10.1071/AH24154
Australian Health Review

Supplementary Material

The carbon footprint of total knee replacements

Forbes McGain[A,B,C,*] (PhD, Associate Professor), *Kasun Wickramarachchi*[D] (MBBS, Doctor), Lu AyeE (PhD, Professor), *Brandon G. Chan*[B] (MBBS, Doctor), *Nicole Sheridan*[B] (FANZCA, Doctor), *Phong Tran*[F,G] (FRACS, Professor) and *Scott McAlister*[A] (PhD, Doctor)

[A]Department of Critical Care, Medicine, Dentistry and Health Sciences, University of Melbourne, Vic, Australia

[B]Department of Anaesthesia, Western Health, Melbourne, Vic, Australia

[C]Department of Intensive Care, Western Health, Footscray, Melbourne, Vic 3011, Australia

[D]Department of Anaesthesia and Perioperative Medicine, Royal Melbourne Hospital, Melbourne, Vic, Australia

[E]Department of Infrastructure Engineering, University of Melbourne, Melbourne, Vic, Australia

[F]Department of Orthopaedic Surgery, Western Health, Melbourne, Vic, Australia

[G]Australian Institute for Musculoskeletal Science (AIMSS), The University of Melbourne and Victoria University, St. Albans, Melbourne, Vic, Australia

*Correspondence to: Email: Forbes.mcgain@wh.org.au

Supplementary File S1: STROBE Statement for Cleaner Environmental Systems for the submission of an observational study:

The Carbon Footprint of Total Knee Replacements

	Item No.	Recommendation	Page No.	Relevant text from manuscript
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	3	"Observational" is included within the Abstract - Methods
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	3	Abstract – Methods and Results
Introduction				
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4	Introduction, paragraph 1-4
Objectives	3	State specific objectives, including any prespecified hypotheses	4	Introduction, paragraph 4
Methods				
Study design	4	Present key elements of study design early in the paper	5	Methods, paragraph 1
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	5-7	Methods, paragraph 1, 3, 8 and 10
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	n/a	No participants
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	n/a	No participants
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	5-7	Life cycling modelling is elaborated in Methods - paragraph 2, including depiction

				of system boundaries (figure 1). Operating room energy use modelling is explained clearly in Methods - (paragraph 6-8).
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	5	System Boundaries (Figure 1)
Bias	9	Describe any efforts to address potential sources of bias	7, 11	Life cycle assessment bias discussed in "LCA Statistical Analyses" in Methods, paragraph 10; and in Discussion, paragraph 8
Study size	10	Explain how the study size was arrived at	n/a	Not applicable

Continued on next page

Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why		Not applicable
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	7	Life cycle assessment bias discussed in “LCA Statistical Analyses” in Methods, paragraph 10
		(*b*) Describe any methods used to examine subgroups and interactions	n/a	Not applicable
		(*c*) Explain how missing data were addressed	5-6	Methods, paragraph 2, 4, 6,
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy		Not applicable
		(*e*) Describe any sensitivity analyses		Not applicable
Results				
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed		No participants.
		(b) Give reasons for non-participation at each stage		No participants.
		(c) Consider use of a flow diagram		No participants.
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders		No participants.
		(b) Indicate number of participants with missing data for each variable of interest		No participants.
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)		No participants.
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time		Not applicable
		Case-control study—Report numbers in each exposure category, or summary measures of exposure		Not applicable
		Cross-sectional study—Report numbers of outcome events or summary measures		Not applicable
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	7-9	Results, paragraph 1, 4, 6-7.
		(*b*) Report category boundaries when continuous variables were categorized	7-9	Results, paragraph 1, 4, 6-7.
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period		Not applicable

Continued on next page

Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses		Not applicable
Discussion				
Key results	18	Summarise key results with reference to study objectives	9	Discussion, paragraph 1
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	11	Discussion, paragraph 8
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	12	Discussion, paragraph 9
Generalisability	21	Discuss the generalisability (external validity) of the study results	12	Discussion, paragraph 9
Other information				
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	23	No funding

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

Supplementary Materials – Index

Supplementary Files (SFs) 1 Methods and Data for Energy Consumption Estimations.

Supplementary File (SF) 2: Attributes of the Operating Room and HVAC Data.

Supplementary Methods

Supplementary Results

Supplementary File (SF) 3: Attributes of the Operating Room and HVAC Data.

Includes five Supplementary Tables.

Supplementary File (SF) 4 : Life Cycle Inventory Assumptions for Total Knee Replacements

References

Supplemental File (SF) 2: Explanations of Methods Applied for Estimating OR Energy Use

Operating Room Four (OR4) is located at Williamstown Hospital in Melbourne, Australia. The OR energy consumption can be considered in four major categories: (i) space heating, (ii) space cooling, (iii) ventilation & pumps, and (iv) lighting & equipment. The space heating is provided via hot water by a gas boiler and the space cooling is provided via cold water by an electric chiller. ventilation fan, hot water pump, chilled water pump, lightings, and equipment are operated by electricity.

The annual gas consumption for space heating was estimated by using the simulated hourly heating loads and the average thermal efficiency of the hospital's gas boiler. The annual electricity consumption for space cooling was estimated by using the simulated hourly cooling loads and the average compressor cooling coefficient of performance (COP) of the electric chiller. The annual electricity consumption for ventilating and pumps was estimated based on the simulated loads and efficiencies of the fan and pumps. The annual electricity consumption for lightings and machines was calculated by using power ratings and usage time. The OR energy use was modelled in TRNSYS 17 Type 56 (Klein, 2010). The indoor air temperature was measured by Onset's HOBO® MX1101 Temp/RH data logger for a fortnight (13^{th}-28^{th} May 2019). The measured average OR temperature was found to be 20.5°C which agrees well with the averaged of the temperatures (19.9°C) recorded by the hospital's Building Management System (BMS). The measured averaged fresh (outdoor) air intake percentage by the BMS was 50.2%. The thermostat set point of 20°C and the ratio between outdoor air and return air of (1:1) (i.e. 50% outdoor air) were selected for the model. N.B. outside air combines with return air to form mixed air, which then is heated/cooled to become supply air. We also obtained the temperatures and relative humidities of the rooms surrounding the OR. The average values were applied as the boundary conditions.

We obtained main attributes of OR4 such as location and dimensions (supplementary data, Table 1), building materials' properties (supplementary data, Table 2) and number of OR occupants for each hour. A typical week's occupants, lightings, and equipment schedules are shown in Table 3 of the supplementary data. OR4 is located on the ground floor of the Williamstown Hospital and it has an inside (zone) volume of 153.3 m^3 and a floor area of 51.5 m^2. It has two external walls, two internal walls, no windows and there is one floor above.

Lighting (fluorescent tubes) and computer power ratings were obtained from manufacturers' specifications. There were 26 T8 (36 W) fluorescent light tubes, two 60W light emitting diodes (LED) surgical light heads (each containing 18 LEDs), and three desktop computers (230 W with colour monitor). Overhead lights were routinely on from 07:00 to 20:00 and the computers were on from 08:00 to 17:30. Surgical lights were estimated to be used for approximately 7 hours per day (less than overhead lighting). An anaesthetic scavenging machine, a suctioning machine and a surgical drill were utilised in the OR, although suctioning and drilling were infrequently used, thus excluded from the estimation. The anaesthetic scavenging machine (400 W) routinely was turned on and ran continuously during 07:00 – 20:00.

All measured parameters were used as input data for the TRNSYS building energy simulation model. Using this model together with the typical meteorological year hourly weather data generated by Meteonorm 7.3 (Meteotest, 2019), hourly heating and cooling loads were estimated. Heating load considers heat losses through the building envelope (i.e. floor, walls, ceiling) and energy required to heat the outdoor ventilation air. It should be noted that heat generated by occupants, equipment and lights reduces the heating load. Cooling load considers heat gain through the building envelope, heat gain from outdoor ventilation air and heat generated by occupants, equipment, and lights within OR4.

To estimate the gas and electricity consumptions for space conditioning the annual average efficiency of the hospital boiler and the annual average cooling coefficient of performance (COP) of the hospital chiller were identified from the name plates. The boiler efficiency and the chiller COP were found to be 85% and 5.5 (Johnson Control, 2016) respectively.

Supplementary File (SF) 3: Attributes of the Operating Room and HVAC Data.

SF3: Table 1
Main features of OR4.

Category	Item	Unit	Value
Location: Williamstown, Vic., Australia	Latitude	Deg.	37.8637868 S
	Longitude	Deg.	144.8922566 E
	Time zone	h	UTC + 10
	Elevation above sea level	m	19
	Ground temperature	°C	18
Dimensions	Length	m	7.28
	Width	m	7.09
	Ceiling height	m	2.97
Thermostat set point	Day and night	°C	20
Ventilation	Outdoor air	%	50
	Air change rate	ACH	20

ACH = Air changes per hour.

SF3: Table 2
Properties of the building envelope materials used in the model.

Component	Material	Thickness (mm)	Conductivity (W $m^{-1}K^{-1}$)	Density (kg m^{-3})	Specific heat (J $kg^{-1}K^{-1}$)
External wall	Plaster board	13	0.171	885	1090
	HD Polyester	90	0.126	1380	1000
	Brick	110	0.720	1920	835

Internal wall	Plaster board	13	0.171	885	1090
	Air space	90	-	-	-
	Plaster board	13	0.171	885	1090
Floor	Concrete	300	1.460	2300	880
	Soil	500	1.180	1387	1344
Ceiling	Plaster board	13	0.171	885	1090

SF3: Table 3
OR4 Occupant Schedule (averaged over all 10 operations).

Time	Number of occupants
00:00 – 07:30	0
07:30 – 08:00	2
08:00 – 13:00	8
13:00 – 13:30	0
13:30 – 18:00	8
18:00 – 24:00	0

SF3: Table 4
Energy use of OR4.[1]

Month	Heating (kWh)	Cooling (kWh)	Ventilation & Pumps (kWh)	Lighting (kWh)	Equipment (kWh)
Jan	827	267	267	288	260
Feb	763	244	241	260	235
Mar	1089	184	267	288	260
Apr	1911	78	258	279	252
May	2706	24	267	288	260
Jun	3431	0	258	279	252
Jul	3884	0	267	288	260
Aug	3546	0	267	288	260
Sep	2803	22	258	279	252
Oct	2270	60	267	288	260
Nov	1512	129	258	279	252
Dec	1190	196	267	288	260
Annual	25931	1203	3140	3389	3066
Energy (kWh) per hour. Total = 4.2 kWh	**2.96**	**0.14**	**0.36**	**0.39**	**0.35**
% total (electricity and gas)	**71%**	**3%**	**9%**	**9%**	**8%**

[1]The total energy use for gas heating and electricity was averaged over 8,760 hr (one year).

SF3: Table 5. Possible energy efficiency measures.
Effects of outdoor air percentage and night setback on cooling and heating loads

Outdoor air %	**Cooling load** (GJ/annum)	**Heating load** (GJ/annum)
100% outdoor air	39.0	166.9
100% with night set back[1]	37.3	116.9
50% outdoor air (**actual for OR4**)	24.5	79.0
50% with night set back[1]	23.7	54.1

[1]Night setback (all nights) from 20 to 10 Air Changes Per Hour (ACH) from 20:00 to 06:00.
Heating load savings from 50% outdoor air nocturnal setback =25 (79-54) GJ/annum = approximately 30% energy savings.
Overall cooling and heating load savings from 100% to 50% return, plus nocturnal setback = approximately 15+111=126 GJ/annum (61% energy savings).

Supplementary File S4: Life Cycle Inventory Assumptions for Total Knee Replacements

Component	Data source	Data assumptions	Manipulation
Single-use polyethylene	ecoinvent	200 g Polyethylene, low density, granulate {GLO}| market for | APOS U	
	ecoinvent	200 g Extrusion, plastic film {GLO} | market for | APOS U	
	Project	200 g Hammermill and landfill	
Single-use polypropylene	ecoinvent	2,902 g Polypropylene, granulate {GLO} market for | APOS U	
	ecoinvent	2,902 g Injection moulding {GLO} | market for | APOS U	
	Project	2,902 g Hammermill and landfill	
Single-use rigid polystyrene	ecoinvent	180 g Polystyrene, general purpose {GLO} | market for | APOS U	
	ecoinvent	180 g Injection moulding {GLO} | market for | APOS U	
	Project	180 g Hammermill and landfill	
Single-use stainless steel	ecoinvent	78 g Steel, chromium steel 18/8 {GLO} | market for | APOS U	
	ecoinvent	78 g Metal working, average for chromium steel product manufacturing {GLO} | market for | APOS U	
	Project	78 g Hammermill and landfill	
Single-use high density polyethylene	ecoinvent	402 g Polyethylene, high density, granulate {GLO}| market for | APOS U	
	ecoinvent	402 g Injection moulding {GLO} | market for | APOS U	
	Project	402 g Hammermill and landfill	

Single-use high density polyethylene / polyvinylchloride	ecoinvent	430 g Polyethylene, high density, granulate {GLO}| market for | APOS U	
	ecoinvent	430 g Polyvinylchloride, suspension polymerised {GLO}| market for | APOS U	
	ecoinvent	860 g Injection moulding {GLO} | market for | APOS U	
	Project	860 g Hammermill and landfill	
Single-use general plastic	ecoinvent	378 g Polypropylene, granulate {GLO} market for | APOS U	Assumed to be polypropylene
	ecoinvent	378 g Injection moulding {GLO} | market for | APOS U	
	Project	378 g Hammermill and landfill	
Latex	ecoinvent	80 g Latex {ROW}| market for | APOS U	
	ecoinvent	80 g Injection moulding {GLO} | market for | APOS U	Used in place of moulding and curing
	Project	80 g Hammermill and landfill	
Single-use cotton	ecoinvent	200 g Textile, woven cotton {GLO}| market for | APOS U	
	Project	200 g Hammermill and landfill cotton	
Reusable polypropylene tray	ecoinvent	1.3 g Polypropylene, granulate {GLO} market for | APOS U	399.5 g tray. Assumed used 300 times
	ecoinvent	1.3 g Injection moulding {GLO} | market for | APOS U	

	AusLCI	1.3 g waste treatment, inert waste, at landfill/AU U	
	Project	399.5 g washing	
	Project	399.5 g sterilisation	
Reusable high density polyethylene	ecoinvent	3.4 g Polyethylene, high density, granulate {GLO}| APOS U	1009.9 g tray. Assumed used 300 times
	ecoinvent	3.4 g Injection moulding {GLO} | market for | APOS U	
	AusLCI	3.4 g waste treatment, inert waste, at landfill/AU U	
	Project	1,009.9 g washing	
	Project	1,009.9 g sterilisation	
Reusable stainless steel	ecoinvent	138.4 g Steel, chromium steel 18/8 {GLO} | market for | APOS U	41,529 g stainless steel. Assumed used 300 times
	ecoinvent	138.4 g Metal working, average for chromium steel product manufacturing {GLO} | market for | APOS U	
	AusLCI	138.4 g waste treatment, inert waste, at landfill/AU U	
	Project	41,529 g washing	
	Project	41,529 g sterilisation	
Polypropylene wrap recycled	ecoinvent	3,208 g Polypropylene, granulate {GLO} market for | APOS U	
	ecoinvent	3,208 g Extrusion, plastic film {GLO} | market for | APOS U	
	ecoinvent	3, 208 g PP (waste treatment) {GLO} | recycling of PP | APOS U	

Stryker battery	ecoinvent	7.3 g Battery, Li-ion, NMC111, rechargeable, prismatic {GLO} | market for battery, Li-ion, NMC111, rechargeable, prismatic |Cut-off U	Assumed battery used 150 times
	ecoinvent	7.3 g Used Li-ion battery {GLO} | market for | APOS U	
	ecoinvent	0.5 kWh Electricity, medium voltage (AU) | market for electricity, medium voltage | Cut-off U	Plasma steriliser, 2,450 Watts per load, 5 batteries per load
Bone cement	ecoinvent	288 g Polymethylmethacrylate {GLO} | APOS U	~~Used for polymethyl methacrylate~~
Tibia	ecoinvent	176 g Titanium, primary {GLO} | market for | APOS U	
	ecoinvent	13.5 g Aluminium, primary, ingot {ROW} | market for | APOS U	
	ecoinvent	9 g Vanadium (Ref. Zhang, below)~~Titanium~~, ~~primary {GLO} | market for | APOS U~~	~~Used for vanadium~~
	ecoinvent	0.6 g Iron ore concentrate {GLO} | market for iron ore concentrate | Cut-off U	
	ecoinvent	0.2 g Carbon black {GLO} | market for | APOS U	
	ecoinvent	0.1 g Nitrogen, liquid {ROW} |market for | APOS U	
	ecoinvent	0.03 g Hydrogen, liquid {ROW} | market for | APOS U	
	ecoinvent	Titanium, primary {GLO} | market for | APOS U	

Femur	ecoinvent	174 g Cobalt {GLO} | market for | APOS U
	ecoinvent	90 g Chromium {GLO} | market for | APOS U
	ecoinvent	21 g Molybdenum {GLO} | market for | APOS U
	ecoinvent	3 g Nickel, 99.5% {GLO} | market for | APOS U
	ecoinvent	3 g Silicon, metallurgical grade {GLO} | market for | APOS U
	ecoinvent	3 g Manganese {GLO} | market for | APOS U
	ecoinvent	2 g Steel, low-alloyed {GLO} | market for | APOS U
	ecoinvent	1 g Carbon black {GLO} | market for | market for | APOS U APOS U
	ecoinvent	1 g Aluminium, primary, ingot {ROW} | market for | APOS U
	ecoinvent	0.8 g Nitrogen, liquid {ROW} |market for | APOS U
	ecoinvent	0.6 g Tungsten concentrate {GLO} | market for tungsten concentrate | Cut-off U
	ecoinvent	0.1 g Phosphorus oxychloride {GLO} | market for phosphorus oxychloride | APOS U
	ecoinvent	0.03 g Sulfur {GLO} | market for | APOS U
	ecoinvent	0.03 g Boron carbide {GLO} | market for | APOS U
OR energy per operation	ecoinvent	4.12 kWh Electricity, medium voltage (AU) | market for electricity, medium voltage | Cut-off U

	ecoinvent	1.17 kWh Electricity, medium voltage (AU) | market for electricity, medium voltage | Cut-off U
	ecoinvent	1.05 kWh Electricity, medium voltage (AU) | market for electricity, medium voltage | Cut-off U
	AusLCI	24.9 kWh Heat, central or small-scale, natural gas {AU REG} | market group for | Alloc Def, U

References

Johnson Control, 2016. YORK® Commercial & Industrial HVAC 2016, Johnson Control, Cork, Ireland.

Klein, S., Beckman, W., Mitchell, J., Duffie, J., Duffie, N., Freeman, T., Mitchell, J., Braun, J., Evans, B., Kummer, J., 2010. TRNSYS 17: a TRaNsient SYstem Simulation program. Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin, USA.

Meteotest, Bern, Switzerland. Meteonorm Handbook Part I: Software, 2019. https://meteonorm.com/assets/downloads/mn73_software.pdf.

Zhang G, Wang Y, Meng X, et al. Life cycle assessment on the vanadium production process: A multi-objective assessment under environmental and economic perspectives. Resources, Conservation and Recycling 2023;192:106926.