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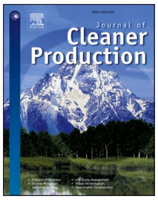

From bandages to buildings: Identifying the environmental hotspots of hospitals

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ABSTRACT

The provision of healthcare leads to high environmental impacts and economic costs for our society. Within the healthcare sector, hospitals are a main contributor to both aspects. In order to determine which areas of a hospital contribute most to the environmental impact, a life cycle assessment of 33 acute care hospitals in Switzerland was conducted. The environmental impact of these hospitals was analysed at midpoint level for 16 environmental impact categories. The functional unit (FU) was defined as healthcare services provided by one full-time equivalent for one year. The analysis shows that building infrastructure and catering are the main contributors for various environmental impacts, followed by heating and electricity. Waste and wastewater, pharmaceuticals, and medical and housekeeping products are relevant for at least three categories, whereas textiles, and paper use and printing are only relevant for one to two categories. Direct water use and laundry, and large medical equipment are only responsible for a small share of the impact in all categories. The carbon footprint of an average hospital is 3.2 tonnes CO_2eq per FU and the main impact stems from heating with 0.82 t CO_2eq per FU. The large variation in the environmental impact of different hospitals reveals that there is a considerable yet untapped potential for sustainability improvements in the hospital sector.

1. Introduction

Health services provide essential services to society by supporting people's health and well-being. However, these benefits come at a high financial and environmental cost. The Organisation for Economic Cooperation and Development (OECD) countries spent an average of 9 % of their gross domestic product (GDP) on healthcare in 2016 (Pichler et al., 2019). At the same time, the sector is responsible for an average of 5.5 % of national carbon footprints in 2014 (Pichler et al., 2019). A more detailed analysis including raw data from hospitals is available for England, where they account for 6 % of the national carbon footprint (NHS England, 2019, p.3). Since climate change is already considered to be outside the safe operating space for humans (Rockström et al., 2009), the carbon footprint of health services should receive special attention. Like the two publications mentioned above, most health service environmental footprint calculations are based on financial data, namely on environmentally-extended input-output analyses (Jungbluth et al., 2011; Tukker et al., 2006) and do not include bottom-up analyses.

Based on expenditure categories in OECD countries, Pichler et al. (2019) showed that hospitals are responsible for 29 % of the carbon footprint of health services, ambulatory healthcare services for 18 %, and medical retail for 33 %. In the US, hospitals are estimated to contribute 36 % (Eckelman and Sherman, 2016) to 39 % (Chung and Meltzer, 2009) to the total impact of health services on climate change. Additionally, hospitals buildings ranked second highest in terms of energy use intensity in a US-study, after only restaurants (Pérez-Lombard et al., 2008). Although hospitals are one of the principle contributors to the environmental impact of health services, comprehensive bottom-up Life Cycle Assessments (LCA) of hospitals are rare worldwide. Environmental assessments are available on certain topics relevant for hospitals such as on the pharmaceutical sector (Belkhir and Elmeligi, 2019; Sauvin et al., 2018), on specific pharmaceuticals (Shermann et al., 2012), on treatments (Alshqaqeeq et al., 2020; Esmaeili et al., 2018; Shermann et al., 2012), or the comparison of single-use versus multi-use medical products (Campion et al., 2015; Carre, 2008; McGain et al., 2012; Sørensen and Wenzel, 2014).

In hospitals' environmental reports, only key parameters like energy and water use, as well as waste are mentioned (Bürgerspital Basel, 2016; Mediclinic international, 2016), or additional aspects like paper use, recycling rate, and wastewater (Carus Green, 2015), while the

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corresponding environmental impact is not reported.

A comprehensive environmental assessment including all hospital areas is currently missing (Djati et al., 2018; McGain and Naylor, 2014) and LCA is considered to be a useful tool for the environmental assessment of health services (Djati et al., 2018; Kløverpris, 2018). Some Swiss hospitals have conducted LCAs of certain hospital areas: The Geneva University Hospitals (HUG) conducted the first LCA for the main areas of their hospital in 2009 and updated it for the years 2013–2017 (HUG, 2016). They assessed water, waste, infrastructure, staff, patient and visitor mobility, energy, and procurement and determined that procurement, mobility, and energy are the most relevant areas while waste and water input contribute little to the environmental impact (HUG, 2016). The University Hospital Bern assessed the environmental performance of four areas with the Swiss Ecological Scarcity Method in 2014 (Inselspital, 2015) and determined that the main impacts arise from heat provision, followed by electricity consumption, and waste. They also concluded that water input and wastewater were less relevant.

This article is intended to close this research gap by detailing a bottom-up LCA based on a unique data set of 33 Swiss hospitals. Key data from these hospitals were collected in a nationwide survey and were both used to directly model hospital processes as well as for extrapolations based on detailed life cycle inventory (LCI) data collected from two partner hospitals. Based on these LCA results, this article aims to answer the following research questions:

(1) Which environmental impacts arise from Swiss hospitals?
(2) What are the differences between hospitals in terms of environmental impact per healthcare services provided per full-time equivalent?
(3) How do the different areas contribute to the environmental impact?

The results of this study can be used by healthcare decision makers to improve the environmental sustainability of the hospital sector. By highlighting areas that are the most relevant and have the greatest improvement potentials, decision makers are enabled to target mitigation measures and by highlighting areas that need to be investigated more closely, the scientific community can target its research focus.

2. Material and methods

A life cycle assessment according to the ISO-standards 14044 and 14040 was conducted (ISO, 2006a, 2006b). The twelve hospital areas depicted in Fig. 1 and described in chapter 2.1 were considered. Detailed data were collected from partner hospitals whereas key data were collected from all 33 hospitals (see chapter 2.2). The environmental impact was analysed for 16 environmental impact categories on midpoint level as described in chapter 2.4.

2.1. System

The twelve hospital areas included in this study are electricity, heating, catering, building infrastructure, laundry and water use, waste and wastewater, textiles, medical and housekeeping products, paper use and printing, pharmaceuticals, electronic equipment, and large medical equipment (Table 2). The areas were chosen based on literature and hospitals' environmental reports (see A.2 in Supporting Materials). For each area, the most environmentally relevant inputs and emissions were taken into account. Waste from all areas were included in the analysis and summarised in the category "waste and wastewater". Hospital grounds, patient transport and staff and visitor mobility, small medical devices, and furniture and fittings were not included. The scope of the study therefore includes the life cycle of all major products consumed in activities within a hospital.

2.2. Data collection

Comprehensive LCI data were collected and life cycle assessments of

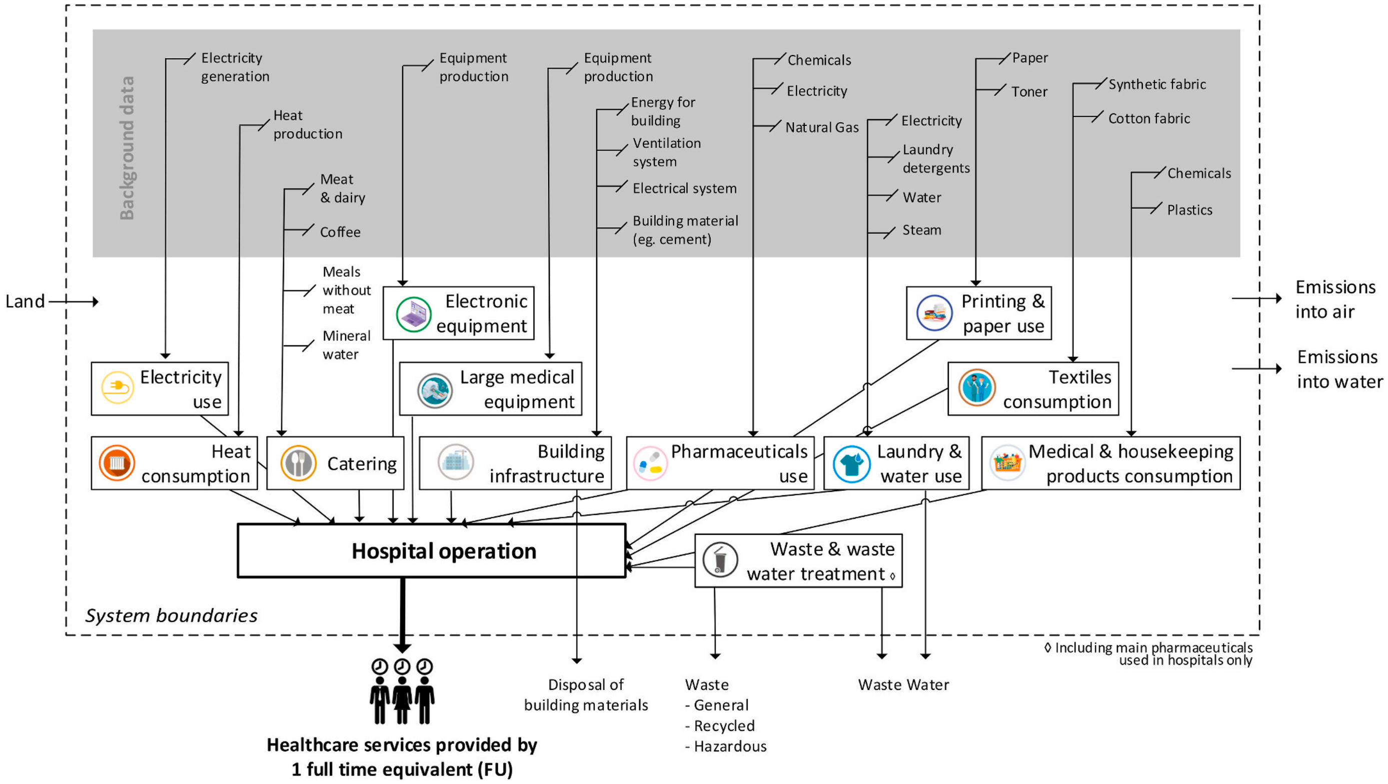

Fig. 1. System diagram for the hospital areas considered in this study of 33 Swiss acute care hospitals. Inputs shaded grey represent background data. Processes in boxes correspond with the categories described in Table 2.

two Swiss partner hospitals, one a small hospital and one large university hospital, were conducted. Based on these LCAs and the aforementioned literature research, a survey was compiled. This online survey was sent out to all 155 Swiss acute hospitals in June 2019 to collect LCI and statistical data from 2018. The topics included in the survey were general key data, infrastructure and resources, food and consumable products, and electronic equipment. In total, 33 hospitals completed the survey and provided key inventory data that were used to model the environmental footprint. More information on the survey is provided in the Supporting Materials. For background data, ecoinvent v3.6. was used (ecoinvent Centre, 2019; Wernet et al., 2016).

2.3. Functional unit

The function of a hospital is to provide healthcare. Therefore, the functional unit is expressed in terms of healthcare services provided by employees to the patients measured according to staff workload. This workload is represented by the FTE, which is calculated by dividing the number of hours worked by the number of hours stipulated in a full-time contract in a given period of time. Examples for one FTE are two part-time staff members working 20 h each or one full-time staff member working 40 h in an institution with a 40-h work week. The average healthcare service provided by one FTE, namely one staff member working 100 % for one year in a Swiss acute care hospital, is 47 inpatient days plus 113 outpatient consultations (calculation based on BAG, 2020).

To compare the environmental impacts of hospitals providing different quantities and types of healthcare services, the functional unit (FU) “healthcare services provided by one average full-time equivalent (FTE) staff member over the course of one year in a Swiss hospital” was defined. This FU represents healthcare services that patients receive in a hospital and illustrates the healthcare related footprint of patients. This FU also allows comparison between institutions since it takes into account inpatient and outpatient care as well as different levels of care. Therefore for each hospital, their yearly inputs and emissions were divided by the healthcare services provided by hospital staff in FTE.

2.4. Impact assessment methods

The environmental impact was assessed at midpoint level for sixteen environmental impact categories (see Table 1) excluding long-term emissions. The environmental footprint method was used for twelve categories. This method is recommended by the European Union Joint Research Centre (JRC) (Fazio et al., 2018) and was used as implemented in the Software SimaPro 9 (PRé Consultants, 2019). This software was also used to model the hospitals and to calculate their impact. The original method based on the IPCC (2013) was used to determine global warming potential, and for human toxicity and ecotoxicity, the updated USEtox version 2.02 from 2016 was applied (Fantke et al., 2017). The selection of impact assessment categories covers all environmental midpoint indicators reported for ‘First Mover’ stories by the UNEP-SETAC Guidance on Organizational Life Cycle Assessment (Blanco et al., 2015).

Table 1
The environmental impact categories, abbreviations used in figures, and methods.

Environmental impact category	Abbreviation	Method
Global Warming Potential	GWP	IPCC, 100 years (IPCC, 2013)
Human toxicity, cancer	H. tox., c.	USEtox v.2.02Fantke et al. (2017).
Human toxicity, non-cancer	H. tox., non-c.	
Freshwater ecotoxicity	FW ecotox.	
Ozone depletion	Ozone depl.	Environmental Footprint 3.0Fazio et al. (2018)
Ionising radiation	Ionising rad.	
Photochemical ozone formation	Ozone form.	
Particulate matter	Part. matter	
Acidification	Acidific.	
Eutrophication, freshwater	Eutr., FW	
Eutrophication, marine	Eutr., mar.	
Eutrophication, terrestrial	Eutr, terr.	
Land use	Land use	
Water use	Water use	
Resource use, fossils	Res., fossils	
Resource use, minerals and metals	Res., min.& met.	

2.5. Uncertainty and sensitivity

The uncertainty of the input variables was determined with the pedigree methodology that classifies different types of uncertainties and is applied in the ecoinvent database (Frischknecht et al., 2004; Weidema et al., 2012). The uncertainty of the results was then determined using a Monte Carlo analysis (Metropolis and Ulam, 1949), the most common method used to determine uncertainty in life cycle assessment (Igos et al., 2019). To insure a stable variance, a total run of 10 000 calculations with random input variables were conducted for each of the 33 hospitals as well as for the average hospital (Igos et al., 2019).

To estimate the influence of the electricity mix on the results, a sensitivity analysis was conducted where the input for electricity for the average hospital was replaced by the European electricity mix provided by the European Network of Transmission System Operators for Electricity (ENTSO-E).

3. Life cycle inventory

An overview of the areas considered, the key data collected for each area, and the methods used to calculate the impact is provided in Table 2. Statistical data that hospitals provided to the Federal Statistical Office (FSO) were also used to calculate selected impacts. These have been highlighted with a hashtag in Table 2. A short description of the modelling approaches used is provided in the following paragraphs. Additional information on the modelling approaches can be found in the Supporting Materials.

Electricity and heating were modelled using data on energy demand and sources collected in the survey. All hospitals provided their yearly electricity demand, and about half the hospitals shared information on their specific electricity mix. When no information on electricity mix was provided, the business mix of the local electricity provider as stated by the Swiss association of electricity entities was used (Verband Schweizerischer Elektrizitätsunternehmen, 2019). Large-scale consumers are free to choose their electricity provider and it is therefore not certain that hospitals use their local provider. However, of the fourteen hospitals that supplied information about their electricity provider, the majority do use their local provider. Two hospitals did not provide any data on heat demand. Their heat-related impact was calculated based on the median energy demand per FU and the average proportion of each energy source of the other 31 hospitals.

Catering was modelled based on the total number of meals served to patients, staff, and visitors, as well as on hospital-specific consumption data for meat, coffee, and mineral water. An average hospital meal excluding meat, mineral water, and coffee was modelled using detailed data from the two partner hospitals. The mass per meal was adapted according to the hospital-specific proportion of meat used, whereas meat, coffee, and mineral water were modelled separately using hospital-specific data.

Hospital building infrastructure per energy reference area was modelled using an average of three different hospital building LCAs. The planning offices “Büro für Nachhaltigkeit am Bau”, “Gartenmann Engineering AG”, and “CSD Ingenieure AG” provided data for Basel

Table 2
Key data of the hospital areas collected in the survey and calculation methods used.

Area	Key data collected	Calculation of impact	Approach if no data provided (Nr. of cases applied)
Electricity *	Annual consumption; Electricity mix/provider	Directly modelled using adapted ecoinvent datasets	Regional electricity provider mix was used (17/33 cases)
Heating	Annual demand; Energy source	Directly modelled using ecoinvent datasets	Median demand and average heating mix for heat sources (2/33 cases)
Catering	Number of meals provided; Share for patients, staff, and visitors; Annual consumption of meat, fish, milk products, coffee and bottled water	An average meal was modelled using data from two hospitals. The mass per meal was kept constant while meat, coffee, and mineral water were modelled individually based on annual consumption.	Median values were used (3/33 number of meals, 5/33 meat, 3/33 coffee, 1/33 mineral water)
Building infrastructure	Energy reference area	Averages from three hospitals, data provided by architecture offices	N/A
Laundry & water use	Annual laundry in tonnes per year; Share washed internally; Annual water use	New dataset was produced based on Eberle (2007). Wastewater and electricity demand were subtracted from the respective areas, marked with an asterisk. Directly modelled using ecoinvent datasets	Median values (5/33 for laundry, water use 2/33)
Waste and wastewater *	Annual waste in kilograms (Annual water use)	An average waste dataset was modelled using data from two hospitals. The proportions of each type of waste were assumed to be the same as the average dataset. Wastewater was considered to be equivalent to water use. Wastewater modelled with an adapted ecoinvent dataset to account for hospital-specific emissions.	Waste: median value (3/33).
Textiles	Household expenditure #	Textiles purchased per CHF spent. 33 % of household costs are for textiles based on data from one hospital	N/A
Medical & housekeeping products	Number of gloves; Proportion of nitrile, latex, and vinyl gloves; Household expenditure #	Gloves were modelled based on quantity used, and quantity of medical products was modelled according to the quantity of gloves used. Quantity of housekeeping articles per CHF spent. 20.3 % of household costs are used for housekeeping based on data from one hospital.	Median for missing (6/33) and implausible (2/33) data. Average for the composition of the gloves. N/A
Paper use and printing	None	Quantity of printed paper used per full time equivalent based on data from one hospital	N/A
Pharmaceuticals	Annual pharmaceutical expenditure #	Active pharmaceutical ingredients per CHF spent	N/A
Electronic equipment	Quantity of laptops, tablets, desktops, monitors, printers	Directly modelled	If no information on one type of device was provided, it was assumed that device is not used
Large medical equipment	Quantity of eight types of equipment modelled	Modelling based on material types stated in Environmental Product Declarations	If no information was provided, it was assumed that device is not used

Key data from Swiss hospital statistics is marked with a hashtag #. Electricity demand and wastewater that arise in connection with laundry are subtracted from the areas marked with an asterisk and are included in the category "laundry & water use".

University Hospital, Lachen Hospital, and Solothurn Public Hospital respectively using the building information modelling software Lesosai. The dataset takes building materials, building services, the energy required during construction, and the disposal of building materials at the end of its lifetime into account. Of the 33 participating hospitals, 24 provided data on their energy reference area. For the hospitals that only provided gross floor area, a share of 83 % of the gross floor area was assumed, which represents the average of the 7 hospitals that provided both types of area data. An operating life of 60 years was assumed (SIA et al., 2008).

The internal and external laundering of hospital textiles (e.g. clothes, bedsheets) includes soap, electricity use (9.38 kWh/tonne), and water use (8 m^3/tonne) based on Eberle et al. (2007) and the resulting wastewater (8 m^3/tonne). To calculate the total impact of internal laundry, electricity, water, and the resulting wastewater were subtracted from the corresponding hospital areas and included in the category "laundry" (marked with an asterisk in Table 2).

Hospitals reported annual water use in the survey and the quantity of wastewater was assumed to be the same as the quantity of water used by the hospitals. Wastewater was modelled using an ecoinvent wastewater dataset for Switzerland (ecoinvent Centre, 2019), adapted to account for the most relevant pharmaceuticals used in hospitals. An average waste treatment dataset was modelled using inventory data from the two partner hospitals. Data on the quantity of waste produced annually were collected in the survey and the share of different types of waste – namely recycled, general, and hazardous waste - was modelled using this average waste dataset. The proportions of each type of waste were assumed to be the same as the average dataset.

Since the production of the active pharmaceutical ingredient (API) is responsible for the majority of cumulative exergetic resource consumption (De Soete et al, 2013, 2014), pharmaceuticals were modelled as the quantity of API per Swiss Franc (CHF) spent. Data on pharmaceutical expenditure were collected in the survey. One partner hospital provided data on the yearly consumption of the 2–3 most commonly used pharmaceuticals in each drug class, which was used to calculate the API content of pharmaceuticals. These pharmaceuticals represented 10 % of the pharmaceutical costs that year. The total quantity of API in the pharmaceuticals purchased was linked to the pharmaceutical costs. Energy-related impacts of the production of the API amount to 90 % of its carbon footprint (Jiménez-González and Overcash, 2014). The environmental impact of the API was modelled with the ecoinvent dataset "Chemical, organic {GLO}" with an additional energy input to account for the more energy intensive production of active pharmaceutical ingredients in comparison with other chemicals.

Gloves were modelled separately, based on the total quantity of gloves and the proportion of each type. For the eight hospitals that did not provide plausible glove use data, the median of 2033 gloves per FU and the average proportion of each type was used. For other medical products like facemasks, scrubs, drapes, and bandages, an average mix of typical quantities and materials was established based on detailed inventory data from the small partner hospital. Single-use metal surgical instruments like scissors, clamps and tweezers were modelled based on

Table 3
Life cycle inventory data used to model the average hospital in the different hospital areas. The functional unit is healthcare provided by one full time equivalent over the course of one year.

Hospital area & selected inputs	Value	Unit
Electricity	5070	kWh/FU/year
Heat	6157	kWh/FU/year
Catering		
Number of meals served	289	#/FU/year
Meat	16.4	kg/FU/year
Coffee	2.28	kg/FU/year
Building infrastructure	38.0	m2/FU
Laundry		
Total amount of laundry	0.36	tonnes/FU/year
Share internal laundry	35	%
Water use, total	41.4	m^3/FU/year
Waste	0.23	tonnes/FU/year
Textiles		
Bedding	0.57	kg/FU
Work clothing (including OP and intensive care clothing)	1.57	kg/FU
Housekeeping supplies (selection): Soap	1.88	kg/FU
Medical products (selection)		
Gloves	1900	#/FU
Bandages	111	#/FU
Crutches	0.64	#/FU
Pharmaceuticals: Active pharmaceutical ingredient	3.46	kg/FU/year
Electronic equipment (selection)		
Laptop	0.29	#/FU
Desktop computer	0.77	#/FU
Monitor	1.17	#/FU
Large medical equipment (selection)		
MRI	1.06	#/FU*1000
CT	1.14	#/FU*1000
Dialysis	8.99	#/FU*1000
Paper use	17.7	kg/FU/year

data from the University Hospital Basel and included relative to the number of gloves used. The quantity of medical products excluding gloves was then extrapolated based on number of gloves as a representative medical product.

Paper use per FU was calculated based on the number of sheets used in the small partner hospital and using a paper weight of 4.99 g per sheet. The quantity of printed paper used in the hospitals was then modelled in relation to their FTE.

To model electronic equipment, the number of the following devices was collected in the survey: desktop computers, displays, laptops, tablets, multifunctional and standard printers. The service lifetimes were taken from literature (Bundesministerium der Finanzen, 2000; Thiébaud et al., 2017).

The large medical equipment MRI, CT-Scanner, PET-Scanner, SPECT-Scanner (gamma camera), and angiography systems were modelled with data from environmental product declarations from Siemens Healthcare GmbH (Siemens Healthcare, 2016a, 2016b, 2017a, 2017b, 2018, 2019, 2017a, 2016a).

For areas of lower environmental relevance, such as textiles and housekeeping products, the environmental footprint was calculated using financial data and extrapolated from LCI data obtained from the partner hospitals. In terms of textiles, the production of drapes and gowns, intensive care clothing, work clothes, catering textiles, bedclothes, towels, and baby rompers were modelled. The quantity of textiles replaced each year was calculated using the quantity of each type of textile laundered and the number of wash cycles these items can sustain before they have to be replaced. These data were collected from one of our partner hospitals. Textile use per CHF household expenditure was calculated, with about 33 % of household expenditure on textiles. The impact of the production of textiles was then modelled in relation to the household costs as provided by the hospitals in the survey.

Household expenditure was used to calculate the environmental impact of housekeeping products. The environmental intensity per CHF was estimated based on data from the small partner hospital, namely data on expenditure for housekeeping products and material quantities in 2017. The environmental impact of housekeeping products was calculated for each hospital by multiplying household expenditure by the share for housekeeping (one fifth of household costs) and the environmental intensity of housekeeping products per CHF.

An average hospital was modelled as the total resource demand of all 33 hospitals divided by the sum of all full-time equivalents: 87 414 FTE in 2018. Key LCI data used to model the average hospital can be found in Table 3.

4. Life cycle impact assessment

The environmental footprint of 33 Swiss hospitals was quantified for 16 environmental impact categories (see Fig. 2). We first analysed the impact of the average hospital, then the impacts of the 33 hospitals in all impact categories, followed by a closer look at the impact on climate change. All impacts are calculated per healthcare services provided by one full time equivalent and year (FU).

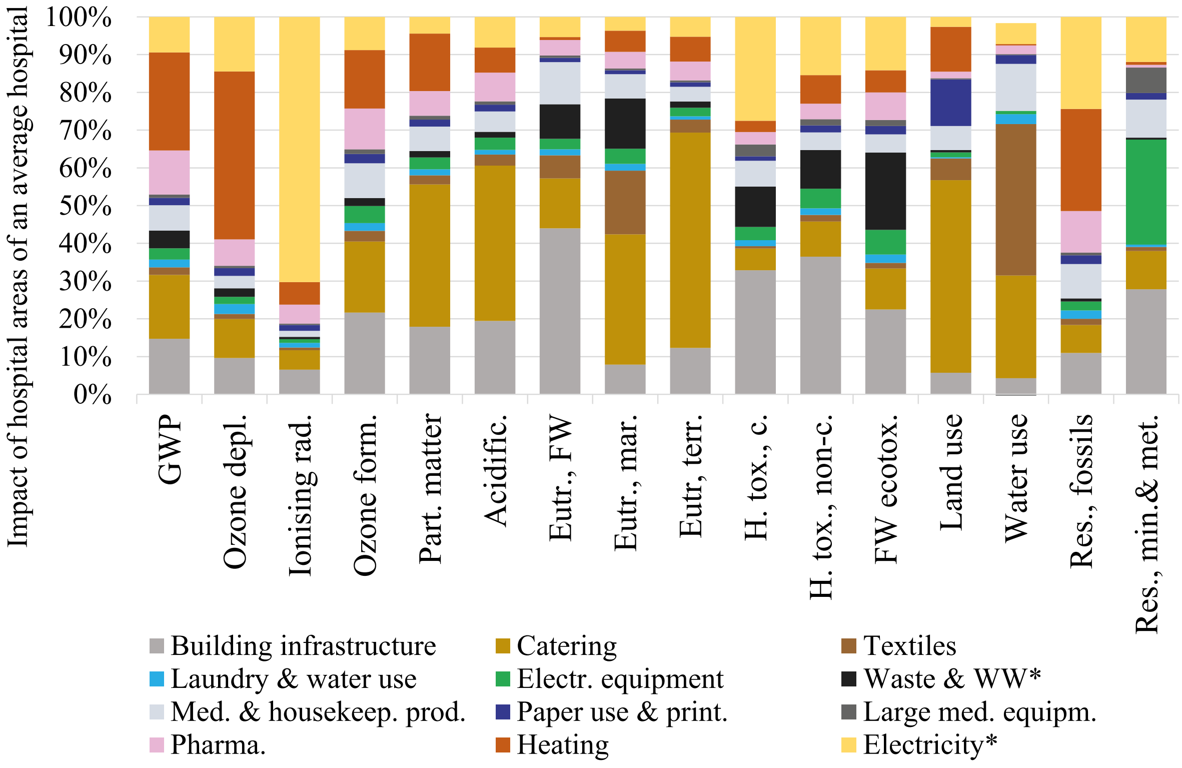

Fig. 2. Average impact contributions of the different hospital areas in 33 Swiss hospitals. Electricity and wastewater that arise in connection with internal laundry have been subtracted from the areas marked with an asterisk and are shown in “water use & laundry”.

4.1. *Impacts of an average hospital*

To represent hospitals of different sizes, an average hospital was calculated. Inputs are weighted according to the healthcare provided by the hospital represented by the FTE. The environmental impacts of an average Swiss hospital per FU in 2018 are presented in Table 4.

In terms of contribution to the total impact, two areas stand out: infrastructure and catering. Building infrastructure is responsible for the largest proportion of the impact for six of the sixteen categories: freshwater eutrophication (44 %), human toxicity (non-cancer, 36 % and cancer, 33 %), mineral and metal resource depletion (28 %), freshwater eco-toxicity (23 %), and photochemical ozone formation (22 %). It is responsible for more than 10 % of the total for most impact categories (12/16). Catering contributes most in terms of eutrophication (terrestrial, 57 % and marine, 35 %), land use (51 %), particulate matter (38 %), and acidification (41 %) and contributes more than 10 % of the total in most categories (12/16). Another environmentally important hospital area is heating: it is the main contributor in the categories ozone depletion (44 %) and global warming potential (26 %), followed by electricity consumption, which contributes considerably to ionising radiation (70 %) and fossil resource consumption (27 %).

Five areas contribute more than 10 % in some categories: waste and wastewater contribute significantly to human toxicity, freshwater eco-toxicity, and marine eutrophication. Pharmaceuticals contribute significantly to the categories global warming potential, photochemical ozone formation, and fossil resources. Textile procurement contributes significantly to water use and marine eutrophication, medical and housekeeping products to freshwater eutrophication, water use, and mineral and metal resources, electronic equipment to mineral and metal resources, and paper use to the category land use. The two categories direct water use & laundry, and large medical equipment contribute less than 8 % of the impact in each of the categories analysed (see details in A.6 in the Supporting Materials).

4.2. *Midpoint impacts of 33 hospitals*

In order to identify the areas with the greatest potential for impact reduction, the individual hospitals’ relative impacts per FU were compared. Ionising radiation arising from electricity shows the largest variation within the hospitals’ results: up to a greater than 1900-fold difference in impact per FU. This results from the different electricity mixes used: the hospital responsible for the highest radiation per FU uses a mix with over 80 % nuclear energy, the hospital responsible for the least radiation per FU uses a mix of 65 % hydropower, 25 % waste incineration plant, and 10 % label-certified renewable electricity. This electricity mix also results in the lowest impact in the category fossil resource depletion: it is 250 times lower than the highest impact which arises from a hospital using an electricity mix composed of almost 40 % fossil sources. In terms of heating, large differences also arise in the impact categories particulate matter with a 380-fold difference between the lowest and highest impact per FU, ozone depletion (240-fold), land use (320-fold), global warming potential (140-fold), and fossil resource use (98-fold). In all other categories, pharmaceuticals are responsible for the largest difference when compared per FU.

4.3. *Climate impacts of 33 hospitals*

A detailed analysis of the impact on climate change, comparing the global warming potential per FU for all 33 hospitals, is shown in Fig. 3. The impact on climate change varies between 1.72 and 7.10 t CO_2eq per FU. The standard deviation of the hospitals varies from 0.13 to 0.93 t CO_2eq per FU and is shown in in Fig. 3 as error bars. The arithmetic mean is 3.28 t CO_2eq per FU. This is lower for university hospitals (−12 %) and marginally higher (+2 %) for other types of hospitals. The largest variation in global warming potential per FU results from electricity (up to an 79-fold difference), pharmaceuticals (up to a 96-fold difference), and heating, with up to a 140-fold difference. For waste and wastewater, the difference is 21-fold, followed by textiles, laundry and water use, and medical and housekeeping products, where the difference is about 10-fold. In terms of infrastructure, catering, electronic equipment, and paper use, there is up to a 4-fold difference in global warming potential between the hospitals.

For the average hospital, heating is responsible for 26 % of hospitals' climate impact: 98 % stems from burning light fuel oil (26 %) and natural gas (72 %). Catering is responsible for 17 % of an average hospital's climate impact. Within this area, meat is responsible for 27%, whereas all other menu ingredients, including milk products and fish, are responsible for 66 %. Bottled water is responsible for 3 % of the catering-related impact and coffee for 4 %. Infrastructure is responsible for 15 % of climate impact. Within this area, 18 % stems from cement, 12 % from concrete, and 12 % from steel. The direct emissions during clinker production used for cement and concrete is responsible for a quarter of the impact. Medical products contribute 3 % of hospitals' climate impact: nitrile gloves are responsible for 45% of this impact, all other medical products for the remainder. In terms of medical products, aluminium crutches are responsible for 9%, disposable drapes and surgical drape kits for 14%, single-use scrubs for 7 %, and bandages for 6 % of climate impact. Housekeeping is responsible for about 4 % of the total climate impact of hospitals, of which plastics, contribute around 70 %, and dishwasher detergents 8% of the area's impact. On average, waste and wastewater are responsible for 5 % of the global warming potential. Waste dominates this area, being responsible for about 4.5 % of impact, while wastewater only contributes 0.5 %. Annual waste varies between 0.07 and 1.61 tonnes per FU.

Comparing the individual hospitals, the heterogeneity of the impact arising from the different areas becomes apparent. For instance, heating is responsible for between 1 % and 56 % of the total climate impact depending on the hospital. This is also the case for electricity, where the impact ranges from 1 % to 45 % of the total. The wide range in climate impact resulting from energy provision is because both energy demand and energy source play a significant role. Specific examples are considered in the discussion.

5. Discussion

This study revealed large differences in the environmental footprint of hospitals, with building infrastructure, catering, heating, and electricity being the main environmental hotspots. Waste and wastewater, pharmaceuticals, textile procurement, electronic equipment, and paper printing and use are only relevant for certain environmental impact categories. Only a small proportion of the environmental impact arises from direct water use, laundry, medical and housekeeping products, and large medical devices. The range in impact between the hospitals, most pronounced in terms of electricity, heating, and pharmaceuticals, implies there is substantial potential to reduce negative environmental impacts by optimising operations in specific hospital areas. In terms of global warming potential, heating, infrastructure, and catering show the largest variation. Hospitals aiming to reduce their carbon footprint may choose to focus on these areas first. The recommendations provided here are specific for acute care hospitals. However, many aspects, such as the importance of catering on the overall impact, are also expected to be valid for other healthcare providers.

5.1. Data quality and uncertainty

For the average hospital, the Monte Carlo analysis with 10 000 runs showed the lowest uncertainty for acidification, terrestrial eutrophication, global warming potential, photochemical ozone formation, and fossil resource use with a coefficient of variation (CV) below 10%, followed by mineral and metal resource use, particulate matter, marine eutrophication, and ozone depletion with a CV between 11% and 18% as well as land use with a CV of 28% (see Table 4). The uncertainty of water use, ionising radiation as well as human- and eco-toxicity is considered to be high due to high uncertainty in the background system and the high dependence on potential long-term emissions.

This environmental footprint assessment covers more than 60 % of all Swiss hospitals in terms of the FTE. The assessment is based on primary data collected from 33 hospitals and therefore provides a good basis to draw conclusions on the importance of different hospital areas. Direct input data on energy and water demand, infrastructure, meals and beverages served, the quantity and composition of gloves, quantity of laundry and waste, large medical devices and electronic devices were collected. In addition to the survey, other hospital-specific data were used for the infrastructure-related material demand, waste composition, medical products, pharmaceuticals, and the quantity of paper used. For these areas, the final environmental impact assessment was carried out by extrapolating key parameters. This extrapolation allowed a good approximation of the environmental impact of these areas. However, some differences in impact may not have been revealed, for example if a particular input is relatively cheap but environmentally impactful, the impact would be underestimated.

The average carbon footprint of the hospitals considered in this study was determined to be 3.2 t CO_2eq/FU in 2018 with a standard deviation of 0.33 t CO_2eq/FU calculated with the Monte Carlo analysis. In comparison, the University Hospitals of Geneva reported 11.5 t CO_2eq/FU in 2015 (HUG, 2016). Mobility was included in their analysis and accounted for 24 % of the total, which partially accounts for the difference. The University Hospital of Bern assessed energy and water use, and waste. They calculated a carbon footprint of 1.2 t CO_2eq/FU in 2014 (Inselspital, 2015), while we calculated the very similar total value of 1.26 t CO_2eq/FU in 2018 for these three areas for an average Swiss hospital. Like this study, the University Hospital of Bern also determined energy use to be more relevant than water use or waste disposal.

For an average Swiss hospital, electricity accounted for 9% of the global warming potential. The electricity mix used was the respective mix of the hospitals weighted according to the healthcare provided by the hospital represented by FTE. For the sensitivity analysis, the electricity mix was replaced by the European electricity mix ENTSO-E. The global warming potential per FU changes from 3.2 to 4.9 t CO2-eq per FU which increases the share of electricity on total impact from 9% to 42%. This large increase is because Swiss hospitals use electricity sources with a low GWP, namely hydropower (77%) and nuclear power (10 %). For European hospitals that use an average European mix, electricity is likely to play a much larger role in the climate impact compared to Swiss hospitals.

Building infrastructure was determined to be one of the most environmentally relevant areas. This is in line with the results of the University Hospitals of Geneva that also identified infrastructure to be one of the most relevant areas in terms of both carbon footprint and primary energy demand (HUG, 2016). Our results of 12.6 kg CO_2eq per square meter and year are very similar the one published for a Norwegian hospital building with 13.9 kg CO_2eq (Grann, 2012).

On average, pharmaceuticals were responsible for 12 % of the climate impact of hospitals in this study. The NHS (2019) found pharmaceuticals to be responsible for 12 % of healthcare's total climate impact and for 14 % when excluding the impact of mobility to allow for comparison with our study. Although environmental impacts arising from the development and production of pharmaceuticals are a source of uncertainty in this study, the carbon footprint of pharmaceuticals in our study is comparable to literature values (see Supporting Materials). Since the applied approach for pharmaceuticals is based on a price homogeneity assumption as typically applied in environmental input-output analysis (Tukker et al., 2018), it cannot differentiate environmental impacts that are not reflected in costs differences. Therefore, further analysis of the environmental impacts of different pharmaceuticals based on drug groups and including the research phase as well as pharmaceutical production is needed. At the end of life, active pharmaceutical ingredients (API) could have a detrimental effect when reaching waterways. However, the share of API emitted by hospitals is

Table 4
Environmental impact of the average hospital per FU as well as the standard deviation and the coefficient of variation calculated with a Monte Carlo analysis with 10 000 runs. For indicators with potential long-term emissions only the average indicator result is available. The functional unit is healthcare provided by one full time equivalent over the course of one year.

Indicator	Average environmental impact per FU & year	Standard Deviation	Unit	Coefficent of variation [%]
GWP	3.17E+03	3.3E+02	kg CO2 eq	8.9%
Ozone depl.	3.04E-04	6.6E-05	kg CFC11 eq	18.1%
Ionising rad.	3.57E+02	n.a.	kBq U-235 eq	n.a.
Ozone form.	8.30E+00	9.3E-01	kg NMVOC eq	9.3%
Part. matter	1.78E-04	2.9E-05	disease inc.	13.1%
Acidific.	2.17E+01	1.7E+00	mol H+ eq	6.7%
Eutr., FW	4.16E-01	n.a.	kg P eq	n.a.
Eutr., mar.	6.43E+00	1.4E+00	kg N eq	15.4%
Eutr, terr.	6.44E+01	5.5E+00	mol N eq	7.3%
H. tox., c.	5.93E-05	n.a.	cases	n.a.
H. tox., non-c.	6.70E-04	n.a.	cases	n.a.
FW ecotox.	1.05E+06	n.a.	PAF.m3.day	n.a.
Land use	3.73E+04	1.6E+04	Pt	28.0%
Water use	2.32E+03	n.a.	m3 depriv.	n.a.
Res., fossils	4.68E+04	4.3E+03	MJ	8.7%
Res., min.& met.	8.39E-02	1.1E-02	kg Sb eq	10.5%

usually only a small proportion of total emissions. According to Le Corre et al. (2012), the load from hospitals is likely to account for less than 15 % of the total. Helwig et al. (2013) calculated values starting from less than 10 % for common substances to well above 50 % for hospital-specific substances. One example are gadolinium compounds that are used as magnetic resonance imaging (MRI) contrast media. They are highly stable, quickly excreted (Lawrence et al., 2009; Ort et al., 2010b), and are not removed by conventional sewage treatment (Verplanck et al., 2010). They are only used within hospitals and are therefore particularly suitable for studying hospital effluents (Ort et al., 2010a, 2010b, 2010b). Due to the lack of specific characterisation factors for impact assessment, gadolinium was not included in this study. Further study of these types of compounds could allow insight into the extent and effects of hospital effluents on waterways.

Compared to hospitals' direct energy and water demand, less is known about patient, staff, and visitor mobility (McGain and Naylor, 2014). Mobility is responsible for 16 % of the climate impact of healthcare in England (NHS England, 2019). The University Hospitals of Geneva collected detailed data on mobility and calculated transport-related emissions of 2.6 t CO_2eq/FU in 2017 (Samson, 2017) with staff commuting responsible for half its impact (1.26 t CO_2eq/FU), visitor mobility for a third (0.88 t CO_2eq/FU) and normal patient transport for 16 % (0.41 t CO_2eq/FU). Less relevant are business trips (3 % of impact), and patient transport with emergency vehicles and helicopters (0.1 %). Assuming the transport-related emissions of an average Swiss hospital are comparable with those of the University Hospitals of Geneva, the climate impact including mobility would be 5.8 t CO_2eq/FU. Hospital-specific mobility impacts should be included in future analyses.

Additionally, further in-depth analysis to determine the environmental impact of each hospital department could highlight reduction potential and provide useful data to decision makers.

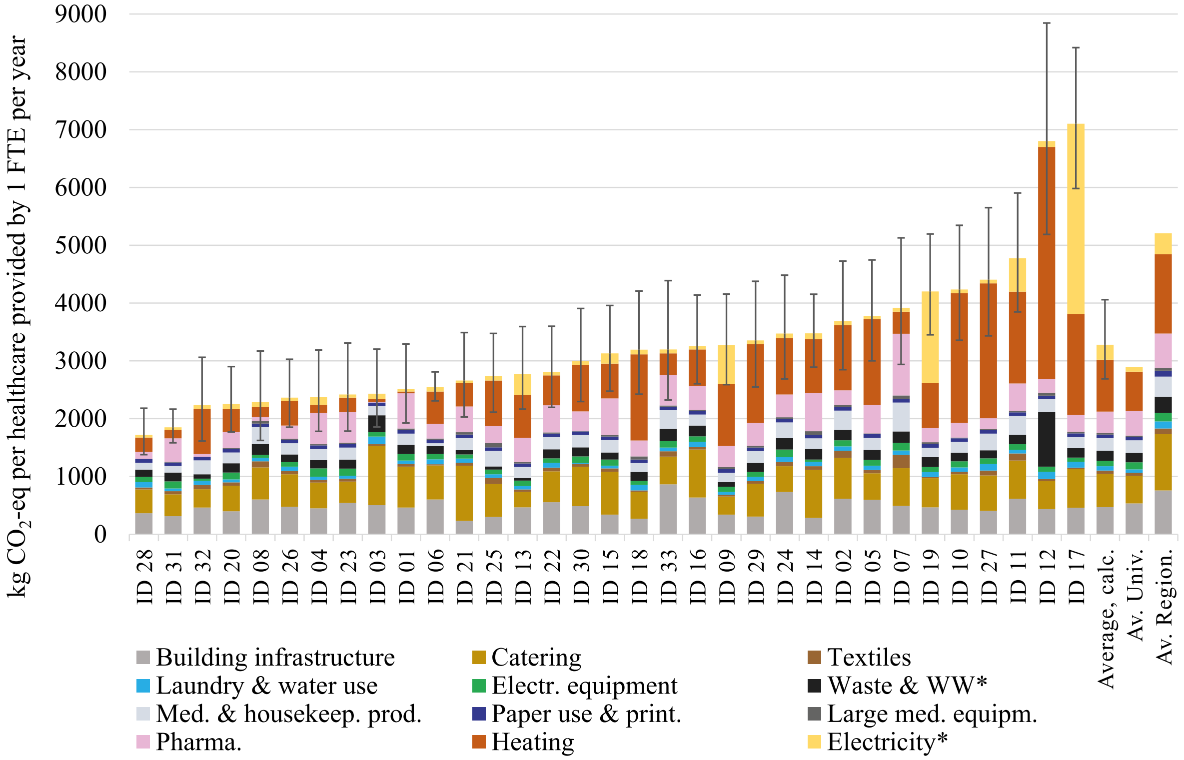

Fig. 3. Global warming potential by hospital area for all 33 hospitals that participated in the survey and three averages: all hospitals, university hospitals, and other hospitals. The functional unit is healthcare services provided by one full time equivalent over the course of one year. The impact of internal laundry is subtracted from the areas marked with an asterisk (*). Error bars show the 95 % confidence interval, calculated with the Monte Carlo analysis.

5.2. Functional unit

A fair comparison of the environmental impact of hospitals relies on the quantification of healthcare services, which is a challenge since services are heterogenous (Wolfson et al., 2019). Data by BAG (2020) for acute treatments in Swiss hospitals show that if the cost of outpatient and inpatient treatments are combined, a third of the cost arises due to outpatient treatment. A hospital comparison per inpatient bed or care days would neglect these outpatient health services provided and therefore lack an important part of hospital activity. Considering the shift from inpatient to outpatient treatment in Europe (Baumann and Wyss, 2021), this type of comparison will become even less adequate in the future. The functional unit "healthcare services provided by one average full-time equivalent (FTE) staff member over the course of one year in a Swiss hospital" is based on the reasonable assumption that healthcare provision depends on staff working hours.

One imprecision arises because the quantification of healthcare services based on full-time equivalents depends on whether hospital services such as catering or janitorial services are carried out by inhouse personnel or by external providers, as this affects the number of employees in a hospital. However, FTE represents health provision adequately since staff providing health services outnumber the staff employed for other type of services (BFS, 2020). A comparison of health service provided per energy reference area (ERA) is another option commonly used in building-related LCA (Frischknecht et al., 2020). However, the ERA has a less direct connection to health services, and a strong connection between the functional unit and the function provided is crucial for LCA (Rebitzer et al., 2004). In addition, inpatient treatments most likely require a larger area to provide health services compared to outpatient treatment, leading to a lower environmental impact for hospitals with a higher share of outpatient care.

To determine how the rank of the hospitals changes due to the choice of functional unit, the environmental impact of healthcare provided per ERA as provided in the survey was calculated and the resulting rank of the 33 hospitals was compared to the rank based on the environmental impact per healthcare provided per FTE. For ten hospitals, only a slight change in rank of plus or minus three occurred, and for only six hospitals a change of more than 11 occurred. For the remaining hospitals, the rank changed between 4 and 10. Alternative functional units based on financial units could be applied to companies, as suggested by Frischknecht (2020). However, using turnover data as a functional unit is problematic since the cost per treatment type is only partly standardised in Switzerland and varies between different regions.

5.3. Reducing the footprint

The large variation between the different hospitals shows that reducing environmental impact cannot be achieved by focusing on the same area in all hospitals. We therefore recommend identifying the areas that have the highest potential for each hospital individually.

Concerning building infrastructure, the area per FU directly influences the impact of buildings: optimal planning could reduce this while also allowing for more efficient workflow. To reduce the impact of buildings on the environment, Younger et al. (2008) additionally suggests using sustainable or recycled materials, and choosing the site carefully. The area heated also directly influences total heat demand and, as the results of this study confirm, energy is relevant for healthcare's environmental impact. The NHS determined that fuels were responsible for 9 % of healthcare's climate impact and electricity for 8 % (NHS England, 2019). Using renewable energy for heating and electricity results in significantly lower environmental impacts compared to conventional energy sources. This study includes a good example: heating is responsible for 56 % of hospital No. 12's carbon footprint due to the high heat demand resulting from its mountainous location, the advanced age of the buildings, which have not been renovated recently and provide poor insulation, and due to the use of carbon-intensive heating oil. Despite the fact that the heat demand per FU for hospital No. 1 is slightly above average, it has the lowest heating-related impact due to the use of district heat from a waste incineration plant. Similarly, the impact resulting from electricity depends on both the demand and the energy source: hospital No. 31 has the third lowest demand per FU and relies mainly on hydropower which results in the lowest electricity-related carbon footprint. Hospital No. 17 has the highest electricity-related impact resulting from having the third highest demand and the use of fossil fuels as the main energy source. From a national perspective, the carbon intensity of energy systems is important for healthcare's carbon footprint as shown by Pichler et al. (2019). They analysed the influence of energy systems' carbon intensity, the economy's energy intensity and healthcare expenditure on the carbon footprint of health. The largest effect was due to the carbon intensity of the energy system, which indicates that investing in a less carbon intense energy system automatically has a positive effect on the impact of hospitals.

Reducing the impact of heating can also be achieved by constructing low-energy buildings. Many Swiss hospitals are currently in the process of renovating, replacing, or expanding their building infrastructure. The University Hospital Bern's new main building will be certified as energy-efficient (Inselgruppe AG, 2020). Increasing hospital buildings' energy efficiency could lead to energy savings of 47 % according to Montiel-Santiago et al. (2020). This value was calculated using Building Information Modelling and assuming optimisation of thermal properties, ratio, and position of windows, the thermal properties of the facade and roof, as well as building occupation and operation. Renovations provide an opportunity to implement energy-related measures that reduce the environmental impact of hospital buildings while also being economically advantageous. Examples are optimised electrical installations (annual savings of around 0.5 kWh/m^2), improving air conditioning and heating systems (1.5–1.8 kWh/m^2 per year), replacing old or introducing alternative water heating systems (0.7 kWh/m^2 per year), and optimised lighting systems (0.1 kWh/m^2 and year) (García-Sanz-Calcedo et al., 2018). Montiel-Santiago et al. (2020) found that introducing energy-efficient lighting could reduce energy use by 13 %. This is of particular interest as hospitals procedures are not affected and investment are quickly amortised. The National Health Service in England reduced their building-related carbon emissions by 9.6 % between 2013/14 and 2016/17 and one NHS Trust saves an estimated 2500 t CO$_2$eq and £600 000 per year as a result of their energy efficiency work (NHS England, 2019).

Catering was responsible for 17 % of hospitals' climate impact in our study and 6 % of healthcare's impact in the study carried out by the NHS (2019). We recommend optimising catering services from an environmental perspective as an initial measure for hospitals since it is a less sensitive area for integrating new processes than e.g. surgery and because measures are readily available. In a recent study, the following measures for improving the sustainability of hospital food services were identified: adopting sustainable procurement, reducing the frequency of meat options on menu plans, reducing the time between ordering and delivery, reducing excess food sent to wards, and preparing detailed waste management plans (Carino et al., 2021). Offering more vegetarian dishes or listing the vegetarian choice first have a high potential to reduce the environmental impact. In a study of refectory meals, the median global warming potential of vegetarian dishes was determined to be 41 % lower than that meals containing meat (Muir et al., 2019). Reducing the number of meals containing meat by 10 % would lead to a reduction in global warming potential of 14.5 kg CO$_2$eq per full-time equivalent and year according to our study. Food waste can be reduced if meal selection occurs at a suitable time to prevent ordering food for patients who leave the hospital before the food is served. Another option is providing untouched food to the staff at a lower price as implemented by several Swiss hospitals. In addition, changing the diet can provide a synergy between health benefits and climate protection as suggested by Pichler et al. (2019). Some hospitals that participated in the survey have implemented measures like offering vegetable components first, followed by starch-containing, and lastly meat components as a nudging strategy or have reduced the quantity of meat served per person. The introduction of a large, centrally-placed salad buffet reduced meat consumption in one hospital canteen by almost 30 %. Other options include offering patients half and quarter portions, which was shown to reduce food waste by almost 14 % in one hospital.

Within the area of medical products, gloves should be given a special attention since large volumes are used in hospitals and since they are responsible for a large share of the environmental impact of medical products. Packages are often densely packed with gloves and opening them can cause unnecessary losses. Specially designed dispenser systems can reduce the quantity of unused gloves that are discarded as well as improve hygiene. The use of single-use surgical instruments is expected to increase for three reasons: a general increase in the number of treatments in hospitals, a tendency to shift from inpatient to outpatient treatment, and the fact that multi-use instruments are not financially compensated for use in outpatient treatment in Switzerland. LCAs that compare specific single-use surgical instruments with those of multi-use alternatives are available (Campion et al., 2015; Carre, 2008; McGain et al., 2012; Sørensen and Wenzel, 2014), but there is currently no consensus whether single-use or multi-use instruments generally have the lower environmental impact. Further research should therefore analyse additional types of surgical instruments.

Generic information on measures to increase environmental sustainability in areas that are relevant for many companies like food or mobility is available, but evidence of the sustainability of specific healthcare interventions is rare and therefore little concrete guidance is available for hospitals (Lyne et al., 2020). Changing processes in hospitals is made even more difficult since mistakes may affect patients' health. In addition, healthcare jobs are notoriously high pressure. According to Siebenhüner et al. (2020), overtime and time pressure are the main causes of stress for Swiss health professionals: about 40 % regularly work overtime of 1–2 h per week, and 25 % more than 3 h. New processes have to be simple and should not increase workload. The potential for success is highest if measures provide additional advantages from a logistical perspective or even reduce costs. Although there are challenges to implementing change within hospitals, some approaches have been successfully introduced: The University Hospital of Grenoble has introduced a mobility plan with measures such as providing sufficient parking for bikes, optimising cycle paths, starting bike maintenance programmes, coordinating car-pooling, and subsidising public transport (HCWH, 2019). The National Health Service in England has implemented measures to reduce their environmental impact, many of which have also reduced costs. Examples include improved medicine management, which has led to saving of between £60–184 per patient per year and has reduced waste, introducing lean processes, reusing equipment such as sharps containers, reducing travel costs by conducting online meetings, as well as reduced travel-related emissions, by making only one weekly meeting online instead of in person (NHS England, 2019).

Hospital operations are also changing due to Covid-19. In a survey of over 100 respondents from US-hospitals, the greater adoption of virtual services was the second most frequently mentioned change (Sage Growth Partners, 2020). Several health news websites have discussed the importance of telehealth in saving lives and better monitoring convalescent patients at home while also saving time and money (Bau, 2020; Lagasse, 2020). Introducing telemedicine programmes has also the potential to reduce the environmental impact and the risk of exposure to infectious diseases (Dullet et al., 2017), increasingly important since the emergence of Covid-19. An analysis of a telemedicine programme in a university hospital in California showed a reduction of 100 kg CO_2eq per consultation via telemedicine if each consultation replaced a trip to the hospital. Telehealth could reduce unnecessary hospital visits and treatments, and reducing the number of hospitals admissions and procedures is likely to have a bigger impact than small changes in how the hospital procedures are conducted (McGain and Naylor, 2014). It is therefore important to have a holistic view considering the whole healthcare system when working towards reducing the impact of hospitals. Another Covid-19-related change discussed is the introduction of automated processes that reduce supply chain risks and increase the availability of data (Plesko, 2020). This would allow better monitoring of environmentally relevant data and better assessment of the impact of procurement. The fact that many procedures have to be adapted due to Covid-19 could be considered as an opportunity to adequately take into account the importance of the climate crisis (see planetary boundaries in Steffen et al., 2015) and include environmental sustainability as a key consideration when decision-making.

6. Conclusions

The largest potential for reducing the environmental impact of hospitals is in the areas infrastructure, catering, and energy consumption. In terms of climate change, the areas heating, catering, and infrastructure are most relevant, followed by pharmaceuticals and electricity. The large variation in the environmental impact of different hospitals reveals considerable potential for sustainability improvements in the sector that some hospitals are already beginning to adopt.

The biggest reduction in the environmental footprint of hospitals can be achieved if hospitals are energy efficient, housed in green buildings using renewable energy with management committed to reducing unnecessary operations, providing more plant-based catering services, and implementing optimised systems that reduce unnecessary pharmaceutical losses and food waste. By reducing its environmental footprint, the healthcare sector can care for both patients and the planet while respecting planetary boundaries.

CRediT authorship contribution statement

Regula Lisa Keller: Conceptualisation, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Karen Muir:** Investigation, Writing – review & editing. **Florian Roth:** Investigation. **Marleen Jattke:** Investigation. **Matthias Stucki:** Conceptualisation, Validation, Writing – review & editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128479.

Author contributions

Matthias Stucki and Regula Keller designed the conceptual approach; Regula Keller wrote the publication and performed the underlying calculations and literature research together with Karen Muir and Marleen Jattke. Matthias Stucki provided feedback on the publication and the underlying methodology. Florian Roth conducted the survey and described its methodology in the publication and provided feedback.

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