complex systems in the design of modern hospital.

4 Case study: plant solutions that make new South Salento Hospital an innovative, safe and sustainable hospital.

The strategic planning illustrated has been applied in governing the design phases of the new hospital in South Salento that will be built by the ASL Lecce (Local health authority in Apulia Region – Italy) in the territory of the municipalities of Melpignano and Maglie. First of all, all the steps from planning to design were monitored according to the framework of figure 7, with particular attention to the aspects of digital transformation and ecological transition from a one health perspective, also in relation to the organizational scenario of the current Italian health legislation (Fig. 2 and Fig. 3), constantly involving the design groups both on the technical and economic feasibility study and on the final project as per the Framework of figure 1. Meetings were provided to guide the project of the new hospital according to the dimensions of sustainability, developing inclusive decision-making processes also with the heads of all the institutions involved (Fig. 4, Fig. 5). Strategic planning was therefore strongly based on a multidisciplinary approach and widely participated by all stakeholders (Fig. 6).

Functional area	Beds
Medical area	144
Surgical area	86
Maternal/Infant Area	75
Intensive Area	27
Day Hospital, Dialysis, Brief Intensive Observation	56
Total	388

Fig. 8. Bed per functional area in New South Salento Hospital.

The design of the new hospital in South Salento has a series of innovative features related to energy efficiency and environmental sustainability. In particular, the production of heat transfer fluids for air conditioning, domestic hot water and steam for humidification of AHUs and sterilization are produced within a Technological Pole located in a separate structure from that of the hospital. The production of heat transfer fluids for air conditioning, including high temperature hot water, is carried out by means of high-efficiency heat pump systems. Heat generators powered by natural gas have only a backup function. A trigeneration plant is also planned for the simultaneous production of high-temperature hot water, chilled water and electricity, consisting of two cogenerators each with an electrical power of 530 kWe and two absorption water chillers suitably sized to transform all the thermal energy produced by the cogenerators into cooling energy. The building is also equipped with an innovative chilled water storage system, the so-called "Cold Bank", which will be powered by heat pumps or refrigeration units at night, when electricity is cheaper, and will constitute a reserve of cooling energy to be used to reduce daily load peaks, making it possible to avoid unnecessary oversizing of the heat transfer fluid production systems. However, they have been sized, in terms of size and number, in order to always have an appropriate redundancy, preventing the malfunction or downtime for maintenance of one of the equipment from compromising the regular functioning of the hospital structure. All the generators are also included in a microgrid which, depending on the energy demand of the hospital, manages the activation of the various generators in order to optimize energy efficiency and environmental sustainability.

Still on the subject of the distribution of heat transfer fluids, given the particular configuration of the building, a distribution network divided into four rings on each floor was opted for.

The ring distribution guarantees a reduction in the pressure drops of the network, ease of modification a posteriori with any shifting of loads according to supervening needs, continuity of operation even in the event of a breakdown of a section of the net-work.

The individual terminals will be derived from each ring, managed with a dynamic balancing by means of 2-way PICV (pressure independent control valve) valves. The variable flow operation of the grids is managed by means of high-efficiency inverter circulators, all redundant.

The air conditioning systems used, diversified according to the various areas, are:

- all-outdoor air system with absolute H14 filtration, in operating blocks and high-intensity care areas;
- inverter cassette fan coil system and primary air in the corridors, changing rooms, storage rooms and maintenance rooms within the Technology Hub;
- radiant ceiling panel system and primary air in all clinics, doctors' offices and hospitalizations;
- heating system with towel warmer radiators in the toilets;
- cooling system with cooling-only inverter fan coils in the technical rooms serving the electrical and special systems;
- hydronic system with precision air conditioners in the ICT Center located in the basement.

Fig. 9. Air Conditioning systems.

The AHUs are all equipped with inverter plug fan fans and a twin coil heat recovery system, which involves a total separation of supply and return air flows, avoiding any cross-contamination phenomenon. The use of inverter fans will also allow the modulation of the air flow according to the demand: for example, the air flow rate of the operating rooms will be modulated depending on whether the room is in standby, standby ready for use, in use. Similarly, airflow management is provided in highly crowded areas linked to the detection of CO2 or pollutants in the air (VOCs). Another particularly relevant element is the provision of a system for the automatic transfer of test tubes from the wards to the analysis laboratory on the second floor. The power supply of the new hospital complex is provided in Medium Voltage 20kV from the Distributor's network. In the external areas, in the cabin called C0 is located the delivery point, which will serve 3 cabins in a closed loop, the MV-LV cabins called C1 and C2 that will serve the hospital building and the C3 cabin that supplies the users of the Technological Pole for the production and treatment of heat transfer fluids. The three substations are served by a second MV ring, totally independent from the main distribution ring, which guarantees the Preferential power supply with short interruption (<15s) in the event of a power failure from the Distributor and/or problems on the Ordinary distribution network. The preferential distribution ring is powered by 4 generators with a power of 1500kVA each in low voltage brought back to Medium Voltage through special step-up transformers. The exchange from the Ordinary Grid to the Preferential Grid is automatically managed directly in Medium Voltage.

The two Medium Voltage rings, normal and preferential, will be managed closed and the protections are coordinated by means of a redundant data network based on the IEC 61850 standard, a standard also used at the national coordination level for the coordination of the User substations.

All the main switchboards, starting from the QMTs and going down to the QGBTs and the general floor panels, are managed with two independent and power-redundant half-busbars, never more than 50% loaded in ordinary operating conditions: this implies that any fault and/or maintenance intervention that may be necessary can be managed by excluding the faulty or maintenance section and ensuring the supply of downstream users through the local resupply from the busbar complementary.

As far as absolute continuity is concerned, two sections will be created, one for IT continuity and the other for medical continuity with redundant UPS for each energy section. For high-density care wards, the implementation of medical IT-M systems with iso-lation transformers is planned. On the roof of the hospital, the construction of 2 photovoltaic fields of about 500kWp each made with monocrystalline silicon panels is planned. The energy produced will be poured into the grid through the Power Centers of the MV-LV substations called C1 and C2.

As already mentioned above, in order to ensure great flexibility in the manage-ment of the different energy sources, the project provides for a close interaction between the different generation systems, forming a real "Microgrid" capable of selecting the different energy sources available both according to the real production costs of the energy carriers and according to the real load demands coming from users.

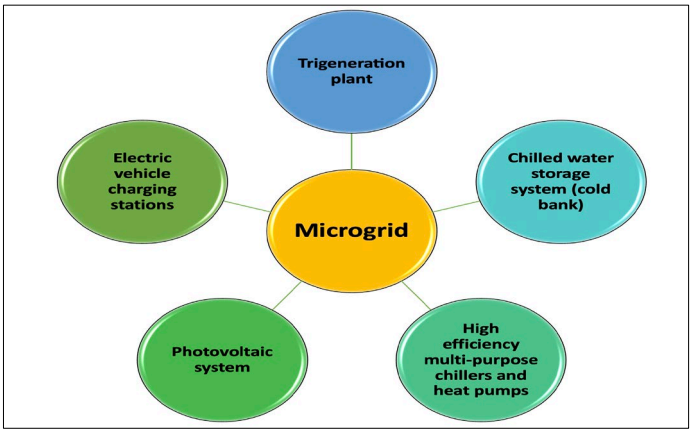

Fig. 10. Framework of Microgrid.

The Microgrid basically consists of the following components: Trigeneration plant, Chilled water storage system (cold bank), High efficiency multi-purpose chillers and heat pumps, Photovoltaic system, Electric vehicle charging stations. In addition to these systems, specifically designed to optimize the use of alternative and renewable sources, there are those that use fossil fuels (heat or steam generators powered by methane gas) or absorb energy from the grid and that are in a secondary position in the order of priority of use. The potential for energy savings that a microgrid can generate is incalculable and is based on iterative criteria for the pursuit of the point of maximum economy, based on optimized coordination of production/user/storage systems and generation systems. The dynamic management of the microgrid will be entrusted to a solid artificial intelligence system, an element whose market is growing very rapidly. Operation models with modeling of the building's digital twin are also implemented. These systems, after an initial period of "learning" the behavior of the building, are able to dynamically resemble different modes of operation of the systems in order to pursue the model capable of maximizing the energy savings of the building. The advanced energy monitoring system (BEMS - Building Energy Management System) makes it possible to ensure the monitoring of preset performance indicators with undoubted advantages from the point of view of reducing the primary energy required for the operation of the structure, the study of consumption by cost centers, air quality and water resource consumption.

4.1. Impact of the use of the proposed new systems, systems and technologies on comfort (acoustic, visual, thermo-hygrometric, air quality, etc.) and on the healthiness of the environments.

A series of plant engineering solutions have been implemented specifically designed to increase the comfort of the users of the structure and optimize the maintainability of the systems. The AHUs are equipped with high-efficiency filtration systems with antibacterial treatment and heat recovery systems on the expelled air that optimize energy efficiency by

categorically avoiding contamination between the air supply and return flows. Particular attention has been paid to the design of the air humidification systems for AHUs, favouring network steam solutions and avoiding the use of independent producers with very high electricity absorption. The water systems, in particular the domestic hot water distribution system, have been designed and built with particular attention to the prevention of legionella, through a series of measures:

- treatment of the DHW mains feed water with a dosage of a concentrated product based on hydrogen peroxide and silver to keep the water clear and crystalline and preserve its microbiological quality;
- configuration of sanitary water networks in such a way as to promote continuous water circulation, avoiding dead branches;
- Loop through-feed distribution system inside the toilets.

To minimize the exposure of electromagnetic fields for the staff and users of the facility, the installation of shielding plates inside the C1 and C2 electrical substations and in the shafts of the electrical uprights is planned. For all the main distribution ducts contained in the technical tunnel, in order to reduce emissions compared to the upper floors, special technical measures will be adopted to achieve the desired shielding effect. In highly crowded areas, CO2 probes will be installed to detect that attention thresholds have been exceeded and to implement the necessary corrective measures on ventilation and air conditioning systems.

5 Conclusions

The holistic approach of the hospital system with peculiar characteristics of innovation, safety and sustainability has made it possible to define a methodology to govern complex design systems starting from strategic planning to the design of smart buildings with BIM, Digital Twin and Deep Learning methodology. The methodology represented in the framework has produced in the case study the simplification of processes and the preparation of an integrated governance and control system based on the creation of a twin ecosystem that can be used throughout the life cycle of the structure. The control logics based on Digital Twin, Artificial Intelligence and Deep Learning have made it possible to perfectly integrate the different design modules (structural, plant, clinical-organizational) through the BIM platform. The project result is represented in the following figures

Hospital area	**Ground floor**	**Hall and Main Street, Polyamulatory, Blood Collection Center, Single Booking Center, First Aid, and Brief Intensive Observation, Morgue and Pathological Anatomy, Molecular Biology**	**15.588 sqm**
	First Floor	Outpatient clinics, doctors' offices, laboratories, hospitalizations, operating blocks, endoscopy, low care gyms	**14.409 sqm**
	Second Floor	Delivery Block, Inpatient Clinics, Outpatient Clinics and Mothers' Area, Intensive Care, Outpatient Clinics and Doctors' Offices	**14.462 sqm**
	Basement	Diagnostics, Technical Rooms, Warehouses, Pharmacy, Changing Rooms and Treasurer	**13.466 sqm**
	Roof floor (kindergarten)		673 sqm
Technological/plant engineering area	First basement floor	Power center	2.555 sqm
	Second basement floor	Power center	2.583 sqm
Shell			13.789 sqm
Outdoor areas			**81.509 sqm**
Parking areas			20.172 sqm

Fig.11. Dimensional data of New South Salento Hospital

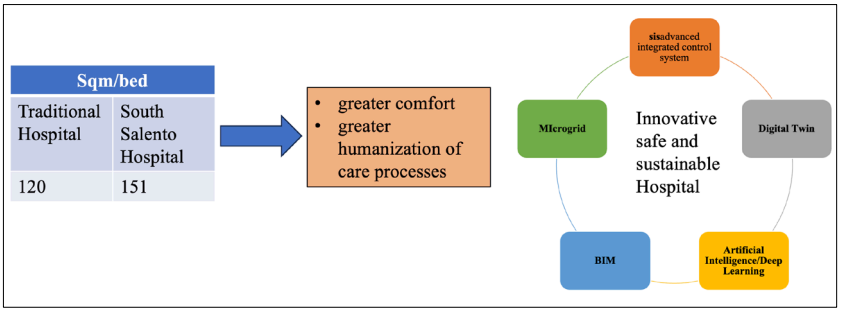

Fig.12. Design results of New South Salento Hospital.

The proposed methodology then directed and guided the design with the aim of creating a "future proof" Smart Hospital based on Advanced Energy Supervision and CPSoS (Cyber Physical System of System) for the optimized management of the hospital's decision-making, management and operational processes. In particular, as a case study, the governance model of the design complexity of the plant systems that constitute the backbone of the modern, innovative, safe and sustainable hospital was addressed. It has been shown that an integrated governance system of energy systems is essential for the sustainability of the structure over time, while the shape factor of the structure and the landscape system around it affect the well-being of patients and operators, contrib-uting with telemedicine processes to a greater humanization of care and assistance. A conceptual framework has therefore been defined to govern complex design systems that can also be applied to simplify the monitoring of the different design phases, from the initial feasibility study of the work to the executive design phases. The framework used is also the reference for the creation of a Knowledge Management System (KMS) integrated with BIM and Digital Twin applications and Artificial Intelligence useful for governing the structure, supporting healthcare professionals and improving clinical and care processes. In addition, since the various complex phases are managed in a multidisciplinary and multi-professional way, the KMS will be able to make use of Block-chain technology for the registration of official documentation. The framework can also be further developed and integrated with the construction management and testing phases.

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