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Systemic sustainability and resilience assessment of health systems, addressing global societal priorities: Learnings from a top nonprofit hospital in a bioclimatic building in Africa

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ABSTRACT

Health services represent a cornerstone to ensure well-being and human rights, particularly in deprived areas. The resource cost and appropriate use for the implementation of a top-quality hospital in Sudan are here investigated. An emerging approach such as systems-based Emergy Accounting is applied to assess its sustainability and resilience, also relying on Life-Cycle Assessment data to calculate some new unit emergy values. Very few similar studies have addressed civil works so far, even less bioclimatic buildings, while the focus on health systems is an absolute novelty. Particular attention is paid to design in adverse climate and economic conditions, to the humanitarian nongovernmental organisation running the hospital, and to the cutting-edge medical staff and technologies imported from abroad, also letting local practitioners train in excellence medicine. The system's direct and indirect socio-ecological requirements are expressed as emergy (resource investment) per patient-day, per cardiac surgical operation, per outpatient visit, and per year. From a quantitative viewpoint, these indicators represent a benchmark for improvement scenarios, comparison with new studies in a deserving field, and future investments, driven by effective healthcare policies. They also provide an overview of the efforts required by nature and society to ensure a human right in conditions of scarcity. Besides the possibility to lower a hospital's environmental impact (sustainability-oriented) and to keep it functioning over time in changing climate, resource, societal, economic, and geo-political scenarios (resilience-oriented), this study leads to original remarks upon societal priorities and upon the challenges of guaranteeing high-quality health systems in an uncertain century.

Credit author statement

Original concept by all authors. Most of the manuscript was operatively contributed to by S.C., including literature search, figures, data curation, calculations, and writing. As a senior expert in emergy accounting, S.U. checked that related method and results were solid, after transferring to S.C. his expertise throughout their joint research years. As a senior expert in systems thinking, F.G. co-authored with S.C. the parts concerning the description of such approach as well as its global health implications, and supervised the whole research process. All authors worked together on the systemic diagram, on the abstract, on the description of the indicators, and on the review and editing phases.

1. Introduction

After the first warnings in the 1970s, a crescendo of voices is now recognising that the ongoing climate, ecological, economic, socio-political, and health crises have common causes and drivers. A complex system requires a complex, systemic approach. The present coronavirus emergency has further highlighted the criticalities of a closely interconnected world. A period like this, exhibiting more visible crises, draws attention on what cannot be given for granted in an uncertain 21st century: a thread can be seen among ecological sustainability, international economics, societal mechanisms, and future resilience to their possible alterations.

In this paper, some urgent topics in the global agenda are addressed,

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List of abbreviations

%Ren	Renewable Emergy Percentage
AEI	Areal Empower Density
ELR	Environmental Loading Ratio
EMA	Emergy Accounting
$Empd_{(r)}$	Renewable Empower Density
ESI	Emergy Sustainability Index
EYR	Emergy Yield Ratio
F	Imported sources from out of the system
L&S	Labour and services
LCA	Life-Cycle Assessment
N	Locally available nonrenewable sources
NGO	Nongovernmental Organisation
NZEBs	Nearly-Zero Energy Buildings
p-day	Patient-day
R	Locally available renewable sources
SA(r)	Renewable Support Area
SDG	Sudanese Pound
sej	Solar emjoule
seJ	Solar equivalent joule
U	Annual emergy use without labour and services
ULS	Annual emergy use with labour and services
UEV	Unit Emergy Value

valid for both the Global South and North: (a) health systems, called to adequately provide a basic right, and the delicate functioning of healthcare facilities; (b) the energy performances of buildings in times of climate change, depleting resources, energy poverty, and rapid urbanisation; (c) the design, assessment, and management – through appropriate tools – of a complex system in a changing world. Multiple international goals [1] are involved; among these: #3 (good health and well-being), #7 (affordable and clean energy), and #13 (climate action).

The organisation, efficiency, and overall sustainability of health systems at all scales have recently drawn new attention due to the Covid-19 pandemic. Precariousness and lack of resources were evidenced worldwide in the reaction towards the coronavirus spread. This has caused even the most advanced economies in the world to struggle to meet a skyrocketing demand for health services [2]. Moreover, this has also led to the necessity to divert the available personnel and equipment from the cure of other pathologies to that of the virus infected, so creating further malfunctioning in medical services and domestic assistance. The Global Risk Report 2020 [3] had already warned [4] that no country was fully prepared to handle an epidemic or pandemic. If the wealthier regions of Global Northern countries are in difficulty, plights are aggravated in the South and in other contexts affected by poverty, conflicts, forced displacement, severe climate conditions[1], and higher risks of a zoonotic viral spill, including Africa [6]. This means that a systemic study on how to set up a sustainable and resilient health service is strongly needed at all levels, and that important weaknesses may come from a bad use of resources, independently of their amount and quality.

The current pandemic has been recently seen as an opportunity to reconsider the collision between an injust "globalised capitalism and the carving up of continental ecosystems" [7]. In this respect, this work assesses health services by a more comprehensive socio-ecological point of view: according to the systems-thinking-based emergy method, it is possible to track direct and indirect resource and information inputs to a given system. Such method has been proposed as a way to "move environmental ethics beyond anthropocentrism" [8]. Haberl et al. [9] outline the need for systemic approaches able to bridge natural and social sciences to pursue global sustainability goals. Social and environmental goals imply environmental change as well as an increasing use of biophysical resources (energy, materials, etc.), which are therefore to be accounted for.

Concerning the resources, the access to energy is quite unequal on the planet, although global energy demand keeps increasing [10], and so does – at least for the moment – energy provision. This means that some contexts undergo conditions of so-called energy poverty [11,12]. Scarce access to energy provision is typical of marginal areas of the Global North and, more often, of the South. Here, energy distribution networks are often limited, especially out of the big cities, with energy shortages however possible also in urban contexts. If "regular life" can keep on anyway and adjust to the current energy availability as per millennial cycles in societies, a crucial aspect of energy poverty is of course related to hospital operations, due to life-saving machineries depending upon electricity, and to the need for adequate indoor temperatures to prevent the diffusion of diseases[2]. This is the case of many African hospitals, whose geographical location in tropical or equatorial areas gives rise to frequent high temperature conditions. The above considerations about energy access also apply to other resources, such as construction materials, machinery, sanitary items, etc. In this regard, the use of tailored building technologies and materials for local and economic contexts is widely insufficient, with imported solutions not always suiting local requirements. Such extreme contexts can paradoxically "be considered as a laboratory for all the planet", for their facing now those same conditions that the Global North "could be led to face in the next future" [14]. Similarly, hospitals might anticipatorily show that saving valuable scarce resources is not only crucial for social and environmental concerns, but also for the very durability of basic societal functions, like the one to save human lives.

The combination of outdoor weather conditions, indoor temperature (hence energy) requirements, and suitable insulation through appropriate materials and technologies seems to play a significant role in civil buildings in general, and above all in healthcare structures, especially those located in energy-poor contexts with unfriendly climate conditions. As a response to unstable urban electricity networks[3], averagely expensive and carbon intensive oil-fuelled generating sets are often employed to ensure the necessarily stable functioning of air conditioning systems and of all the life-saving biomedical appliances inside operating theatres, intensive care rooms, and even in common wards where basic services such as aided respiration are required. In a transition towards clean energy sources, facilities in temperate and especially tropical areas can exploit one of the most abundant source, i.e., solar radiation, a "democratic" source balancing higher requirements with higher availability [16,17]. Bioclimatic design [18–20] and investments on low-tech solar-based systems appear therefore as appropriate strategies for the specific energy needs of African hospitals. Parallel to this, solutions aimed at using renewable sources [21] and at providing buildings with passive mitigation to reduce the total energy demand for air conditioning would also appear as suitable for the reduction of both resource and monetary costs [16,22], thus partially making up for the energy poverty. Local, clean, renewable materials (wood, vegetable fibres, etc.) can also play a role in sustainable building construction and furnishing.

In recent years, the sustainability of building design has undergone several assessments, mainly based upon the LCA-based methods [23].

[1] About climate risks, pandemics, and health systems' preparedness, see Phillips et al. [5].

[2] Energy access as a pivotal driver to ensure health in emergencies such as the Covid-19 pandemic has been recently addressed [13].

[3] Further information about electricity networks in Sudan and surrounding countries is provided in Ref. [15].

Some of these can be integrated with Building Information Modeling [24,25], especially for the design of plumbing, heating, ventilation and air conditioning, and electrical systems [23]. One of the most used voluntary certifications to evaluate supposedly sustainable civil constructions is the Leadership in Energy and Environmental Design suite [26]. At the regulatory level, national plans for Nearly-Zero Energy Buildings (NZEBs) [27,28] have been encouraged in Europe in the past decade. As reported by the International Energy Agency [29], since 2007 an interest has increased for the calculation of the embodied energy [30] in building design [31]. In some cases, e.g. Switzerland, this has entered the public guidelines supporting decision-making for new constructions [32].

However, Braham [33] claims that NZEBs offer no much more than an environmental "style", focused on operational energy requirements, and that important inputs are neglected: e.g. construction and maintentance and free, unpaid inputs such as renewable environmental inflows. Similarly, although explicitly including many environmental costs, voluntary standards would "lack a rigorous metric with which to reconcile the costs and effects of different environmental impacts" [33][4]. In Braham's view, a similar reconciliation can happen through a sustainability science rooted in systems thinking [35] and based on the emergy metrics. This way, it would be possible to account for the entire network of environmental and human work required for a building to be constructed, maintained, and operated, while trying to minimise its impacts.

In the light of the crises we are facing, Braham [33] can be relevant again, for his suggesting that the notion of sustainability that can be acquired through systems thinking and the emergy approach may help in preventing alternative and maybe more dramatic outcomes, responding to the effects of scarcity. Details about the opportunities of using emergy in architecture and building design are treated by Srinivasan and Moe [36] (whose monograph includes a meaningful epigraph by Braham [37]), and by Cristiano [38], in addition to theses and dissertations [39–41]. The opportunities offered by the enlargement of the analytical boundary compared to the embodied energy and LCA approaches are illustrated, respectively, in Brown and Herendeen [42] and Raugei et al. [43]; the latter also expain the integration between LCA and emergy accounting.

Through the same approach that is used here, very few civil works have been investigated so far. Some authors analysed [44–46] or suggested to analyse [47] transport systems and infrastructures, but studies about entire edifices are even fewer, none of which can be anyhow defined as "bioclimatic". Meillaud et al. [48] focused on an academic building using solar energy through a photovoltaic façade. Others analysed some residential units in Canada [49] and an off-grid residence located in an ecovillage of North Carolina, USA [50]. Cristiano and Gonella [16,22,51] compared low-tech vernacular innovation with conventional building technologies, including construction requirements and lifetime savings. Other authors [52] addressed the emergy inputs in the life cycles of key building materials, including recycling options. Similarly, Pulselli et al. [53] analysed some energy and material inputs for building construction, maintenance, and operation[5]. Through a different approach, i.e. LCA, hospitals can be only partially investigated: some [55,56] focus on the technical aspects of their construction, others [57,58] on solid waste disposal or treatment. Other LCA works address more partial processes and are therefore even farther from the aims of the present paper.

To the best of the authors' knowledge, except for the above cited doctoral thesis by Cristiano [41], no previous work has ever addressed a complex system such as a hospital in the same terms, encompassing the three aforementioned topics (a), (b), and (c)[6],[7]. A systems-thinking-based emergy accounting evaluation is performed to comprehensively and quali-quantitatively assess the sustainability and resilience of a hospital and its related healthcare system[8]. The systems thinking perspective, which is intrinsic in emergy accounting although not always evident in published emergy evaluations, receives here particular attention, as per the Results and the Discussion. Where unit emergy values are not available (or not satisfactory) in scientific literature, data resulting from Life-Cycle Assessment calculations are used as a basis for the definition of some new values, functional to the emergy evaluation of the case study at hand. This work may be regarded as a first step to: (i) systemically understand the main requirements, strenghts, and vulnerabilities of health systems and their hospital facilities, especially in a period of dire need of health like this; (ii) learn, from both method and results, how to best address energy-performative building design in a challenging era of scarcity; and (iii) provide an example of systemic design, assessment, and management of a complex system in a complex epoch, undepending of its nature (here, a humanitarian health facility). This study also aims at providing a benchmark for future comparisons, including possible improvement assessments of the same case study and – above all – an extension to the design, rethinking, and assessment of other expectedly long-term sustainable buildings and resilient, long-lasting hospitals.

2. Materials and methods

2.1. The Salam Centre for Cardiac Surgery in Khartoum, Sudan

The case study at hand is represented by a top-level, nonprofit specialised hospital, designed, built, and run by Italian humanitarian NGO *Emergency*[9]: the *Salam* Centre for Cardiac Surgery in Sudan (Fig. 1). The hospital is located in Soba, 20 km south of capital city Khartoum (Fig. 2), by the shores of the Blue Nile river. Built between 2004 and 2007 on a lot of land of roughly 40,000 m^2, its buildings cover an area of 12,000 m^2. Its design as a top-level hospital in the Saharan-Sahelian adverse climate conditions required specific strategies. Outdoor temperatures can reach 50 °C, while operating theatres require 18 °C, and intensive care rooms 24 °C [17]. Design attentions were paid to make the structure sand- and heat-proof [62]. A 60-m long underground labyrinth-shaped tunnel, inspired by Persian wind towers (*badgir*) [63], contributes to natural ventilation and cooling (averagely, channelled air is 9 °C cooler than the outside temperature). The external walls are 60 cm thick, built with multiple brick layers with insulated air chambers inbetween. The windows are small and equipped with double sun-screened glasses. The non-built land around the hospital pavillions is extensively planted with trees and hedges, directly watered from the nearby river. Following biomimetic principles [64], the porticoes around the main building are screened by panels of intertwined vegetable fibres (from Sudanese *saf* leaves), locally woven inspired to a traditional Sudanese technique for bed manufacturing. 288 vacuum-sealed solar collectors (covering 900 m^2), matched to two absorption chillers, help reducing the amount of fuel required to circulate 28,000 cubic metres of cold air every hour. The low-tech innovations for cooling, insulation, and filtration, and their related energy savings are illustrated and discussed in Cristiano and Gonella [16]. They confirm that, against the mainstream cultural

[4] In addition to this, most ratings do not assess a building's post-occupancy performances and rarely refer their calculations to comparable units such as energy consumption per square metre [34].

[5] These studies are part of the extensive use of the emergy approach at micro levels [54].

[6] We report that we are co-authoring a smaller case-study exercise in this direction [59].

[7] Pineo et al. (2020) have recently addressed health issues through systems thinking, yet their causal loop approach is very different from the one used here, and anyway focused on health in relation to urban planning policies [60].

[8] Pertinent dissertations on a similar assessment, but applied to urban systems, are available in Cristiano et al. [61].

[9] https://en.emergency.it/(accessed May 2020).

Fig. 1. The Salam Centre: surrounding vegetation, entrance of the wind tunnel, and vegetal panels (photo by M. Bonfanti, courtesy of *TAMassociati* and *Emergency*).

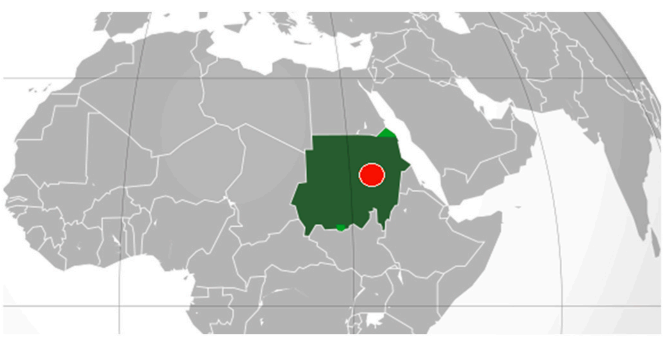

Fig. 2. Location of Khartoum (CC-BY-SA 3.0, Dinamik).

colonisation, learning from context-specific vernacular wisdom [65] can yield interesting energy savings [66], or at least mark promising paths in design.

The structures of the Salam Centre include: 3 operating theatres, 15 intensive care unit beds, one sterilisation room, one catheterisation laboratory, reception, outpatients consultation rooms, radiology, ultrasound, laboratory and blood bank, pharmacy, 48-bed ward (including a 16-bed sub-intensive care unit), nurses' room, physiotherapy, recreation room for staff and patients, storage areas, administration and offices, laundry, ironing, kitchen, library, conference and teaching room, children's playroom, cafeteria, guesthouse, and a technical area. The hospital is equipped with biomedical machineries that are accounted for in this study. Most patients go by themselves to the *Salam* Centre, without been referred by physicians or medical facilities. After an initial triage, patients with known or potential cardiac problems receive further cardiac investigations. Between 2007 and 2018, 75,312 patients were triaged, and 69,996 underwent cardiological examinations; 9146 were admitted, someone twice or more, for a total of 11,636 admissions; surgeons offered 8093 operations to 7676 patients, and 1382 cath lab procedures. Annual numbers used for our assessment are reported in Table 1.

The mean age of operated patients was 26 years. Most patients had valvular heart diseases, many others congenital heart diseases, and a minority ischemic heart diseases. Although most of them were Sudanese, in the time span at issue patients arrived from 30 different countries. The *Salam* Centre is the only facility offering free-of-charge, qualified cardiac surgical care in a very large region[10], covering 11.5 million km^2 (i.e., three times the size of Europe), with a population of over 300 million people and with frequent healthcare coverage gaps [67]. The managing NGO promotes a regional health system comprising a network of medical facilities and activities in Sudan and in surrounding countries, so as to ensure adequate screening (especially paediatric) and post-operative follow-up for those coming from far away. When required, the NGO provides free transportation for foreign patients. Relatives who accompany minors are hosted in the hospital's guesthouse. *Emergency* has ongoing agreements with several ministries of health in the Sub-Saharan region, including the Sudanese one, co-financing the hospital. The present study is mostly based upon both the information provided by the hospital administration. Some data come from original calculations. Anyway, sources and procedures are all specified in the Results section.

Table 1
Salam Centre's clinical activities in our reference year.

Clinical activities	Amount
Outpatients visits (triaged patients)	5748
Cardiological visits	6619
Cardiac surgical operations	518
Cath lab procedures	34
Inpatients per day, average	44.1

2.2. The emergy method

This study is based on the Emergy Accounting (EMA) concept and method. Emergy allows to quantify, through the same unit, all the investments that are required to realise a project or a service – in our case, the complex system formed by the nonprofit hospital in a purposely designed bioclimatic building. The emergy concept was first introduced by Howard T. Odum [68–71], sometimes considered as an expansion of the aforementioned embodied energy concept [72]. Emergy is defined as "the available energy of one kind previously used directly or indirectly

[10] Including Sudan, Egypt, Libya, Chad, Central African Republic, Democratic Republic of Congo, Uganda, Kenya, Ethiopia, and Eritrea.

to generate a service or a product". Through emergy, it is possible to assess the performances of a given system based on a common energy metrics: the solar emjoule (sej), elaborated through solar equivalent exergy, whose unit is the solar equivalent joule (seJ). The emergy requirement per unit of output (energy, matter, labour, information, services, money) is defined as Unit Emergy Value (UEV) and measured in sej/unit (sej/J, sej/g, sej/h, sej/currency, etc.). Unlike other social environmental accounting methods, EMA keeps track of both the natural processes that were required to generate and concentrate resources over time and of the anthropic activities to extract, manufacture, and delivery such resources. If compared to the embodied energy approach, the EMA method presents a boundary expansion over space (in that accounts for large scale phenomena that indirectly contribute to the local dynamics), over time (processes for resource generation), and over resource categories (since it also includes natural flows such as solar radiation, deep heat, wind, rain, and gravitational energy) and material flows (like metals and mineral ores) [46]. Moreover, in an EMA assessment also the resources supporting direct labour and services are included (with the latter representing indirect labour). Labour and services carry fractions of the infrastructure, information, and know-how associated with the larger economy in which the investigated system is embedded [73] – something that cannot be disregarded if a comprehensive sustainability evaluation is the goal. These innovative features of EMA provide an added value to the assessment, much beyond and certainly complementing the usual monetary and energy evaluations.

The first steps of an emergy accounting procedure are the definition of the boundaries of the investigated process or system and the drawing of the diagram, using the energy systems language [74]. After these, the flows (energy, matter, etc.) driving the process or system are identified and quantified, usually grouped in categories: (R) local renewable resources, provided for free; (N), locally available nonrenewables; and (F) imported goods from out of the system. All these inputs are then expressed in emergy units after a conversion using suitable UEVs, referring to the same global emergy baseline (GEB, the total renewable emergy driving the geobiosphere in one year) – in this paper, the GEB_{2016} of 1.20×10^{25} seJ/yr [75].

At the end of an emergy assessment, selected indicators can be calculated, suitable for investigating the system at issue [69]. Among these, we calculate the emergy yield ratio (EYR), the environmental loading ratio (ELR), the renewable emergy percentage (%Ren), the areal empower intensity (AEI), and the emergy sustainability index (ESI). The EYR is the ratio between U, the total emergy output given by R + N + F, and what is purchased from the economy, F, thus indicating how much the emergy output of a system actually depends on purchased resources, whose emergy is in principle already available at the society level. It therefore addresses the question of how well the environmental resources are used for a given input from the economy, without distinguishing between renewables and nonrenewables. The ELR=(F + N)/R indicator compares what is received from the economy plus local nonrenewables to the emergy coming from local renewables. It indicates in general the level of environmental impact. The Emergy Sustainability Index, ESI = EYR/ELR, is an integrated measure of economic yield and environmental performance, and addresses the contribution to the overall support environment per unit load of the local system. By putting together two indicators sensitive to local/nonlocal aspects (EYR) and renewable/nonrenewable ones (ELR), it provides an integrated evaluation of the system's long-term sustainability. New UEVs and indicators may be then defined for specific case studies, and this is also the case of the system here investigated. Wherever the UEV of a given input is not available in the scientific literature, or not suitable for the assessment at hand, a new value is calculated. For the calculation of new UEVs, the inventory of the inputs is built thanks to an integration with the LCA method [43,76], based on database *Ecoinvent 3.1* [77], also considering the Cumulative Energy Demand [78] in the same database. Some UEVs, tailored for a hospital, also emerge as a result of the emergy assessment.

The emergy evaluation is performed by following the usual procedure of first diagramming the system while choosing its boundaries, then creating a comprehensive inventory of the resources directly and indirectly involved in the system setting up and operation, converting them into emergy terms, and finally calculating a set of standard (here, also brand-new) indicators, representing the actual investment. By investement, one means what is provided by outer human economies and by the *rest* of [79] the geobiosphere. Physically, the boundaries of the healthcare system at issue include the entire lot of land where the hospital lies and a portion of the adjacent river, supplying the water-bearing strata underneath the lot. The temporal boundary is one year, i.e., 2015. At the beginning of this study, it represented the most recent year with full and validated data for a reliable assessment. Based on communications with the *Emergency NGO* staff members as well as on comparison with the decennial data illustrated in section 2.1, that year the hospital operated at the 70% of its full capacity. As partly specified above, some pertaining activities (screening, administration, public relations, patient transportation) are performed out of the gates of the hospital, but are of course still accounted in our analysis. For inputs to stocks lasting longer than one year, allocation is made according to the related lifetime. Clinical records for the reference year are reported in Table 1.

The driving flows of the system are assessed in terms of energy, materials, goods, labour, information, and services, so as to provide detailed information about the requirements of the hospital, including its key inputs, processes, and feedbacks. In addition to standard indicators [69], some novel indicators are specifically designed and calculated to pioneeringly address a health system: the emergy per (cardiac) surgical operation; the emergy per patient-day, referred to inpatients; and the emergy per outpatient visit. This allows to make the emergy accounting more suitable for decision-making in the health sector, since the number of operations, patient-days, and outpatients visits are all part of the management, accounting, and economic languages of health systems.

3. Results

3.1. The hospital system

The diagram reporting the main stocks and flows of the *Salam* Centre is shown in Fig. 3. Environmental inputs, including renewable sources, enter the system from the left. Granted that all of them are to be accounted for, some of these are specifically exploited in the specific configuration of the system, namely, green areas, solar thermal panel system (with connected chillers), and natural ventilation and air conditioning by filtration throughout the sand tunnel. Inputs imported from human economies enter from the top. Among such inflows – and this is a peculiar feature of a system involving an NGO (see also [80]) – one can distinguish paid and voluntary labour, and paid and donated services. Inasmuch as a hospital co-funded by an NGO and the Sudanese ministry of health, monetary (i.e., dashed) inflows come from both international donors and – through the local government – the Sudanese people. Voluntary work, donated money or services, private and public funding are all activated by the image the hospital shows to the outer world. In fact, the reputation of the NGO is a leverage point for the overall system, crucial for the regulation of flows coming from out of its boundary. Nevertheless, the main operations of the hospital naturally involve patients. For those reading a coloured version of the diagram, the patient cycling is highlighted in red: patients enter the *Salam* Centre encouraged by screening and health promotion activities and/or attracted by their trust in the hospital – again, by its public image (reputation). Contributions to the hospital's image come from both internal and external press activities and from public relations, in addition to the very quality of the hospital care (professionalism, hygiene and safety, medical success, etc.).

After being cured, most patients usually leave the hospital premises as recovered. This is the main desired output of a system pursuing free-

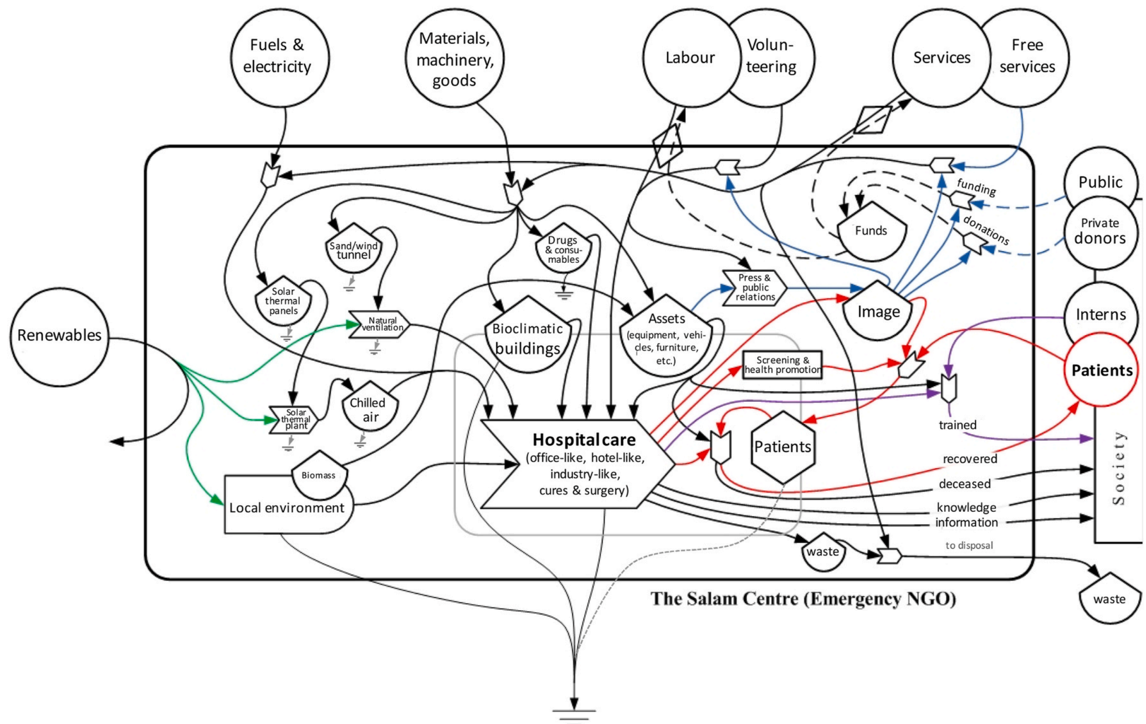

Fig. 3. System diagram of the *Salam* Centre (after Cristiano & Gonella [51]).

of-charge specialised health provision as its main goal. Side outputs are represented by: (i) the specialised training of local staff (medical doctors, nurses, other medical operators), happening through an agreement for accepting interns from Sudanese medical schools; (ii) knowledge and information produced during the hospital care activities, useful for future medical visits and surgical operations, and for possible health policy-making procedures.

3.2. Assessing social ecological costs: the emergy table

The main inflows for the *Salam* Centre to operate in the reference year are expressed (Table 2) with both their original unit and their emergy unit, converted through either already published or original UEVs. Data sources, UEV references, and calculation processes are all reported as footnotes to Table 2. Whenever goods and machinery flows are referred to stocks (e.g. for construction and equipment), the item's lifetime considered for the annual allocation is reported in its related footnote; the remaining inputs can be considered as annual operational ones. Inasmuch as not performed by hospital staff, construction labour is reported as a service, together with the services associated with building materials. In order to make results comparable with other emergy studies, phases that are typical of other approaches (e.g. end-of-life disposal in LCA) are not considered; however, context-based assumptions co-formulated with the hospital's designers suggest that efforts will be made to maintain and refurbish the buildings to extend their lifetime, and that progressive reuse and downgrading are likely to happen before any ultimate disposal of valuable materials in a deprived area.

Footnotes: Hospital area: 4.0E+04 m^2 (i.e. 4 ha). 1. Solar radiation = (daily solar insolation per square metre) x (365 days/year) x (lot area) x (1 – albedo); daily solar insolation in Khartoum: 6.18 kWh/m^2/day (data from hospital administration, double checked with Boukelia & Mecibah [81]); albedo of built/green mix: 0.3 (assumption based on Taha [82]). 2. Geothermal heat flow = (lot area) x (local heat flow) x (8760 h/year); local heat flow: 55 mW/m^2 (based on Hamza & Vieira [83]). 3. Wind, kinetic energy = (lot area) x [(average annual local surface wind speed)/(surface wind over geostrophic wind ratio)]^3 x (air density) x (drag coefficient) x (31,536,000 s/yr), average annual local surface wind speed: 4.7 m/s (based on offical records from local HSSS weather station at Khartoum International Airport); surface wind/geostrophic wind ratio: 0.58 (Reiter [84], as cited in Ref. [85]); drag coefficient: 1.00E-03 [86]; average density of air in the area: 1.2 kg/m^3 (assumption based on local elevation). 4. Rain, geopotential = (lot area) x (annual rainfall) x (runoff) x (elevation) x (gravity acceleration, 9.8 m/s^2); elevation: 382 m (Khartoum official records); annual rainfall: 135 mm [87], i.e. 0.135 m/yr; runoff on the *Salam*'s built/green mix environment: 0.4 (estimation based on previous literature). 5. Data from hospital administration, double-checked. 6. Data from hospital administration, already provided in volume units. 7–8. Data from hospital administration, originally provided in volume units (480,000 L/yr and 30,200 L/yr, respectively), then converted into mass units by considering an average density of 0.835 kg/L 9. Data from hospital administration, originally provided as 273,000,000 kWh/yr. 10–11. Lifetime: 80 yrs. 12–18. Lifetime: 40 yrs. 19. Lifetime: 10 yrs. 20–23. Lifetime: 40 yrs. 24–31. Lifetime: 20 yrs. 32–36. Lifetime: 15 yrs. 37–39. Lifetime: 20 yrs. 40–45. Lifetime: 30 yrs. 46–51. Lifetime: 20 yrs. 52–55. Original calculations based on NGO and hospital records. 62–67. Adjusted to items' lifetimes; including air, maritime, and on-road transport; due to their significant order of magnitude, fuels only are considered. 68–69. Original economic calculations based on hospital records and (where applicable) lifetimes; maintenance is included among the other services (general maintenance as local, biomedical maintenance as international).

UEV references: 1. By definition. 2–6. After De Vilbiss & Brown [88]. 7–8. Brown et al. [89]. 9. National Environmental Accounting Database (NEAD), Sudan, 2014 (after [90,91]). 10. Original calculation based on Brown & Buranakarn [52] and Pulselli et al. [53]. 11–14. Brown & Buranakarn [52]. 15. Meillaud et al. [48]. 16. After De Vilbiss & Brown [88]. 17–18. Brown & Buranakarn [52]. 19. This work#. 20. Björklund et al. [92]. 21. Brown & Buranakarn [52]. 22–23. This work#. 24. Original calculation based on Odum & Collins [93]. 25. After De Vilbiss & Brown [88]. 26. This work#. 27. Brown & Buranakarn [52]. 28. This work#. 29. Brown & Buranakarn [52]. 30–35. This work#. 36. Brown & Buranakarn [52]. 37–44. This work#. 45. Brown & Buranakarn [52]. 46–48. This work#. 49. Lou et al. [94]. 50–51. Original calculation based

Table 2
Emergy accounting assessment of the *Salam* Centre's activities on an annual basis.

Note	Item	Unit	Amount	UEV ([a])	Emergy
			(unit/yr)	(sej/unit)	(E+14 sej/yr)
Locally available renewable inputs (R)					
1	Solar radiation	J	2.27E+14	1.00E+00	23
2	Geothermal heat flow	J	1.73E+06	4.90E+03	<<1
				Sum of the primary flows	23
3	Wind, kinetic energy	J	8.05E+10	7.90E+02	<1
4	Rain, geopotential	J	8.09E+09	1.28E+04	1
5	Water, from Nile-supplied local wells	m^3	2.37E+04	4.96E+11	118
				Largest of the secondary and tertiary flows	118
				Driving renewable input[b]	118
Locally available nonrenewable inputs (N)					0
Imported inputs (F)					
Fuels and electricity					
6	Natural gas	m^3	1.82E+04	5.36E+12	976
7	Diesel, for power and heating	kg	4.01E+05	6.12E+12	24,541
8	Diesel, for vehicles	kg	2.52E+04	6.12E+12	1542
9	Electricity	J	9.83E+12	2.21E+05	21,724
Goods and machinery[c]					
	(Bioclimatic building)				
10	Concrete, reinforced 18%, groundwork	kg	9.82E+04	1.58E+12	1552
11	Steel, for ground floor framework	kg	5.94E+03	3.26E+12	194
12	Clay bricks	kg	7.22E+04	1.83E+12	1321
13	Expanded polystyrene (as plastics)	kg	7.87E+01	6.48E+12	5
14	Gypsum plasterboard (as gypsum)	kg	1.13E+04	7.89E+11	89
15	Plaster	kg	2.28E+03	2.60E+12	59
16	Sand, unspecified, for screed	kg	1.00E+04	1.56E+09	<1
17	Cement, for screed	kg	2.19E+03	1.64E+12	36
18	Ceramic tiles	kg	5.51E+03	4.27E+12	235
19	Paint	kg	1.83E+03	1.38E+13	253
20	Rockwool	kg	1.87E+03	1.45E+12	27
21	Steel plate	kg	1.72E+03	3.26E+12	56
22	Door windows (2 m × 1 m)	item	5.75E-01	2.27E+15	13
23	Windows, double-glass (0.7 m × 0.7 m)	item	3.00E+00	5.56E+14	17
24	*Saf* leaves, dried, for screening panels	kg	8.44E+01	4.64E+08	<<1
25	Wood, hard, mixed, for screen. panels	kg	3.39E+01	9.38E+09	<<1
	(Solar thermal plant)				
26	Solar thermal panels, ground-mounted	m^2	4.95E+01	4.85E+14	240
27	Steel main pipes, for solar plant	kg	1.13E+02	3.26E+12	4
28	Glass wool, insulation for main pipes	kg	2.50E-01	7.69E+12	<1
29	PVC tubes (as plastics)	kg	5.02E+01	6.48E+12	3
30	Chillers (as air compressors)	item	5.50E-01	3.29E+15	18
31	Lithium Bromide	kg	1.25E+00	8.01E+12	<1
	(Biomedical and technical equipment)				
32	Electric/electronic appliances (7.5 kg)	item	2.43E+01	1.26E+14	31
33	Electric/electronic appliances (30 kg)	item	9.67E+00	9.90E+14	96
34	Electric/electronic appliances (75 kg)	item	3.40E+00	5.40E+14	18
35	Electric/electronic appliances (125 kg)	item	2.00E+00	9.02E+14	18
36	Surgery equipment, extra small (steel)	kg	1.20E+00	3.26E+12	<1
37	Bed and stretchers, as inpatient bed	item	3.65E+00	3.34E+14	12
38	Monitors (as displays, liquid crystal)	item	2.70E+00	6.06E+14	16
39	Printer, laser, colour	item	3.50E-01	1.93E+14	1
	(General furniture)				
40	Chairs, wood/steel mix	item	6.93E+00	5.85E+12	<1
41	Benches, wood	item	1.13E+00	1.33E+13	<1
42	Desks, wood	item	1.13E+00	1.33E+14	2
43	Cabinets and lockers, wood	item	3.90E+00	2.97E+11	<1
44	Sanitary ceramics	kg	3.90E+01	3.71E+12	1
45	Steel taps and fittings (as steel)	kg	4.13E+00	3.26E+12	<1
46	Kitchen equipment (ad Fridge)	item	4.00E-01	6.42E+14	3
47	Bedframes, wood, non-medical	item	2.10E+00	3.46E+13	1
48	Matresses, polymer foam, non-medical	item	2.10E+00	3.73E+13	1
	(Vehicle fleet)				
49	Cars	item	5.50E-01	9.48E+15	52
50	Mini-vans	item	1.00E-01	1.82E+16	18
51	Pick-ups	item	1.00E-01	1.57E+16	16
	(Consumables)				
52	Drugs, pharmaceuticals	kg	1.53E+04	5.76E+12	881
53	Pharmaceutical containers, glass	kg	2.12E+03	1.71E+12	36
54	Pharmaceutical containers, plastics	kg	1.22E+04	6.48E+12	791
55	Pharmaceutical containers, aluminum	kg	2.48E+03	9.90E+12	246
56	Vegetables & fruits, Sudanese local	kg	9.50E+03	2.83E+11	27
57	Meat, Sudanese local	kg	3.05E+03	1.94E+13	591
58	Fish, Sudanese local	kg	1.52E+03	6.21E+13	946
59	Dairy products (as milk)	kg	2.54E+03	2.66E+13	675
60	Bread, cereals, eggs (as average food)	kg	7.51E+04	8.84E+12	664
61	Fabric for uniforms (textiles)	kg	3.65E+02	1.80E+13	66
	(Transportation of goods and machinery)				
62	Transportation, items 10–25 (as diesel)	kg	2.96E+03	6.12E+12	181
63	Transportation, items 26–31 (as diesel)	kg	3.08E+01	6.12E+12	2
64	Transportation, items 32–39 (as diesel)	kg	2.97E+01	6.12E+12	2
65	Transportation, items 40–48 (as diesel)	kg	1.06E+01	6.12E+12	1
66	Transportation, items 49–51 (as diesel)	kg	1.41E-01	6.12E+12	<1
67	Transportation, items 52–61 (as diesel)	kg	3.29E+03	6.12E+12	202
Labour and Services (L&S)					
68	Labour, as full-time equivalent workers				
	- local staff (Sudan-based)	unit	700	8.90E+15	62,300
	- international staff (from Italy)	unit	20	7.96E+16	15,920
69	Services				
	- items 6–9, fuels and electricity	SDG	2.47E+06	1.01E+12	24,975
	- items 10–31, building materials & construction	SDG	1.30E+06	1.01E+12	13,130
	- items 32–39, biomedical & technical	€	3.24E+05	3.08E+12	9973
	- items 40–51, furniture & vehicles	SDG	1.19E+05	1.01E+12	1207
	- items 52–55, pharmaceuticals	€	1.94E+06	3.08E+12	59,771
				3.08E+12	13,451
			4.37E+05	3.08E+12	13,451

(continued on next page)

Table 2 (*continued*)

Note	Item	Unit	Amount	UEV ([a])	Emergy
	- other international services				
	- items 56–61, other consumables	SDG	1.10E+06	1.01E+12	11,129
	- shipping (courier, container, cargo)	€	1.73E+05	3.08E+12	5325
	- other local services	SDG	2.20E+06	1.01E+12	22,210
Total input and main output					
Total Emergy input (U)					5.86E+18
Total Emergy input with labour & services (ULS)					2.98E+19
Annual patient-days		p-day	16,097		

[a] Calculated or converted from other works according to the $\mathbf{GEB_{2016}}$ **of 1.2E+25 seJ** [75].
[b] Based on [71]; one only uses the largest between the sum of the tripartite sources (solar radiation, heat flow, and tides, where applicable) and the largest of secondary and tertiary sources.
[c] Original engineering calculations based on data from NGO *Emergency* and hospital administration.

on Lou et al. [94]. 52. This work[#]. 53–55. Brown & Buranakarn [52]. 56–58. NEAD, Sudan, 2014 (after [90,91]). 62–67. Brown et al. [89]. 68–69. NEAD, Italy and Sudan, 2014 (after [90,91]); based on 2010–2015 trends, 1.3 EUR/USD and 5.0 USD/SDG conversion rates are adopted for UEV adjustments; SDG = Sudanese pound, USD = United States dollar.

[#]LCA-based emergy calculations for item production (including energy and material generation, concentration, extraction, transportation, and processing).

3.3. Hospital UEVs and emergy indicators

Some UEVs are specifically calculated for this evaluation (Table 2), since several items typical of hospitals and buildings were not present or reliable in the scientific literature of such underexplored fields. Some more UEVs are proposed and calculated at the end of our evaluation (Table 3), specifically designed for health systems, and associated with the hospital's main co-products. Following the metrics of patient-day, common in healthcare management, an original UEV named "Emergy per patient-day" is first introduced, related to the number of inpatients hosted at the hospital, and to their days of bed occupancy (similarly to the concept of emergy per passenger-kilometre as introduced for transport systems by Federici et al. [44]). Likewise, two more new unit emergy values express the emergy per cardiac surgical operation and the emergy per cardiological visit. The former also includes a small number of cath lab procedures (as per Table 1), the latter encompasses both inpatient and outpatient visits. An outpatient visit is usually functional to hospedalisation and operation, if required, or acts as a post-operative follow-up. In hospitals offering other fields of specialisation, these UEVs could be generalised as "Emergy per surgical operation" and "Emergy per medical (or specialised) visit", or – especially in Emergency Rooms – "per triage".

As introduced in section 2.2, some emergy indicators from existing literature are calculated (Table 4). All indicators are expressed both with and without the emergy associated with labour and services. If several of them are usually present in most emergy evaluations, a remark ought to

Table 3
New unit emergy values for the *Salam* Centre.

UEV	Value without L&S	Value with L&S	unit
Emergy per patient-day	3.64E+14	1.85E+15	sej/p-day
Emergy per cardiac surgical operation	1.06E+16	5.40E+16	sej/operation
Emergy per cardiological visit	8.86E+14	4.50E+15	sej/visit

Table 4
Emergy indicators for the *Salam* Centre.

Category	Equation	Value (sej/yr)
Locally available renewables (**R**)		1.18E+16
Locally available nonrenewables (**N**)		0
Imported sources from out of system (**F**)		5.85E+18
Labour and services (**L&S**)		2.39E+19
Annual emergy use without L&S (**U**)	R + N + F	5.86E+18
Annual emergy use with L&S (**ULS**)	U + L&S	2.98E+19
Indicator	**Equation**	**Value**
Emergy Yield Ratio (**EYR**)	U/F	1.002
EYR with L&S ($\mathbf{EYR_{L\&S}}$)	ULS/(F + L&S)	1.000
Environmental Loading Ratio (**ELR**)	(F + N)/R	496
ELR with L&S ($\mathbf{ELR_{L\&S}}$)	(F + N + L&S)/R	2524
Percentage renewable emergy (**%R**)	R/U	0.20%
%R with L&S ($\mathbf{\%R_{L\&S}}$)	R/ULS	0.04%
Emergy Sustainability Index (**ESI**)	EYR/ELR	0.002
ESI with L&S ($\mathbf{ESI_{L\&S}}$)	$EYR_{L\&S}/ELR_{L\&S}$	0.000
Outdoor Areal Empower Intensity ($\mathbf{AEI_{outdoor}}$)	U/(outdoor area)	1.5 E+14 sej/m^2
Outdoor AEI with L&S ($\mathbf{AEI_{outdoor\ L\&S}}$)	ULS/(outdoor area)	7.5 E+14 sej/m^2
Indoor Areal Empower Intensity ($\mathbf{AEI_{indoor}}$)	U/(indoor area)	4.9 E+14 sej/m^2
Indoor AEI with L&S ($\mathbf{AEI_{indoor\ L\&S}}$)	ULS/(indoor area)	2.5 E+15 sej/m^2
Renewable Support Area ($\mathbf{SA_{(r)}}$)	$(F + N)/Empd_{(r)}$	1983 ha
Renewable Support Area with L&S ($\mathbf{SA_{(r)\ L\&S}}$)	$(F + N + L\&S)/Empd_{(r)}$	10,098 ha

be dedicated to the Renewable Support Area ($SA_{(r)}$). As explained by Brown and Ulgiati [95], this suggests the carrying capacity (here, as Earth surface necessary to support the hospital activities). The calculation of the $SA_{(r)}$ resorts to the local renewable empower density ($Empd_{(r)}$), which is the annual renewable flow (R) divided by the total area of the lot where the *Salam* Centre lies. In Brown and Ulgiati's own words [95], $SA_{(r)}$ is "the necessary area of the surrounding region that would be required if the economic activity were using solely renewable emergy inputs". Through a parallel with the way more popular *ecological fooprint* [96], the Renewable Support Area might be defined as an Emergy-based land fooprint.

4. Discussion

Working side by side with many members of the *Salam* Centre and the Humanitarian Office of NGO *Emergency*, a very detailed inventory was obtained, partly expressed in Table 2. Such table, together with its footnotes, provides insights for a thorough understanding of the quality and original quantities of the manifold inputs required to run a top-level hospital like the one at issue. However, it is the associated emergy units – core of the present study – to offer interesting results. As a top-level specialised hospital with advanced Global Northern healthcare standards, the system is alien to the native ecosystems of a shore of the Nile river. This has implications in both the emergy evaluation (Table 2) and its indicators (Table 4).

In spite of an accurate architectural and engineering design and of a relatively short lifetime, imposed by adverse climate conditions, the annual amortisation of the material inputs for the construction of the bioclimatic structures and energy systems requires relatively low resources (one order of magnitude smaller than the driving energy and material inputs). This can be read as a success, and positively matches with the *Salam* Centre's benefits of low-tech design in energy saving, which was previously found out [16]. Savings apart, the major inputs are rather represented by fuels and electricity. Diesel is required to ensure the demanding indoor climate conditions, and electricity to supply the complex biomedical equipment, including ventilators, often active 24/7. Although typical of a hospital, such machineries consume large amounts of energy but are relatively "light" in terms of annual allocation of emergy for their production and delivery. Instead, after energy resources and building inputs, the third largest cluster of inputs is represented by consumables. Here, besides patients' food, another typical healthcare input is present, i.e., pharmaceuticals.

The situation is different when services are included. In this respect, pharmaceuticals are maybe the most representative item. The emergy associated with their services (based on their price) is nearly 30 times larger than the geobiophysical emergy required for the concentration, extraction, and progressive processing of their ingredients. While their chemical accounting can be considered as averagely easy, and their ingredients usually not rare, know-how and decennial experiments might play a role, together with other features of an exceptional sector. For instance, price-related issues involving market dynamics such as oligopoly and profit, which might be able to alterate the significance of the associated emergy values, and which the authors will further specifically address in specially dedicated works in progress.

Similarly, also labour has a prominent role in emergy accounting. Again, this can be ascribed, on the one hand, to the number of workers required to run such a complex system, where medical professionals are only a part of the total involved labourforce; on the other hand, for the specific characteristics of the *Salam* Centre, to the reliance upon international medical and sanitary staff, coming from abroad and averagely living Global Northern lives. It might be worth to stress that this is calculated through the emergy associated with equivalent full-time workers, i.e., to the emergy per capita of the societies and economies from where the workers come, hence a differentiation between Sudanese residents and international (Italian) temporary expats. A similar distinction would be theoretically still present if labour emergy were calculated through their wages, but this would distort our analysis since there is a presence of interns, workers in traineeship, and sometimes voluntary workers, so a partial or symbolic salary would alter the results. It is here proposed that this featuring dilemma related to nonprofit systems might be the basis for further discourses on labour, upon which the authors are also working, and which will be resumed in future works.

Concerning local renewables, if the solar thermal plant yields positive outcomes, the driving source is surprisingly represented by the freshwater supplied by the nearby river, and available for pumping and safe filtration in the water-bearing strata under the lot of the hospital. It might be worth noticing that the tailored UEVs for hospitals are calculated as associated with co-products. In fact, specialised visits, operations, and stays in the hospital wards are all functional and interconnected one to another. Similarly, the knowledge and information that are included in the diagram, if quantified, would still be a co-product, since they would emerge from the medical practice. Since such UEVs, first proposed and introduced here, are pioneers in the emergy field, no comparison is possible for the moment. Nevertheless, they represent a benchmark for possible future studies in the field of health systems, requiring more and more attention in these turbulent times.

Considering labour and services altogether, one can realise that they account for nearly the 80% of the total annual emergy requirements of the *Salam* Centre. This is the highest ratio ever found in an emergy assessment, yet some explanations exist. They indeed belong to a complex system like a specialised hospital operating far away from where its key factors are produced or trained. Before this study, few other high skills- and patent-intensive systems have exhibited ratios higher than 50%. This is the case of those involving agricultural processes through transgenic technologies [97,98]. The level of complexity of the *Salam* Centre is evidently higher, and so is the alien nature of a specialised hospital with Global Northern standards in a context not at all rich in the resources that are required to fuel its featuring processes. Moreover, if a hospital partly operates similarly to an industry, its inputs are all from secondary and tertiary sectors, i.e., skilled labour and top-quality highly sophisticated final products, which do not deliver a product, but a service: healthcare. Therefore, this condition can be here proposed as a "double-level tertiary" activity, with very few similar processes that at present cannot be found in any other previous emergy accounting evaluation.

Based on such a peculiarity and following some warnings about possible uncertainties affecting the emergy assessment [99], a sensitivity analysis [100] is also performed. Well then, artificial alterations of up to 20% onto the major inputs would only yield minor changes (i.e., usually one or more orders of magnitude smaller) in the total emergy driving the process as well as in the various indicators. This might be mostly due, on the one hand, to the variety of inputs with similar emergy value, and on the other hand to the impressive number of items that are analysed thanks to an extremely detailed inventory. The quality *and* quantity of the used data ensure a fair protection from uncertainty.

Finally, important considerations can be drawn from a careful interpretation of the emergy indicators. The emergy yield ratio (EYR), very close to its minimum value (1, i.e., total emergy coinciding with imported emergy) confirms that the *Salam* Centre is mostly a "consumer" system, scarcely able to make local resources available, and for which the outer societies and economies operate (or, at least, should operate). The latter seems as a reasonable insight, to be recalled in the Conclusions. The environmental loading ratio (ELR) records a relevant pressure, disturbance of the system at issue onto the native environment: as mentioned above, the shores of a river in a quasi-desertic area are not the most suitable place for a highly specialised hospital, yet a need for free-of-charge quality specialised healthcare is present in an area of 300,000 millions, and the value of the ELR is a clear consequence of such "daring the impossible". This also suggests that such a challenge is quite framed in complex international North-South relations, not independent of the local and international economic and socio-ecological conditions. Like the EYR, also the emergy sustainability index (ESI) registers a higly-developed, final-user-oriented system. Besides being to some extent an intrinsic feature of a hospital, this is even more true in a structure with Global Northern standards, mostly run by a foreign NGO. The renewable emergy percentage (%Ren) confirms an overall dependence upon imported inputs, yet its location on the shores of a major river provides the *Salam* Centre with non-obvious values compared to the other indicators (i.e., up to 0.2%). So does the Renewable Support Area ($SA_{(r)}$). In reason of its own nature, it is unfrequent that a Global Northern specialised hospital, depending on sophisticated technology, is *sustainable* and fully relying on its local resources[11]. Nonetheless, its strategic location next to a major river and rich in solar radiation seems to partly make up for its starting conditions. As suggested for civil structures [41], the hospital administration can use an assessment like this to improve its performances over time. More in general, this evaluation approach is something that can be replicated at the *Salam* Centre, at other hospitals, and at other complex public or private, profit or nonprofit organisations.

Starting from the emergy requirements associated with a complex system such as a hospital, which are anyway huge, some considerations ought to be made. The emergy approach allows to identify possible critical points in the system so as to suggest strategies – where applicable – to reduce resource consumption in the industry-like processes [101] of the hospital. However, some positive hints already arrive from one last indicator. Indeed, it might be worth underlying that the areal empower intensity (AEI) of the *Salam* Centre still results one or two orders of magnitude smaller than the single- or multi-unit residential buildings studied [49,50,53] in Europe and in North America. With one tenth or even one hundredth of resources compared to those required to just tickle spoilt dwellers of maybe fancy "sustainable" apartments, lives are saved at the *Salam* Centre. This appears as an extremely important datum, since it might bring to address and question the general societal attitude of the wealthier parts of the world towards scarcer and scarcer global resources, and hence towards the implicit or explicit priorities of

[11] Please note that such a heavy dependence upon imported labour and goods regards specialised hospitals, typical of conventional medicine; addressing general symptoms by millennial natural cures such as in Chinese or indigenous American traditional medicine are out of the scopes of this paper, and out of the competences of non-medical scholars.

our societies. Considering some UEVs already used or at least cited in the present paper, 18 kg of meat require as much emergy as one day as a patient at the *Salam* Centre (and it is well-known that meat production is per se quite impacting and resource-demanding). The emergy required for one sport utility vehicle (SUV) would allow for no less[12] than one and a half life-saving open-heart operations at the *Salam* Centre. And one SUV transported on a hypothetical[13] brand-new high-speed train[14] from Turin, Italy, to Lyon, France would take away from ecological systems and human societies the same emergy amounts that would allow for a cardiological visit. This is not to blame on single consumers, but rather to frame the issue of resource scarcity in a wider discourse on societal priorities, including wealth distribution (as systemically drafted in Ref. [79]), so as to possibly address resource distribution and health systems in a comprehensive and coherent way.

In fact, it ought not to be forgotten that North-South medical cooperation is still framed in unbalanced postcolonial relations and subject to economic, geo-political, and social oscillations, which in parallel might be addressed too. It is in this framework that this systemic diagramming of health systems highlights the criticalities that are just now re-emerging with the Covid-19 pandemic. As noted [2] soon after the outbreak of such emergency, closing borders and self-concerned wealthy nations unmask the asymmetrical power structures dominating both Global Northern and Southern countries, including Africa. This can also remind of how unsustainable and hardly resilient the whole sector can be at present (with a special regard to poor contexts in wealthy countries and to disadvantaged countries in general) if a human right and *universal value* [104] like health is commodified or at least not prioritised, and the issues are not addressed at a systemic level. A systems-based perspective also suggests that the number of patients plays a role in the delivery of health services. Thus, health prevention can reduce the need for cures, and make the still required ones more effective. In this sense, the recent Covid-19 crisis also teaches that its zoonotic origin [105] is linked to the ecosystemic alterations structurally caused by a predatory and exploitative paradigm. Following a recent stream [2,106,107], this work aims at contributing to global meditation in such critical period to find adequate solutions to increase the sustainability and resilience of health systems, i.e., reinforcing the global preparedness to “the next big one” instead of coming back to the same, problematic *business as usual*.

From a qualitative viewpoint, as per the systems diagram (Fig. 3), the dependence upon know-how and products from the outer economy is a critical point of the *Salam* Centre. This is even more true if required goods and workers come from far away. The development of local specialised manufacturing for biomedicals and pharmaceuticals is something hard to propose and control in delicate ecological and socio-economic contexts. The decrease in the dependence on foreign labour force, instead, seems as a promising strategy. In this sense, the circle of interns, helping out in medical operations while being trained in excellence specialised medicine, stands out as a reinforcing mechanism for the whole system, towards its resilience to external changes. Indeed, the willingness of foreign specialised staff to leave for Sudan and work there for a while, just like the possibility and desire to donate labour, money, and services, all depend upon social, ecological, economic, and geo-political factors. (The ongoing pandemic and related re-emerging structural economic crisis in the Global North can serve as examples; wars and other extreme events might play a role too.) For a hospital run by a humanitarian NGO, the image of the organisation becomes a leverage point; as a matter of fact, it can activate or stop the crucial inputs to the system: medical success, hygiene, integrity, and overall reputation are all important aspects to keep in mind while managing such a complex structure. Nevertheless, the image by itself is not able to ensure a full control over the system, since the complex socio-economic and geo-political features of a closely interconnected world are involved: these depend upon predatory and often belligerent mechanisms, as per the types of exploitation of humans and resources described for instance in Ref. [79].

Concerning the resources, the management of the valuable local renewables can be improved, and the quali-quantitative environmental accounting method that is here used can be of great help in this. As also recently outlined [61], systems thinking can play a pivotal role in the strengthening of the sustainability and resilience of complex systems. This can be especially useful while facing an uncertain, fast changing century, not necessarily ensuring the same conditions upon which humanity now bases, and thus, maybe, still to be re-invented. H.T. and Elisabeth Odum [108] talk about preparing information packages to save some key aspects of civilisation after possible global collapses, or to at least mitigate a collapse. The provision of health for everyone is presumably a cornerstone independently of the social and economic main values of a given civilisation; in this framework, the emergy-supported systems thinking application to health systems can be seen as much important as urgent in turbulent times like this.

5. Conclusion

In this paper, a systems-thinking-based emergy assessment is applied to health systems. In particular, to a top-level specialised hospital in Sudan, designed in a brand-new bioclimatic building, and run by a humanitarian NGO from Italy. This is an absolute novelty for both hospitals and bioclimatic buildings. This study suggests that:

- For their representing a complete novelty in both health systems and bioclimatic buildings, the novel emergy results, UEVs, and indicators are benchmarks for future studies. A first step is offered toward systemic studies on how to set up sustainable health services, needed at all levels; if crucial weakness may follow resource misuses, independently of their amount and quality, the comprehensive socio-ecological point of view allowed by systems thinking and emergy accounting can be a valid starting point to support health services.
- As an end-user service by definition, a hospital is a highly demanding system, for which imports from the outer economies and societies are crucial, being local inputs clearly not enough. Its indicators confirm that a health system cannot be created and maintained by itself, but the outer society is rather called to operate and leave resources for it to be granted. In other words, if health is a societal priority, then social and economic systems ought to be re-adjusted so as to promote it and, in a context of scarcity, to leave adequate resources (be them socio-ecological and/or financial) for healthcare systems and facilities. In particular, North-South medical cooperation is still framed in unbalanced postcolonial relations and subject to economic, geo-political, and social oscillations, which might be addressed too.
- At the *Salam* Centre, and one could dare to say in a nonprofit hospital, the image of the facility as well as of the managing organisation is a possibly strong leverage point.
- The evaluation of the hospital at hand yields the highest ratio of labour and services ever found in emergy accounting; this is related to both a specialised hospital and a cooperation project. Actually, specialised healthcare can be seen as a “double-level tertiary activity”, for it requires high-quality labour and final products to be used in industry-like processes delivering a service.
- The bioclimatic building suggests to actually have socio-ecological sustainability features, and the emergy requirements for its construction are limited; future developments on both this kind of building design, supported by a sound assessment tool like the one that is used here, may help address energy poverty and the demand for safe housing, in Africa and elsewhere. Improvements in the socio-ecological efficiency of a hospital are anyway possible; a systems-based emergy evaluation here shows its potential to support them.

[12] Lou et al. [94] do not account for some inputs in their UEV of a vehicle (as adapted in Table 2, item 51).

[13] See Refs. [102,103].

[14] Transportation UEVs by Federici et al. [45].

- At the *Salam* Centre, the performances in terms of emergy per area unit (areal empower density) are stunningly positive if compared to other previously investigated civil works, namely, residential units; with much less, delivering top-quality healthcare instead of pure housing is remarkable. Similarly, future fruitful applications can come for the design, assessment, and management of other complex systems (public or private, profit or nonprofit) in a complex, fast changing world: the lower the dependence upon scarce or uncertain inputs, the higher the system's resilience.
- The importance and the complexity of our study appears as particularly high in the light of the ongoing pandemic, with the entire world called to ensure a human right like health, again, through resilient societal and health systems.
- While it cannot be denied that the outputs of a cardiac surgical hospital require significant amounts of social ecological resources (here, in emergy terms) in global conditions of scarcity, this can be seen as a definitive reason to finally revise the priorities of many current human societies. Granted that, from a systemic perspective, health prevention is likely to be more effective than cures and that the ecosystemic alterations structurally caused by a predatory and exploitative paradigm do play a role, when the resources required by medical services are compared to often superflous (and sometimes positional) goods and services, and when inequalities and uncertainty arise from those predatory and exploitative dynamics, then discourses on the ecological sustainability and social fairness/equity of the dominant economic system and societal values are implicitly involved, and a path to walk suggested.

Based on these conclusions, future research directions may be envisaged. On the one hand, more emergy studies on health facilities and health systems worldwide might follow, using these pioneering data as benchmarks, to similarly detect and possibly improve their current sustainability and resilience. On the other hand, the same approach might inspire – at larger scales – transdisciplinary efforts to ponder on the overall resource allocation to allow for public healthcare provision, thus bringing together: on the scientific side, systems, ecological, political economic, and human geographical studies; on the decision-making side, societal choices, priorities, and consequent planning, concrete actions, and new societal and economic paradigms.

Ethical statement

The authors declare that they adhere to the Journal's Publishing Ethics.

Declaration of competing interest

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

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