Modular analysis of the environmental impact of clinical pathways in paediatric intensive care

A proof of concept and case study

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MSc Thesis – Technical Medicine

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Modular analysis of the environmental impact of clinical pathways in the paediatric intensive care unit: a proof of concept and case study

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Abstract

The large environmental impact (EI) of healthcare is of growing concern, especially given the increasing negative health effects of environmental deterioration.[1,2] Paediatric intensive care units (PICU) are major contributors to this EI, partly due to the use of consumables and electricity.[3–5] Environmental hotspots in clinical pathways (CP) must be identified to guide practical and effective interventions to lower the EI.[5,6] Life cycle assessment (LCA) is currently the golden standard for EI assessment. However, LCA is time-consuming and highly complex. Thus, execution of LCAs on a large scale to analyse full CPs is not feasible in healthcare settings. Furthermore, the required data are often not available. Financial costs may be used as a proxy (spend-based LCA), but their representativeness is questionable.[6,7] Furthermore, the CPs of patients in the PICU differ highly and cannot be represented by a single standard CP. Therefore, this research aimed to develop a process-based framework for environmental hotspot identification that requires less time and expertise compared to LCA and accounts for differences between patients, using a case study of six PICU post-cardiac surgery patients. Modules were designed as building blocks to represent medical events in the CP with the flexibility to deal with interpatient variation. Associated consumable and electricity use were allocated to each module based on medical protocols and discussions with clinical staff. From this iterative process, a set of allocation rules was established. The material composition of each product was analysed and recorded in a database. Per module, the median frequency of occurrence was calculated in the patient cohort data. The carbon emissions (kg CO_2-equivalent) associated with each module per occurrence were calculated based on impact factors from an open-source database.[8] The total of each module was defined as the EI per module occurrence (in kg material and in kg CO2-equivalent) multiplied by the median module frequency. This research was a first step towards an accurate and flexible approach to environmental hotspot identification within CPs related to consumable weight and bedside electricity consumption. The modules and the data analysis algorithm can be reused and expanded for other CPs, saving time and effort in future analyses. The allocation rules ensure standardised allocation of consumables and electricity across the current modules and when new modules are added. Challenges in this approach lie in the availability of product information from manufacturers and reliable, open-source impact factors, especially for pharmaceuticals.

1. Introduction

The environmental impact (EI) of healthcare is a growing concern, with healthcare systems contributing significantly to greenhouse gas emissions, resource depletion, and waste generation.[2] There is a myriad of EI sources within the healthcare system, ranging from on-site energy use to indirect emissions in the supply chain of medical products.[9,10] (Paediatric) intensive care units (PICU) are recognised as hotspot departments due to the resource-intensive care provided.[11–15] The relationship between healthcare and the environment is a vicious cycle: environmental degradation exacerbates health challenges such as heat-related illnesses, malnutrition and the spread of infectious diseases. Paradoxically, healthcare processes contribute to environmental harm.[1,2] In the Green Deal Sustainable Healthcare 3.0, several sustainability goals have been defined, which the Erasmus Medical Centre (EMC) in Rotterdam, The Netherlands, has committed to.[16] Efforts to lower the EI of healthcare have led to various initiatives and research within EMC, including projects targeting energy consumption, waste reduction, and resource efficiency.[10,14,17] The EMC Sophia Children's Hospital Green Team has played a pivotal role in advancing these efforts, emphasising bottom-up, staff-driven initiatives that are feasible, actionable, and aligned with clinical priorities. These projects usually involve low-hanging fruit regarding electricity consumption, waste reduction, and resource efficiency.

A holistic and systems-oriented approach is necessary to assess the environmental impact of healthcare.[18,19] Clinical pathways (CP) cover multidisciplinary management for a specific patient group (such as diagnosis) or within one department, such as the PICU.[20] These frameworks encompass the full spectrum of diagnostics and treatment for specific patient groups. This approach enables analysis of interconnected processes, offering insights into the environmental hotspots within specific CPs. It also allows comparison of different treatment options within CPs. Traditional CP modelling, usually in decision trees or timelines, is designed to reflect and support clinical decision-making processes and chronology. A different CP structure might be necessary for the analysis of EI.

Previous research on the environmental impact of CPs has often relied on methods such as life cycle assessment (LCA).[19,21] While LCA provides detailed insights, it requires specialised expertise, human resources and data that are often unavailable in healthcare.[19] Material flow analysis (MFA) offers a more straightforward framework but lacks the level of detail needed to assess a care pathway and specific opportunities for change fully.[14] Data availability presents a challenge in any EI assessment of healthcare processes. Suppliers rarely disclose detailed information about the environmental impact of their products, and there is not yet a legal obligation to do so. Alternative methods, such as spend-based analyses, rely on financial data but assume a linear relationship between cost and environmental impact, which may not be valid in healthcare due to factors such as patents and complex value chains.[7,22] For example, biologicals, a type of pharmaceutical, are extremely expensive but, according to the current evidence, do not have a particularly high EI.[23] Given these limitations, there is an urgent need for accessible, pragmatic EI methods that can provide insights into environmental hotspots without excessive demands for data collection on healthcare staff, who already face significant and increasing workload pressures. The analysis should also be feasible with the (often limited) available expertise without the need to hire external parties. These new methods should furthermore be open-source and enable collaboration across departments and healthcare institutions to maximise resource efficiency and prevent unnecessary duplication.

Defining a clear analysis scope is essential in this context. The breadth of potential analyses requires careful prioritisation to ensure efficient use of human resources and comparability across processes, patient groups,

and timeframes. A focused scope allows for results that guide specific action while acknowledging inherent limitations. When choosing a CP to analyse high-impact, high-volume patient groups are a logical starting point, given their potential to yield meaningful reductions in environmental impact. However, interpatient variation, particularly in the PICU, complicates the definition of a CP, underscoring the need for flexible analyses.

This research aimed to address these challenges by developing a systematic framework for EI analysis of CPs that (1) is flexible and applicable to many CPs and (2) requires less human and data resources than LCA. Using the CP of cardiac surgery patients in the PICU of Erasmus MC Sophia Children's Hospital as a case study, the research focused on the consumption of disposable medical items and bedside electricity. The goal was to design a framework to quantify material consumption throughout the CP, providing actionable insights to guide EI-reducing interventions. Given the limitations of LCA and MFA, the methodology prioritised feasibility and the use of process-based data. This research served as a foundation for developing an EI assessment framework that can be used across departments and institutions to advance sustainability in healthcare.

2. Methods

2.1 Requirements and Study Design

Several key requirements were defined to develop a comprehensive framework for analysing the EI of CPs. These requirements address the need for a robust and scalable framework capable of integrating limited clinical and environmental data. Table 1 outlines these requirements and the approaches taken to fulfil them, ensuring reproducibility, scalability, practicality and flexibility regarding variability in CPs. A process-based EI approach was chosen because it allows for accurate and detailed insights into the EI of ICU care pathways. Data integration should ensure feasibility, with a data analysis structure designed to be reusable and manageable by healthcare staff. Scalability was addressed by creating distinct modules – explained in 2.3 - that can be expanded and reused for other clinical pathways or departments supported by open-source software.

Furthermore, the framework should be dynamic and allow for ongoing adaptation as new data, insights, or tools become available. Collaboration should ensure that these developments are shared across departments and healthcare institutions. Open-source databases are crucial for this collaboration and data exchange, enabling healthcare institutions with limited or no funds to perform this type of analysis. Finally, practical visualisation of findings is essential, providing clear insights for stakeholders to inform further interventions or analyses.

Table 1. *Requirements for the methodology and corresponding approaches*

Requirement	Description	Approach to meet the requirement
Process-based	Representation of processes from practice, rather than top-down analysis based on financial spending	Exploration of medical and product data sources
Accurate representation of clinical events	Identification of care pathway elements and their frequency of occurrence in clinical practice	Module frequency calculation based on EHR data; Validation if possible
Account for CP variability	Account for variability in care provided within the selected patient group	Modules as building blocks
Detailed insight	Provide insight into EI of different parts of a CP	Dissection of the CP into modules
Data integration	Combination of medical and environmental data in a unified framework	Integration of EHR data, modules and product database
Feasibility	Feasible with current human resources	Analysis can be performed by medical staff members; Reusable data (analysis) structure
Scalability	Ensure the methodology is applicable to other clinical/care pathways, departments and hospitals	Distinct modules that can be reused for other clinical pathways; Expandable analysis algorithm in open source software; Product database
Expansion options	Option to expand the scope and level of detail of the analysis (more types of resources, more life cycle stages, etc.)	Module structure that allows for additions and further detailing
Open-source and collaboration	Possibilities to collaborate as a community across departments and institutions to improve the method	Open source software; Product database
Dynamic	Option to adapt the methodology when new insights or data sources are identified	Open source databases containing product and impact data that can be adjusted over time;
Adaptability to different practical or research goals	Option to perform further analyses (e.g. comparison of patient subgroups)	Expandable analysis algorithm in open-source software; Automatic processing of datasets with more patients
Practical data visualisation	Present finding in a way that enables stakeholders to get clear insights to take further action (analysis or intervention)	Hotspot focused visualisation with options for further details

The overall methods of this research are shown in Figure 1. The methodology consisted of a few general process steps, indicated in dark blue. The first step was identifying relevant care elements and their representation in distinguished modules. This modular approach was chosen to account for variability between patients within one CP and allow data reuse for analysis of other CPs. Based on the primary protocol for the CP or patient group and discussions with paediatric intensivists, an initial set of modules representing medical events was established (light orange section). These initial modules were used as a basis for (1) consumable and electricity use analysis (light green section) to assess the material and electricity use per module per occurrence and (2) medical data analysis (light blue section) to assess the frequency of occurrence of each module in the CP (henceforth called module frequency). Several data sources (in green in Figure 1) were explored that could be used to represent medical events, use and EI of consumables and electricity. Several process steps were iterative, indicated by the two-way arrows in Figure 1. Each process step is explained further in the upcoming sections.

2.1.1 Scope

The environmental scope of this study encompassed disposable medical products (i.e. consumables) and bedside electricity consumption, focusing solely on direct or attributable processes as defined by the Greenhouse Gas Protocol.[24] Included processes were those occurring within the PICU that are directly linked to individual patient care. Indirectly associated processes, such as those related to human resources, capital goods, staff and patient transportation, infrastructure, and administrative functions, were currently excluded from the scope. Long-term reusable products were also excluded, because these products are used for multiple patients. Adequate allocation of the impact of these products, involving assessment of, for example, the lifespan and number of uses of each product and repairment possibilities, was currently not feasible. Medications were included if clinical staff considered them integral to one of the modules.

2.2 Clinical Pathway Case Study

Framework development and application to a patient cohort of six cardiac surgery patients were done simultaneously. The CP of paediatric patients in the PICU after cardiac surgery was the case study for this research. The complete care pathway of these patients includes many aspects, usually in several departments, outpatient clinics, or even several hospitals. Within the context of this research, the scope was limited to CP within the PICU and radiology during admission. The definition of the CP for this analysis is shown in Figure 2. A subgroup of patients who received extracorporeal membrane oxygenation (ECMO) treatment was chosen because this is a highly intensive type of care often associated with an extensive CP, compared to cardiac surgery patients without ECMO treatment. Therefore, this subgroup could be expected to represent the most extensive care pathways (and therefore EI) possible. Patients who fit the inclusion criteria were identified through an ECMO patient database managed by medical staff.

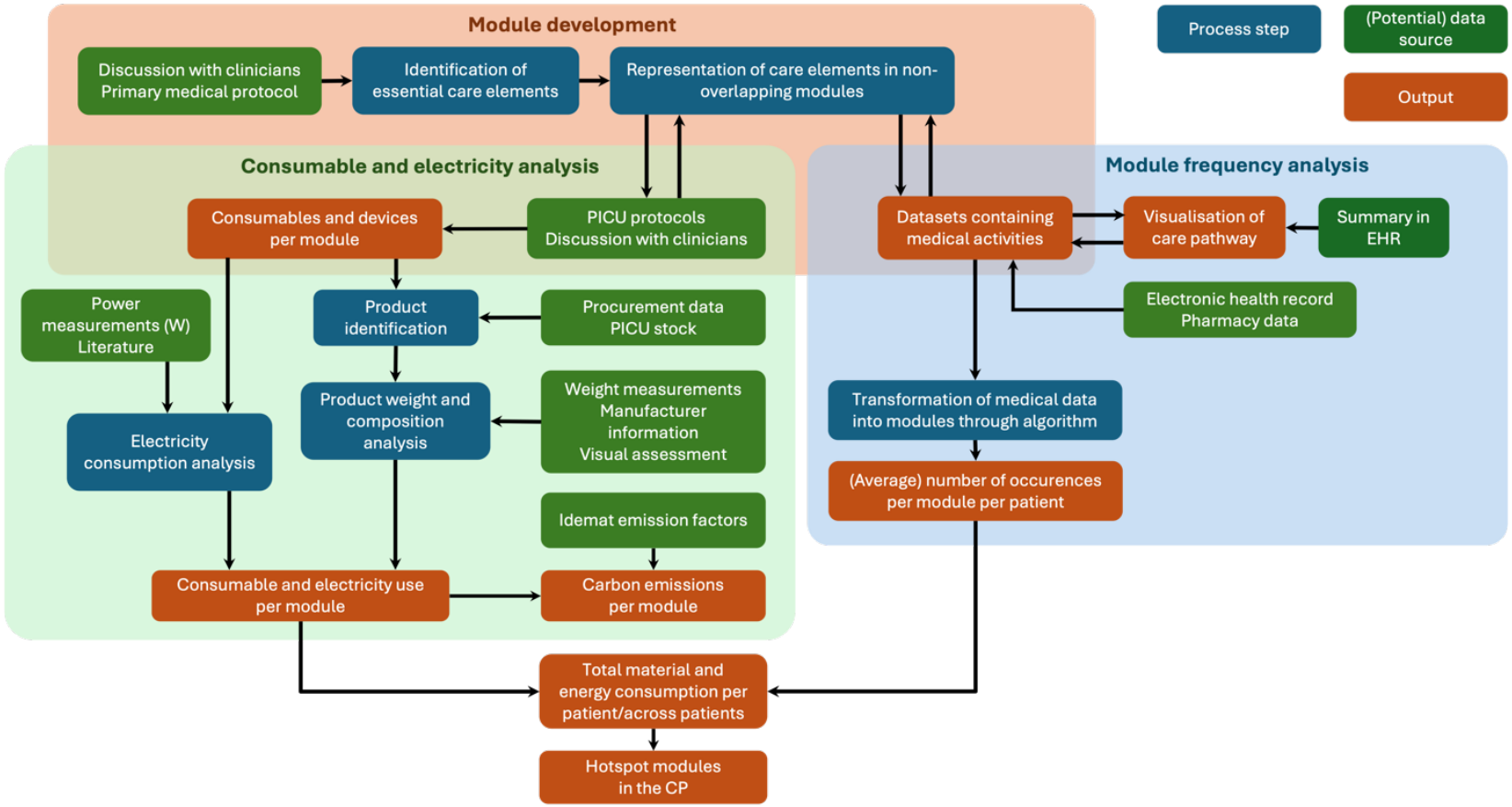

Figure 1. *Overview of the methods of this research, indicating process steps, explored data sources and outputs. PICU = paediatric intensive care unit; EHR = electronic health record; CP = clinical pathway*

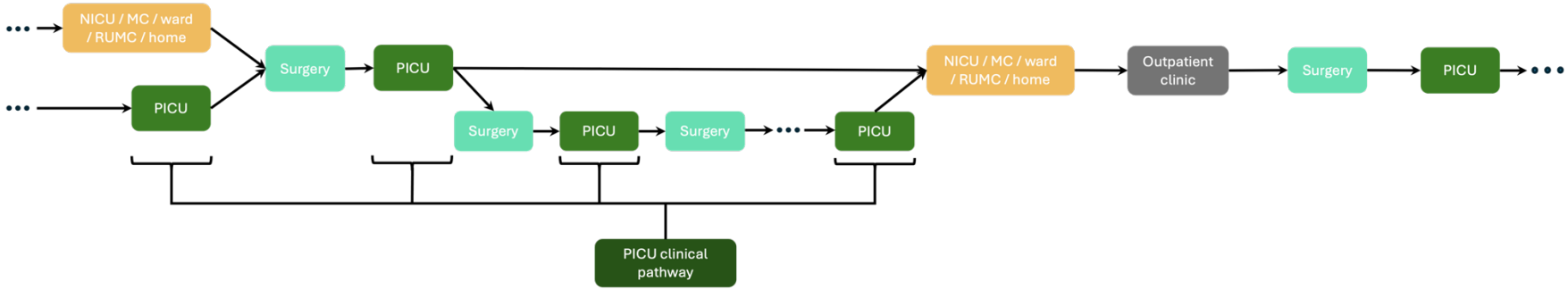

Figure 2. *General care pathway of cardiac surgery patients and the medical scope of this research. The scope (the PICU clinical pathway) covers only a part of the complete care pathway, which usually includes multiple surgeries, admissions to other departments or hospitals, and outpatient clinic visits.*

2.3 Module Development

2.3.1 Module Definition

The EMC Sophia Green Team has previously collaborated with an external research group to analyse the EI of childbirth and subsequent admission of a neonate in the PICU, titled *Sustainable Childbirth*.[25] In this analysis, a set of modules was created to represent the associated PICU care, including modules such as standard care, mechanical ventilation and insertion of certain catheters. This module set was used as a starting point for the modules in this case study and was adapted as necessary. Through discussion with paediatric intensivists (SV and MS) and the primary medical protocol, the standard or regularly provided care elements to these patients during PICU admission were identified. A first set of modules was established based on these care elements, such as mechanical ventilation and extracorporeal membrane oxygenation (ECMO). The modules were defined to account for differences in the duration of CP elements between patients. Additional modules were added when events were identified in the medical data or protocols that could not be represented by the existing modules. Care elements that did not occur in the medical data of the included patients were excluded from the analysis.

2.3.2 Consumable and Electricity Use per Module

The standardly used products and medical devices were identified to assess the consumable and electricity use associated with each module. Assessment of medical consumable use is often done through waste audits. However, this is a time-consuming process that would have to be performed for many different medical situations and CPs and that (currently) cannot be automated. Therefore, in this research, the aim was to use medical protocols as a basis. Only protocols that are used by PICU staff were included.

Firstly, all medical protocols covering the care provided in the initial set of modules were collected. As modules were added or expanded, corresponding protocols were added. When several protocols were available for the same type of care, for example, one for each age or weight group, the protocol applicable to most of the patients in the case study was used. From each protocol, all mentioned consumables and medical devices were extracted. If stated, the maximum duration of use was extracted. Unclarity about the products in the protocols was resolved by discussion with intensivists and nurses. Allocation of products to the different modules was reevaluated after each update of the module definitions. From this process, a set of product allocation rules was established to ensure systematic allocation and to prevent double counting of products that are shared across multiple modules.

Powered medical equipment was included in each day module as applicable. An existing dataset, based on power measurements with a plug-in power meter in the PICU, was used to determine the power consumption per device. For electricity consumption associated with radiology, data on power consumption during scanning and scan duration were extracted from literature.[26,27]

2.4 Product Identification and Analysis

Multiple approaches were taken to identify the products used (brand, product reference number, size, type, etc.). In the *Sustainable Childbirth* project, PICU products' weight and material composition were previously researched.[25] The product information was extracted from this project's database when possible. Samples were used for the remaining products. These were expired products, products designated for training purposes

or if the previous were not available, new products with packaging. When a product was packaged in bulk, the packaging weight was allocated to each product.

The material composition of the product and the primary packaging were analysed separately. The material groups were soft plastic, hard plastic, metal, paper, fluids, medication, etc. If possible, the exact type of material, e.g., plastic or metal, was also defined. The following data sources and collection strategies on material composition were consulted consecutively:

1. *Sustainable childbirth* project database, if not available;
2. Manufacturer reports and product labels, if not available;
3. Weighing of each part of the product that was made of different materials, if not available;
4. Visual estimation of the material percentages based.

2.5 Medical Data Collection and Analysis

The goal of the medical data analysis was to identify reliable data to determine the frequency of occurrence per module. Based on the initial set of care modules, medical data representing the occurrence of the care modules were extracted from the electronic health record (EHR) system (HiX, ChipSoft) through the Health Data Platform (HDP) and from the PICU's pharmacy. HDP is a data extraction platform that is connected to the EHR. However, it is not a direct translation. Therefore, not all data in the EHR can be extracted through HDP. Data extraction through HDP was performed by a clinical staff member of the PICU (BW, technical physician). This was an iterative process of evaluation and expansion of the dataset. When certain essential events were missing or incomplete in the dataset, other options and parameters in HDP were explored. EHR data were used to construct a rough CP timeline for each patient. This included PICU admission and discharge time, surgeries, circulatory, respiratory and renal support, and other significant events. This timeline was used throughout the medical data analysis process to assess the representativeness of the medical datasets and whether other datasets had to be explored. When an event was identified in the medical data which was not yet represented by the existing modules, the module set was revised to describe the new event inductively. Events that occurred during surgery were excluded from the analysis. Medical data evaluation and analysis was done in Python 3.12.4 using Visual Studio Code 1.90.2.

2.6 Impact Assessment and Environmental Hotspot Identification

The weight per material type (kg) and electricity consumption (kWh) were determined per module per occurrence. These were multiplied by corresponding emission factors (EF) to determine the carbon emissions (CE) in terms of kg CO_2-equivalent (CO_2-eq). This standardised unit of measurement covers the effect of seven greenhouse gases on climate change. EFs for materials were obtained from Idemat 2024 V2-3.[8] This database provides emission factors for certain materials (e.g., plastics, metals), depending on their origin and whether they are recycled after use. The EFs are calculated to reflect the average impact of a product made of a certain material. These data are mainly based on peer-reviewed papers and life cycle research from Delft University of Technology. It is an open-source alternative for EcoInvent, one of the most used databases for LCAs, but requires a license. The completeness of Idemat for the current purpose was assessed during the analysis. An EF representing the production of the Dutch electricity mix (0,536 kg CO_2-eq / kWh) was obtained from a national database. This is the EF used for all electricity use analyses in the EMC.[28] The calculation of the total carbon emissions of each module per occurrence is shown in Equation 1, where CE is the carbon emissions (kg CO_2) of a module, M is the consumable weight (kg) of a certain material in that module, $EF_{material}$ is the

emission factor of that material, W is the electricity use (kWh) in that module, and $EF_{electricity\ NL}$ is the emission factor for the Dutch electricity mix.

Equation 1. *Calculation of the carbon emissions of each module per occurrence*

$$CE_{module} = W_{module} * EF_{electricity\ NL} + \sum_{material} (M_{module,material} * EF_{material})$$

All relevant EFs were imported into the data analysis algorithm in Python. The CE per module per occurrence were multiplied by their median frequency to obtain the CE per module across the CP. Hotspots were defined as the modules with the highest weight and/or CE across the CP.

2.8 Ethical Considerations

This research adheres to ethical standards and hospital policies regarding patient data usage. Data extraction from the ECMO database was justified based on the research objective and was approved by the database managers. This study obtained a waiver from the Medical Ethics Committee. Patient privacy and data security were maintained throughout the research. All medical data was pseudonymised, and processing and storage were conducted on a secure research server approved for medical data storage.

3. Results

The methods resulted in multifaceted results. Firstly, the iterative module development process resulted in module definition and product allocation rules, described in 3.1. The analysis of EHR datasets of the patient cohort resulted in a set of metrics to represent the occurrence of each module, described in 3.3. The results of the consumables and electricity analysis of the modules in the cardiac surgery CP are shown in 3.4. The combination of the former resulted in preliminary hotspot identification in the cardiac surgery CP, described in 3.6. The medical datasets, product and electricity database, module database and data analysis algorithm are available on the EMC Sophia's PICU research server.

3.1 Modules

3.1.1 Module Definition

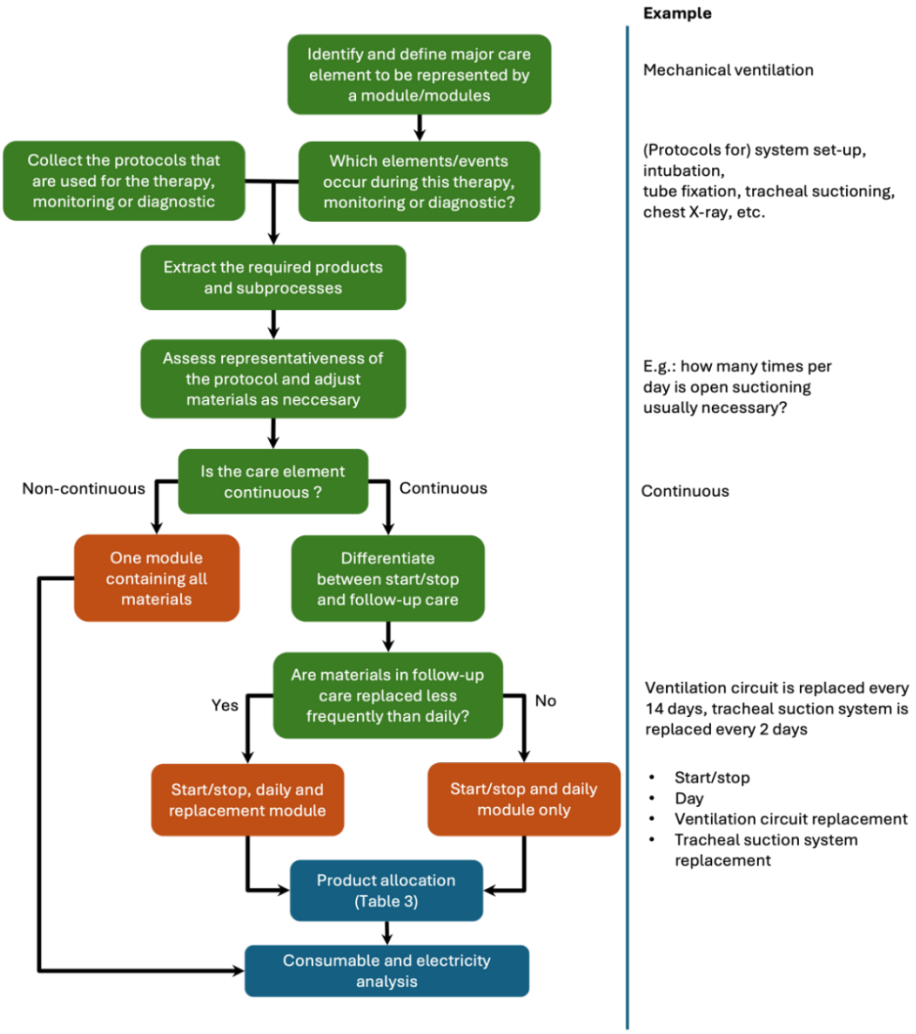

Figure 3. *Flowchart of the module definition and illustration with mechanical ventilation as an example*

The module definition process that took place during this research is visualised in Figure 3. The module definition process resulted in a hierarchical organisation of care elements, modules and submodules. At the highest level, medical events were grouped into care elements (e.g. mechanical ventilation), which were then categorised into modules as shown in Figure 3: per day, per single event, or per replacement period. Replacement modules were added to the module framework to include products used at the start of an event accurately and replaced less than daily (e.g., a ventilation circuit). Each module was further detailed into submodules to capture each aspect of the module.

3.1.2 Modules in the Cardiac Surgery Clinical Pathway

Table 2 shows the final set of modules that represented the medical events in the cardiac surgery CP. Sometimes, the protocol did not define the exact type and number of products used for a particular module aspect. For example, this was the case when products were replaced when they were full or empty, e.g. disinfecting fluid and urinary catheter bags. In this case, a nurse estimated the replacement period. When necessary, a patient weight of 4 kg was assumed based on the median weight of the patient cohort to select the appropriate protocol. This was supported by clinical experience that most cardiac surgery patients in this PICU are babies.

For some events, no reliable medical data source was available to represent them as separate modules. When the frequency of such an event was explicitly outlined in a protocol for another module (e.g. daily blood cultures during ECMO), it was directly incorporated into that module. If an event was closely associated with another module (e.g., suctioning saliva from the mouth and throat for patients on respiratory support), but the frequency was not standardised per protocol, the frequency was estimated based on discussions with clinical staff.

Lab tests are technically part of many modules, but the different analyses are usually combined in one lab test. Therefore, separate modules were created for each lab test type that could be differentiated from the medical data.

Isolation (of any type) and parenteral feeding with lipids were excluded from the module set because they did not occur in the current patient cohort.

Table 2. *Overview of all modules in the case study: paediatric intensive care admission after cardiac surgery*

Care element	Module	Module type[a]	Submodules	Comments
Standard care	Admission	S	Monitoring (e.g. blood pressure cuff), standard materials (e.g. Jackson Rees, needle container), nutrition (breast pump set)	
	Day	D	Medication, monitoring (replacements), standard materials (e.g. kidney trays, wash cloths, diapers), wound care	Prefilled NaCl flushes used frequently every day, mainly for medication administration, were estimated and included in this module
	Replacement	R	Monitoring (pulse oximeter), standard material replacements (disinfectants, baby wipes, plaster rolls)	A replacement period of 7 days for most standard products was estimated. Units of products that are replaced more or less frequently were adapted accordingly

ECMO	Start	S	Priming, cannula fixation, aEEG[b], NIRS[c], medication administration	Cannulation and decannulation materials were excluded since these occurred in the operating room
	Day	D	Cannula care and fixation, blood culture, medication	Blood cultures were included here because these could not be represented in medical data
	CRRT[d] start/stop	S	Priming, connection to ECMO	CRRT occurred only during ECMO, which means a small filtration system was connected to the ECMO circuit
	CRRT[d] day	D	Medication (haemodialysis solution)	
	Circuit replacement	R	Priming, connection	
MV	Start/stop	S	Ventilation circuit setup[e], intubation, intubation medication, extubation	The ventilation circuit and tracheal suction system were included in respective replacement modules
	Day	D	Mouth care, filter replacement, sputum suctioning, tube fixation, stomach deaeration, medication	Open sputum suction frequency was estimated
	Tracheal suction system replacement	R	Tracheal suctioning system, connection	
	Circuit replacement	R	Ventilation circuit	
NIVS[f]	NIV[f]	S	NIV system	
	Optiflow replacement[g]	R	Optiflow system	This system is installed at the start of Optiflow therapy and replaced every 14 days
	Oxygen therapy start	S	Oxygen therapy system	This system can be reused for the duration of the PICU admission
	Aerosol therapy day	D	Aerosol therapy system and medication	This system is replaced daily
Catheters[h]	Start/stop (per type)	S	Insertion, fixation, removal, medication during insertion or removal,	Infusion systems are included in the system replacement modules
	Day (per type, if applicable)	D	Medication, care (if applicable)	Only heparin to prevent coagulation in the catheter was included
	System replacement (per type, if applicable)	R	System, fixation	Infusion systems are replaced at various intervals for the central venous line, arterial line and peripheral line
Nutrition	Parenteral feeding day	D	Infusion bag	Infusion system is included in the central venous line replacement module
	Enteral feeding day	D	Feeding bottles, administration	A combination of breast milk and formula in eight portions per day was assumed
Lab diagnostics[i] and blood product administration	Blood gas	S	Sample collection	Arterial blood was assumed
	Blood arterial line	S	Sample collection	Two small blood containers per occurrence were estimated. This also includes blood counts.
	Blood coagulation	S	Sample collection	

Blood capillary	S	Sample collection
Sputum	S	Sample collection
Urine	S	Sample collection
Faeces	S	Sample collection

S = single event, D = daily, R = Replacement (b) aEEG = amplitude-integrated electroencephalogram; (c) NIRS = near-infrared regional spectroscopy; (d) CRRT = continuous renal replacement therapy; © Ventilator tubes excluded as these are included in the replacement module; (f) NIVS = non-invasive ventilatory support; (g) NIV = non-invasive ventilation (e.g. BiPAP); (h) Set of modules per catheter type as applicable: central venous line, arterial line, peripheral line, thoracic drains, pleural drain (if placed in the PICU), enteral feeding tube and urinary catheter; (i) All processes after sample collection were not included, since these happen outside the PICU.

3.1.3 Product Allocation

Table 3 shows the final product allocation rules established during the iterative module development process, as shown in Figure 1.

Table 3. *Final rules for allocation of products to the modules.*

Element	Start/stop module	Follow-up day module	Replacement module	Examples / comments
Material used for insertion/attachment or removal of therapy/monitoring devices	✓ if they are PICU materials used in the PICU (e.g. materials used during intubation)	x	x	ECMO cannulation materials that do not come with the patient into the PICU from the OR were not included
Materials that are used continuously or periodically during therapy/monitoring	✓ If only replaced on indication (e.g. urine catheters)	✓ If replaced or used daily	✓ if replaced or used periodically but less than daily	
Blood tests, radiology per protocol	✓ If performed in relation to initiation or cessation of the therapy/monitoring; include the number of occurrences (e.g. one chest X-ray after intubation)	✓ If performed on a following day during therapy/monitoring; include the number of occurrences per day (e.g. all blood tests during one day of ECMO as per protocol)	x	
Standard materials in larger units, used in many modules	x	x	✓ In standard care day module (e.g. disinfecting fluids, plaster rolls)	
Medication, blood products and infusion fluids	x	✓ If standard for all patients per protocol	x	
Non-disposable plug-in devices that are used continuously	x	✓ Power consumption in Watts (e.g. mechanical ventilator, ECMO console, etc.)	x	
Other non-disposable products	x	x	x	E.g. non-disposable scissors. Not currently included

PICU = paediatric intensive care unit; ECMO = extracorporeal membrane oxygenation; OR = operating room.

3.1.4 Medication Representation

The pharmacy data were not usable for quantifying medication use since unit quantities were not included in the data structure. Therefore, non-standard medication could not be included in the analysis. The medications that could be included as standard medications in the modules were:

- *Standard care day*: stomach protection (esomeprazole)
- *Arterial line day* and *central venous line day*: anticoagulant (heparin)
- *ECMO day*: anticoagulant (heparin) and prophylactic antibiotics (cefazolin)
- *ECMO continuous renal replacement therapy (CRRT) day:* dialysis solution (phoxilium)
- *Mechanical ventilation start/stop* (intubation): sedative (esketamine), pain killer (fentanyl), muscle relaxant (rocuronium)
- *Mechanical ventilation day:* sedative (midazolam), pain killer (morphine, paracetamol), cardiac support (milrinone)
- *Thoracic drains start/stop* (removal): sedative (esketamine)
- *Thoracic drain day:* pain killer (morphine)
- *Parenteral feeding*: carbohydrate solution (glucose 10%, most common type in the patient cohort)

All other types of medication were not standard for all patients and thus were excluded from the modules. If necessary, a body weight of 4 kg was assumed based on the median weight of the patient cohort to estimate the total required amount of medication per module.

3.2 Module Frequency

Table 4 shows the datasets and metrics used to determine each module's frequency. Therefore, the PICU and operating room admission and discharge times could not be extracted accurately and were manually selected from admissions data.

Table 4. *Metrics from patient records to represent each module*

Module	Dataset and metric	Reliability[a]	Comments	Median frequency
Standard care	Admissions: number of days between start and end of the PICU admissions, minus OR admissions	++	Start and end dates of PICU admission and OR admissions were selected manually	12
Standard material replacements	Admissions: number of days of PICU admission divided by replacement period (7 days), rounded up	++		2
ECMO start	Inserted materials: number of venous cannulas that were in place >12 hours	+-	Arterial cannula was missing in one of the patients, thus venous cannula was chosen. Assumption that cannulas <12 hours were used during surgery only. Manually logged by nurse	1
ECMO day	Inserted materials: number of days between insertion and removal of each venous cannula	+	Manually logged by nurse	3.5
ECMO CRRT[b] start/stop	Observation of ultrafiltrate in fluid balance	++	Does not differentiate between CRRT on ECMO versus on Prismaflex (separate circuit) Manually logged by nurse every ±2 hours	0
ECMO CRRT[b] day	Number of days between first and last ultrafiltrate observation[c]	++	Manually logged by nurse	0
ECMO circuit replacement	Events: number of ECMO circuit switches	-	Manually logged by nurse At least one occurrence is missing	0

			Events are generally not logged consistently	
Mechanical ventilation start/stop	Inserted materials: number of tubes	+	Manually logged by nurse	1
Mechanical ventilation day	Inserted materials: number of days between tube insertion and removal	+	Manually logged by nurse	9.5
Mechanical ventilation circuit replacement	Inserted materials: number of days per tube, divided by replacement period (14 days), rounded up	+	Manually logged by nurse	0
Tracheal suction system replacement	Number of MV days divided by replacement period (2 days)	+	Manually logged by nurse	5
NIVS start/ replacement[d]	Observation of each type of support: number of consecutive observation series with < 24 hours between observations	+	Manually logged every ± 2 hours; Blanks were assumed to be oxygen therapy (based on the low oxygen flow in blank entries); Several description options per type	0
Aerosol therapy day	Medication administration of aerosol medications	?	There may be other types of medications that were not included Not logged in another way systematically, thus not verifiable retrospectively	1.5
Enteral feeding day	Medication administration of all enteral nutrition types (number of unique days)	?	Not logged systematically in another way, thus not verifiable retrospectively	9
Parenteral nutrition	Medication administration of all parenteral nutrition types (number of unique days)	?	Not logged systematically in another way, thus not verifiable retrospectively	6
Catheters	Inserted materials: number of each catheter type[e]	?	Not logged systematically in another way, thus not verifiable retrospectively Manually logged by nurse	various
Catheter system replacements	Inserted materials (number of days / max. period of use, rounded up)	?	Manually logged by nurse	various
Lab tests	Lab results: number of unique time points, grouped based on materials[f]	?	All blood and viral tests should be included, although not verifiable due to large numbers; Cultures were not included; Only type of blood (arterial, venous or capillary) is described in data	various
Radiology[g]	Functional diagnostics: number of occurrences per type	++		various

(a)Reliability was assessed based on how well the extracted data corresponded with reports in the patient's medical record,? Means that the reliability could not be determined; (b) CRRT = continuous renal replacement therapy; (c) To check whether CRRT occurred during ECMO treatment, observations were filtered based on the start and end time of ECMO therapy; No differentiation was made between separate CRRT runs because it did not occur more than 1 time per patient based on reports in the medical records; (d) Non-invasive ventilation, Optiflow or oxygen therapy; © Catheter types that were surgery-specific were excluded, and pacemakers were excluded because the 2 out of 3 were missing (f) Blood tests were grouped as follows: blood gas, blood coagulation, capillary blood and other (assumed to be arterial) (g) Radiology was not a module, but the median frequency of each modality was calculated.

3.3 Module Weight

Figure 4 shows each module's consumable weight (kg) per occurrence. In the modules with the highest weight, the largest contributing products are shown in Table 4. The *ECMO CRRT day* module and the *parenteral feeding day* module involved large units of medication that comprised most of the modules' weight: haemodialysis solution (5 L) and glucose 10% (500 mL), respectively. For the haemodialysis solution, the standard infusion rate per protocol was 25 ml/kg/hr, which would, assuming a body weight of 4 kg and replacement every 24 hours, result in a total of 2.5 L per day and thus 50% waste. For glucose, 10%, the mean infusion rate in the patient cohort was 48 ml/day, and hence, 90% was wasted. There were several types of parenteral feeding with carbohydrates, but glucose 10% was the most common option in the patient cohort.

Table 5. Hotspot modules and large volume medication waste

Module	Product[a]	Description	% waste
ECMO CRRT day	Phoxilium bag 5L[b] (5.1 kg)	Haemodialysis solution	**50%** (based on standard 25 ml/kg/hr per protocol)
ECMO circuit replacement	Priming set MiniLung[c] (3.4 kg)	Pre-packaged kit containing most materials for priming of an ECMO circuit	N.a.
ECMO start	Priming set MiniLung[b] (3.4 kg)	Pre-packaged kit containing most materials for priming of an ECMO circuit	N.a.
ECMO CRRT start/stop	NaCl 0.9% 1L (1.0 kg)	Fluid used for priming of the CRRT circuit	N.a.
Parenteral feeding day	Glucose 10% 500mL[b] (0.6 kg)	Carbohydrate solution for intravenous feeding	**90%** (based on mean infusion rate of 48 ml/day in patient cohort)

(a) Based on patient weight of 4 kg and replacement every 24 hours; (b) most common in the patient cohort; (c) based on median patient weight of 4 kg in the patient cohort

3.4 Carbon Emissions Analysis

For some products, the exact materials could not be identified. In those cases, a general material type (e.g. plastic, metal) was recorded in the product database. Production processes could not be included in the analysis based on the currently available product data. Hence, only the CE of the materials themselves could be included. Idemat did not provide emission factors for all materials in the product database. An overview of the EFs that were used and which ones were not available is shown in Appendix A. The following assumptions and approximations had to be made:

- *Plastics*: a mean EF of all identified plastics was used for all plastics since some were unknown and the differences in EFs between types of plastic are relatively small.
- *Metals*: an average of the available EFs was used, excluding silver, which was much higher than the other EFs.
- *Glass*: Borosilicate glass was assumed.
- *Medication:* the EF of ultrapure water from EcoInvent 3.10.1 was used as a proxy for all medication.[29] No reasonable proxy was available in Idemat.

The CE per module per occurrence are shown in Appendix B. The hotspots regarding CE per occurrence were *ECMO CRRT start/stop, urinary catheter start/stop, mechanical ventilation start/stop, ECMO start* and *ECMO circuit replacement*.

3.5 Case Study Hotspots

Figure 5 shows the weight across the CP (weight per module x median module frequency, in kg), aggregated to the care elements. The median material impact of the total CP in the current case study was 29.5 kg of consumables, including primary packaging. The standard care modules had the highest combined weight. Primary packaging made up 14.0% of the total material consumption. The influence of packaging was most prominent in the ECMO modules, mainly due to the *Xenios MiniLung* ECMO priming kit, which has multiple layers of packaging. However, only the weight of the most prominent products in the kit could be determined. Therefore, the actual relative packaging weight is lower.

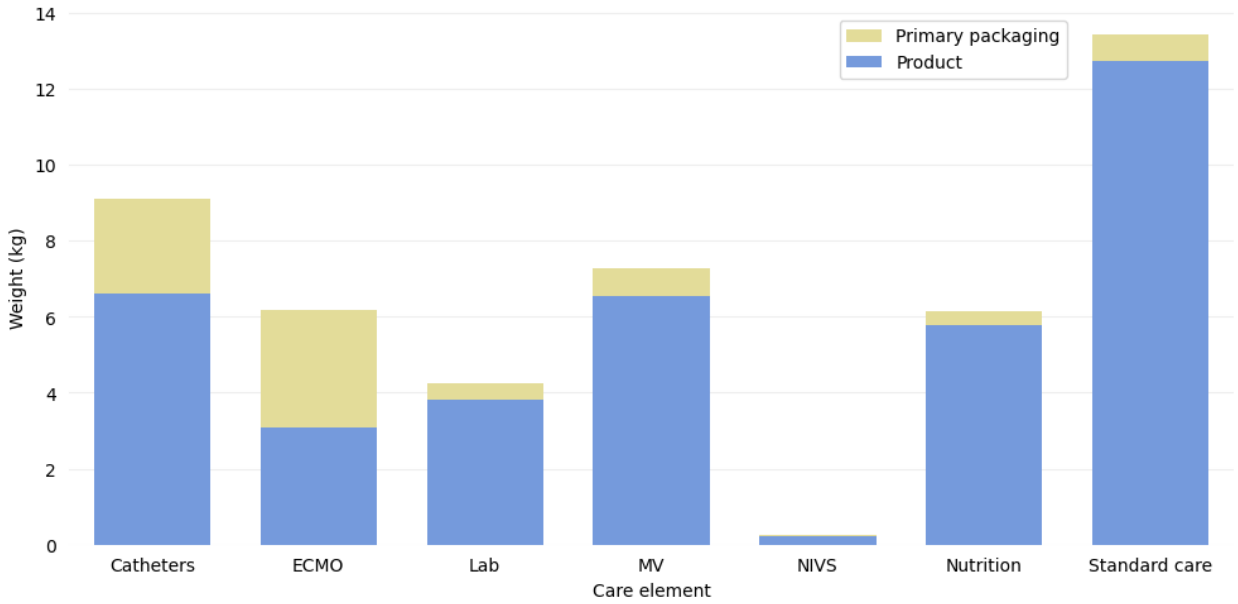

Figure 5. *Median material impact (kg) across the PICU clinical pathway in the case study. ECMO = extracorporeal membrane oxygenation; Lab = laboratory diagnostics (sample collection only); MV = mechanical ventilation; NIVS = non-invasive ventilatory support.*

The five hotspot modules in terms of weight and CE are shown in Figures 6 and 7, respectively. Standard care had the highest total weight in this case study. The median admission duration, and thus the standard care day module frequency, was 12 days. Mechanical ventilation was associated with higher CE than weight due to the relatively high electricity consumption. The module with the highest median frequency was blood gas (91.5 occurrences), other blood tests (28.5 occurrences) and blood coagulation tests (19.5 occurrences). ECMO CRRT and sputum, urine and faeces tests each occurred in only two out of six patients, rendering the median frequency of these modules zero. The median frequency of each module, the weight per occurrence and the total weight across the CP (i.e. the product of the former two) are shown in Appendix C.

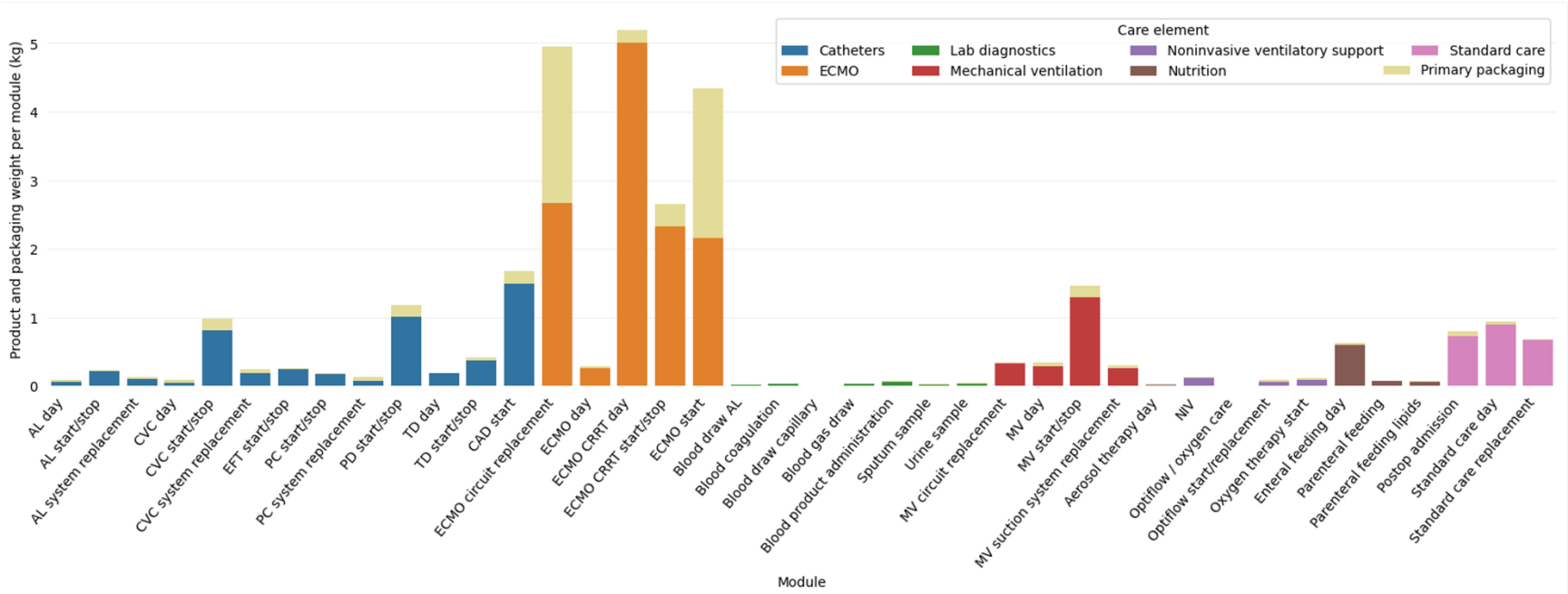

Figure 4. *Consumable weight per module per occurrence. Yellow bars show the contribution of primary packaging to the total weight. AL = arterial line; CVC = central venous line; EFT = enteral feeding tube; PC = peripheral line; PD = pleural drain; TD = thoracic drain; CAD = urinary catheter; ECMO = extracorporeal membrane oxygenation; MV = mechanical ventilation; NIV = noninvasive ventilation.*

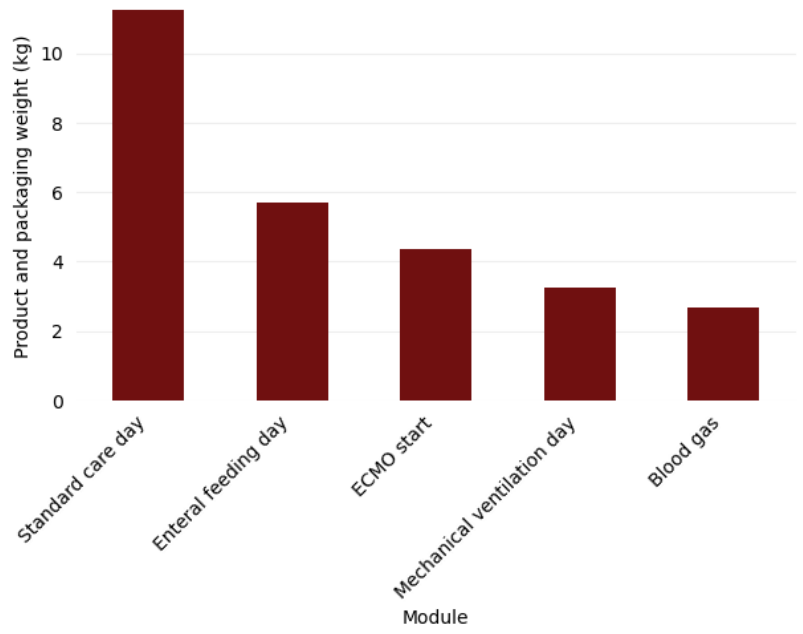

Figure 6. *Modules with the highest median associated consumable weight (kg) across the clinical pathway of the patient cohort. ECMO = extracorporeal membrane oxygenation.*

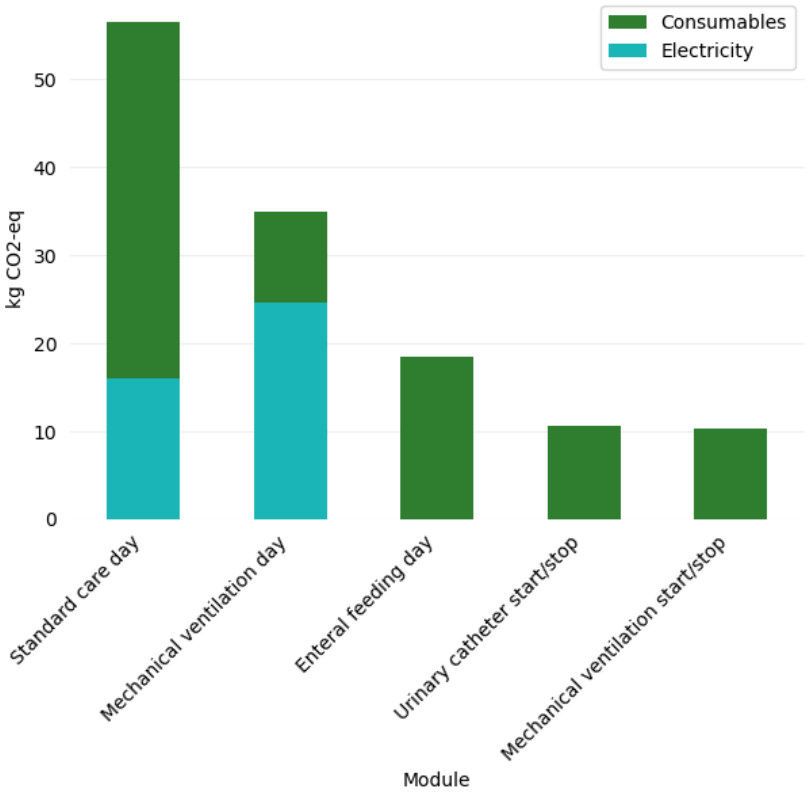

Figure 7. *Modules with the highest median associated emissions (kg CO_2-eq) due to consumable and bedside electricity use across the clinical pathway of the patient cohort. CO_2-eq = CO_2-equivalent.*

4 Discussion

4.1 Summary

This research aimed to lay the groundwork for a new scientific framework to analyse the EI of CPs. It was an attempt at tackling challenges around EI analyses in healthcare: (1) the complex CP definition due to interpatient variation, (2) the time and human resources to perform these analyses, (3) the availability of accurate data representing medical processes in CPs, (4) the fact that financial costs are not necessarily representative of EI in healthcare. The representation of medical events in CPs through modules makes the CP definition flexible to account for interpatient variability, and they are reusable, which saves time and effort during future analyses. Each module encapsulated the direct medical consumable and electricity use associated with specific care events, as defined through medical protocols and clinical staff input. A bottom-up, process-based approach, instead of a top-down, spend-based approach, can provide accurate insight into resource use at the CP level.

Idemat was evaluated as a source of impact factors to determine the carbon emissions associated with each module. EHR data was analysed to identify reliable datasets to represent the occurrence of the modules in the CP. Method development and application to six cardiac surgery patients were performed simultaneously to ensure the method fits the practical possibilities. The modules were applied to the case study by determining the frequency of each module per patient across the CP. Integrating EHR data, modules, and a product database provided insights into EI hotspots in the chosen CP. This study focused on developing the CP analysis with modules and exploring data availability and validity usability. Further development of results and inclusion of more processes and sources of EI is necessary and possible in the current structure. The case study provided a first glance at hotspots of EI across the CP of cardiac patients in the PICU. The limitations of the underlying emission factors and the simplified impact analysis limit the extent to which conclusions can be drawn from the carbon emission results. Nonetheless, the modules, product and electricity databases and the analysis algorithm can serve as a foundation for a scientific EI analysis method and hotspot identification in complex and variable CPs.

4.2 Comparison with Previous Literature

Previous research (methods) on the EI of healthcare and CPs is limited since this is a relatively new field of research. A few previous studies have used the LCA framework for EI analysis of CPs. Zhang et al. performed a spend-based LCA using diagnosis-related group (DRG) accounting data, which encompasses all costs associated with hospitalising a specific type of patient. This way, more processes, departments and sources of EI were included in the analysis than in the current study. An existing data (infra)structure like the DRG can be a valuable basis for developing a scalable and generalisable method for hotspot identification and monitoring of EI of CPs. However, this spend-based analysis has not been validated, so the representativeness of these financial data is unclear. Furthermore, the data were often too aggregated to give detailed and transparent insight into processes in clinical practice.[19,22] McGain et al. performed a hybrid LCA, using financial data when process data was unavailable. This study showed a systematic error between spend-based and process-based results, which underlines the uncertainty around using both data types.[7] The current approach is solely process-based, eliminating this problem. Hunfeld et al. performed a top-down material flow analysis using department-level procurement data. The results gave clear insights into consumption at the product type and material level. However, due to the top-down approach, it gave no insight into CPs and processes

associated with the consumption.[14] Hence, the current bottom-up approach has more potential to guide interventions on those levels.

Two published studies have performed bottom-up, process-based CP analyses. Both studies' data on medical events were solely based on medical protocols. Furthermore, the CP modelling approach in these studies did not account for interpatient variation sufficiently to be used for PICU CPs. Furthermore, the CP representativeness of the CP models in these studies was not verified through real medical data or by clinical staff. Lastly, none of the previous studies provided reusable and expandable databases and data analysis algorithms.[19,30,31]

4.3 Strengths and Limitations

4.3.1 Module Development Process

The current CP analysis was a simplification of medical practice, which is a complex system influenced by many medical, practical and human factors. However, measures were employed to ensure that the modules represented medical events in the CP as accurately as possible.

Firstly, stakeholder involvement was integral to the module development and the subsequent data analysis. Collection and assessment of medical, electricity and product data were done in close collaboration with nurses, intensivists, technical physicians, and care assistants. Engaging the professionals directly involved in patient care as early as possible proved invaluable, saving time and reducing errors. Nurses and intensivists highlighted when clinical protocols were outdated and provided information on current product use. They also highlighted the personal preferences of staff members for specific products. In those cases, the chosen product option in the corresponding module may not have been the most common. This underscored that protocols alone are not a representative basis for module development. Procurement staff and PICU management were also consulted to identify potentially valuable data sources. These collaborative discussions provided critical insights into care workflows, product utilisation, and interpatient variation, ensuring that the methodology accurately reflected clinical reality and practical considerations.

The development and refinement of the module set was an iterative process, evolving through multiple revisions to ensure alignment with clinical practices and accurate representation of material usage. For example, deciding whether to include specific activities, such as blood draws, within certain modules required careful consideration to avoid double counting. Similarly, the identification and allocation of products within modules were refined to address challenges such as varying replacement frequencies. Replacement modules were introduced to account for periodically replaced materials, such as the ventilation circuit. This ensured accuracy by avoiding underestimations or overestimations. Each iteration improved the robustness of the methodology, ensuring that the module-based approach accurately captured the variability and material impact of ICU care.

4.3.2 Scope

Not all medical events in the cardiac surgery CP could be included in the modules. Certain care elements were excluded from this study for one of two reasons: either the included patients did not receive this type of care, or the occurrence of these events could not be reliably extracted from the EHR. Some modules had to be adapted to align with the available medical data; for instance, in the ECMO day module, blood cultures were included because these could not be extracted from medical data. Lab tests that could be extracted consistently were placed in a separate module since they also occur independently of ECMO. This separation

improved the consistency of the modules but also introduced fragmentation; when analysing a single module in detail, it may be necessary to reassess whether all desired elements are included within the module or if a combination of modules is required to capture the events and their associated EI fully. For example, for a complete image of the impact of an ECMO day, all blood test occurrences during ECMO need to be considered.

The study focused exclusively on the PICU scope, but separating PICU and OR care was complex due to overlapping types of care and multiple OR admissions within a single PICU pathway. For each module that could have occurred in both the PICU and the OR, the events were filtered based on the start and end times of surgeries. This separation may have skewed module frequency results where the two overlap, such as the *thoracic drain* and *ECMO start* modules. All patients in the current cohort were cannulated via an open sternum. This type of ECMO cannulation and decannulation happens in the OR and is performed by a cardiothoracic surgeon. Therefore, cannulation materials and the cannulas themselves were excluded from the module. Hence, the *ECMO start* module's consumable weight was much lower than in the case of percutaneous cannulation performed in the PICU by an intensivist.

Several sources of EI were excluded from the scope. Non-disposable items, for example, were excluded because analysis of their EI would require allocation of the EI of their lifespan, which was not currently feasible. Electricity consumption of devices on standby was also not included since this is not attributable to a single patient. However, as shown in previous research, this might be substantial for both bedside devices and radiology.[26,32] Other excluded sources included remote energy consumption (e.g., HVAC systems, computers, and lighting) and higher-level processes beyond the direct CP. Consumption data on these sources of EI are only available at the hospital level. Therefore, including these factors would require allocation to a single patient. These sources of EI have been included in previous research in several ways, although no method has been validated.[7,22] It is debatable to what extent the inclusion of these factors, which are not directly associated with individual patients or CPs, should be included in a CP-level analysis. Clinical staff and green teams usually do not control remote energy, administrative processes and infrastructure. Therefore, it may be more effective to analyse, monitor and tackle these EI sources at the department or hospital level. On the other hand, including more processes can provide more perspective on the relative EI of consumables and electricity within the healthcare system.

Medication was included only when it could be standardised in one of the modules. Due to the many medical and non-medical factors that determine medication use, this was very limited, and assumptions had to be made. For example, cefazoline (a prophylactic antibiotic) was included in the *ECMO day* module because transthoracic ECMO is only possible with an open sternum, which is an indication for cefazoline. However, closure of the sternum does not necessarily happen simultaneously with ECMO decannulation and is not logged systematically. Thus, there is a possibility of underestimation of cefazoline use. An overestimation of medication use is likely in the drain day module. This module counts one syringe of morphine per day per drain. However, multiple drains are usually in place simultaneously, requiring only one syringe per day in total. On a single module or medication level, errors like these may be negligible, but the cumulative error due to assumptions like this should be considered.

Pharmacy data on medication preparation per patient was currently not usable for analysis of medication weight or volume because the total amount of prepared medication was often missing. This analysis would require the identification, collection and weighing of each variation of each type of medication, which was currently not feasible.

4.3.3 Product, Electricity and Impact Analysis

The product analysis had a few limitations. Firstly, only primary packaging was included in the weight, while secondary and tertiary packaging weight may be substantial. Secondly, packaging weight was estimated for most products since unpacking them would render them useless for clinical use. Thirdly, the contribution of each material to the total weight was estimated for most products since taking them apart would render them useless. Manufacturer information provided minimal information on product composition. Lastly, the exact type of material (e.g. type of plastic, metal, etc.) was not always traceable, making assumptions necessary. However, the difference in impact between types of plastic, e.g., types of plastic, is relatively low, limiting the effect of assumptions on the results.

Data on electricity consumption and scan duration from the radiology department could not be obtained. These data were, therefore, extracted from Australian research on the electricity consumption of radiology. These may, however, be different in the radiology department of the EMC Sophia Children's Hospital.

Idemat did not cover all materials in the product database. Therefore, no complete analysis of the EI could be performed. The EcoInvent impact factor database was used to obtain a proxy impact factor for medication since Idemat did not provide suitable data. EcoInvent could further supplement the Idemat data, but it does not solve the missing data problem, especially regarding medication. Furthermore, EcoInvent is not open-source and does, therefore, not comply with one of the main requirements of the new method. Thus, the impact factors provided in Idemat could be an underestimation in the case of the EI of medical products. Another option would be to use the open-source HealthcareLCA database, containing the results from published healthcare LCAs.[33] However, this database does not (yet) have a quality assessment, leaving the accuracy of the data unknown, and it does not provide location-specific data. When this database does introduce an integrated quality assessment, it may be reconsidered as a data source.

The current analysis covers only part of the total EI of products, as only the impact of the materials in the products was included. This makes the current approach less rigorous than LCAs, in which all processes from raw material mining to waste treatment are included. The EI of the production of medical products may be significant due to resource-intensive processes such as sterilisation. Robust LCAs of medical products will be necessary to gain more insight into the contribution of these processes. This will, however, require data about production processes from manufacturers and their suppliers.

The only included impact category was carbon emissions (i.e., climate change). This was chosen pragmatically because it is the most common impact factor and because the selection of other impact categories is not clear-cut. However, it might be relevant to include other impact categories that are substantial in healthcare, such as freshwater use or ecotoxicity.[14,34] Human toxicity could also be considered since this endpoint impact factor highlights the adverse health effects of the EI of healthcare. However, these endpoint impact categories are based on more approximations and assumptions.[35] Therefore, sticking to the most direct impact categories, such as carbon emissions or simply material weight, may be the most reliable approach.

4.3.4 Medical Data Analysis

Accurate representation of the occurrence of the modules in medical data was a priority in this research. Medical data collection and analysis were revisited throughout the process, with methods and datasets refined to address gaps or inconsistencies identified during preliminary analyses. The validity of the medical data was assessed thoroughly through manual CP analysis in the EHR. Several datasets were excluded and, if possible, replaced with an alternative. For example, a dataset containing all billed events per patient covered

many medical events, but because of a registration lag and no documentation of the location or date of the event, the events could not be linked to the chosen PICU admission. Currently, no data quality metrics were used since the patient cohort and dataset size were deemed too small to do so. Modules with limited consumable use and no reliable representation in the medical data, such as external pacemakers, were excluded. For ECMO circuit replacements, the data source was unreliable, but the module was included nonetheless because of the high consumable use per occurrence.

The module frequency analysis was heavily based on time points in the medical data. These time points in medical data may not be accurate and may have influenced the results. The time point-based analysis may have especially influenced the results of the blood test modules; multiple blood tests may have been registered at the same time point and thus counted as one test.

4.4 Implications of the Case Study Results

The very small sample size should be considered when interpreting the case study results. They should be regarded as a proof of concept rather than an absolute truth. A larger patient cohort is crucial to better represent the CP, especially given the large variation between PICU patients.

Standard care was the most significant hotspot in the case study. That is mainly due to the high frequency of this module, which is, per definition, equal to the number of PICU admission days. ECMO and CRRT have the highest impact per occurrence. However, CRRT had a median frequency of zero. This indicates that the patient cohort was too small to represent rare events such as CRRT accurately. Several other events that potentially involved substantial material use have been excluded entirely because they did not occur at all. This was the case with parenteral feeding with lipids, for which all tubing must be replaced daily. A larger patient cohort may provide a more comprehensive set of modules. It is furthermore important to note that, at the PICU level, ECMO and CRRT are relatively rare events (30-40 ECMO patients per year estimated). Since standard care broadly applies to other patient groups, the total impact of standard care for the entire PICU could be much higher.

A larger sample size would enable comparison between subgroups. In the case of cardiac surgery patients, subgroups could be made based on clinical measures to differentiate between complex patients and less complex patients. Currently, patient weight or age was not a selection criterion. Adding one of these could improve the accuracy of the analysis, considering the weight-dependency of medication use and, in some cases, material use. The weight used for the analysis, including the number of medication units in the modules, should be adapted to the median or mean weight of the patient cohort in future studies.

The module weight was exceptionally high in modules with large medication units, such as CRRT and parenteral feeding. An alternative would be to choose prefilled bags of these medications, which must be replaced only once every 7 days. No prefilled version of glucose 10% was present in the medical data, which may indicate that this does not yet exist or that it is not prescribed. Efforts should be made to promote better use or production of these prefilled bags.

4.5 Application in Practice

Key users of this methodology and its results would be the green team of the Sophia Children's Hospital. This is a group of clinical staff members of varying disciplines (intensivists, nurses, technical physicians, etc.). The structure and names of the modules were designed with the expertise of all clinical staff members in mind to enhance usability. However, given the PICU's complex and highly specialised nature, a different results

structure might be necessary to collaborate effectively with non-medical stakeholders such as procurement staff. This could be done by highlighting and visualising specific products that contribute significantly to the overall impact of a module.

The module development flowchart and product allocation rules provide guidance when adding new modules. The standardised module structure (Figure X) and product allocation rules (Table X) enable the comparison of hotspots over time and between hospitals, which, in practice, can ignite the exchange of best practices and interventions. Figure 8 shows the general process when applying the method to a different CP.

The modules also provide a chance to review products for each event. Personal preference or habit of using certain materials varies between clinicians. By modelling different combinations of products, the medical team can assess whether choosing the product with the lowest impact as the standard would be worthwhile or whether personal preference is more important. The submodules can be used to see the exact indication of use of each product within the module. By grouping products on the submodule *Medication*, one can see the total impact of medication across the CP.

Future use of the model in other patient groups will require alterations or additions to the data analysis algorithm, especially if new modules are to be added. This requires a staff member with adequate skills in Python. Some aspects of the data analysis could currently not be automated, which might be a barrier to applying the model to other, larger patient cohorts.

A dashboard with a simple user interface could significantly improve the usability of the model and remove barriers to using the model routinely. This may guide the correct use of the product allocation rules to prevent errors. The newly published Microsoft Excel-based PROMEZA tool has a dashboard where products and their general material composition can be filled in with an underlying analysis algorithm.[36–39] While highly accessible, this tool is unsuitable for complex and variable PICU CPs.

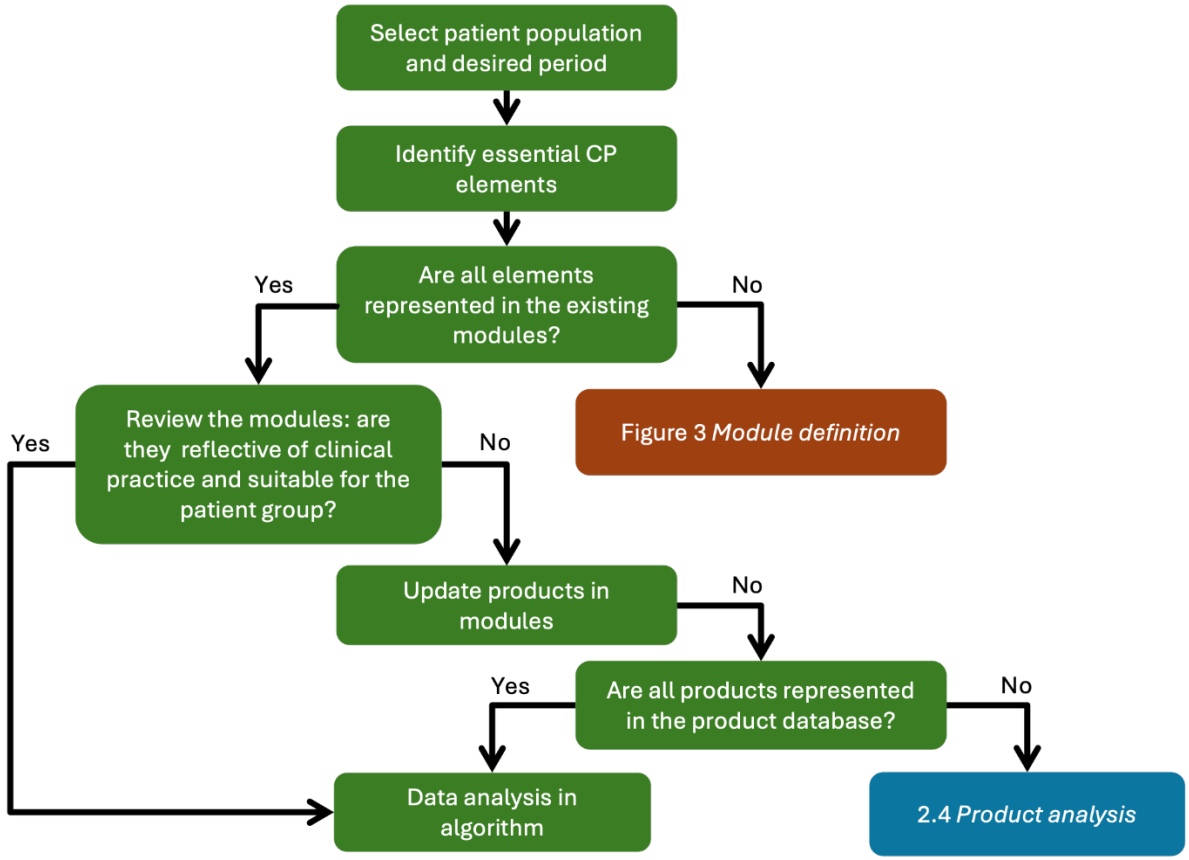

Figure 8. *Flowchart showing the intended process when applying the method to a new patient group*

4.6 Future Recommendations

Testing the current module definition rules, product allocation rules and data analysis algorithm on other CPs would help ensure their applicability and identify necessary adjustments. By refining and generalising these methodologies, the approach can better accommodate the nuances of different CPs.

Including non-standard medication in the analysis would be crucial for a comprehensive overview of medication use in the CP. The usability of medication administration data from the EHR and pharmacy data should be studied further. The most efficient approach would incorporate total volume and packaging type into the pharmacy data structure. However, these data do not reflect all medication since prefilled medication use – a substantial part of all medication use - is not included in the pharmacy data. A combination of pharmacy and medication administration data from the EHR could also provide insight into post-pharmacy medication waste, although both data structures are currently unfit for analysis. At the EMC, research on medication weight and EI is ongoing. Using these findings after publication could be considered in the future.

Including surgical events – which also involve high consumable and electricity use - would be an obvious expansion of the medical scope of the analysis.[38,39] Other expansion options would be the clinical pharmacy and the laboratory, given that many PICU processes are closely related to these departments. Including all other involved departments, such as cardiology, would expand the scope from the clinical pathway to the complete care pathway.[20] This could be relevant since the PICU is not necessarily the most significant hotspot at the care pathway level, as previous care pathway analysis has shown.[22] However, it should be up to the

Green Team, given their goals, mandate and resources, to decide whether expansion to other departments is appropriate.

High-quality LCA would be the only way to validate this research's methodology fully. As this is not feasible, other methods may be considered. Waste audits of each separate module may give more insight into the material used in clinical practice, including mishaps and unused products. This can help validate the contents of the modules or differentiate between theoretical and practical material use. Validation of the impact assessment would be more complicated and require an environmental researcher's involvement. A starting point could be to perform a spend-based analysis of the same products based on the product cost per item. A comparison of the results could give an insight into the difference between process-based and spend-based analyses. This would not directly validate the methodology but could establish a valuable frame of reference by identifying discrepancies and potential biases in both approaches. Another approach could be to perform an LCA or use available LCA data for a sample of products. This could provide perspective on how much the current approach underestimates the complete EI of products and how much the contribution of other life cycle stages differs between products.

Efforts to integrate the product database with procurement data from the PICU cost centre encountered challenges due to incomplete procurement catalogues and inconsistent product descriptions. Future collaboration with the procurement department should focus on standardising naming conventions and linking procurement data, such as through AOC codes, with the procurement data to overcome these limitations. Establishing these connections would enable the alignment of CP and top-down product levels, facilitate a comprehensive overview of alternative products with equivalent functions, and provide data on product impact. Additionally, incorporating this information into existing digital infrastructures could support sustainable procurement practices and streamline future environmental analyses.

Based on the case study results, unit quantities of parenteral feeding and dialysis solutions specific to this patient group should be reevaluated. Significant waste, particularly with dialysis fluid and parenteral feeding, could be mitigated by exploring alternative solutions such as smaller packaging sizes or more extended replacement periods. Collaborating with clinical pharmacists to investigate these options is an essential next step. A larger patient cohort is crucial to gain more comprehensive and reliable insight into the hotspots within this CP and other CPs.

As new insights and data become available, the methods presented here must be further refined to ensure accuracy and relevance. By stimulating the continuous development of these approaches, it has the potential to contribute to sustainable healthcare practices that balance quality patient care with environmental stewardship.

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43.

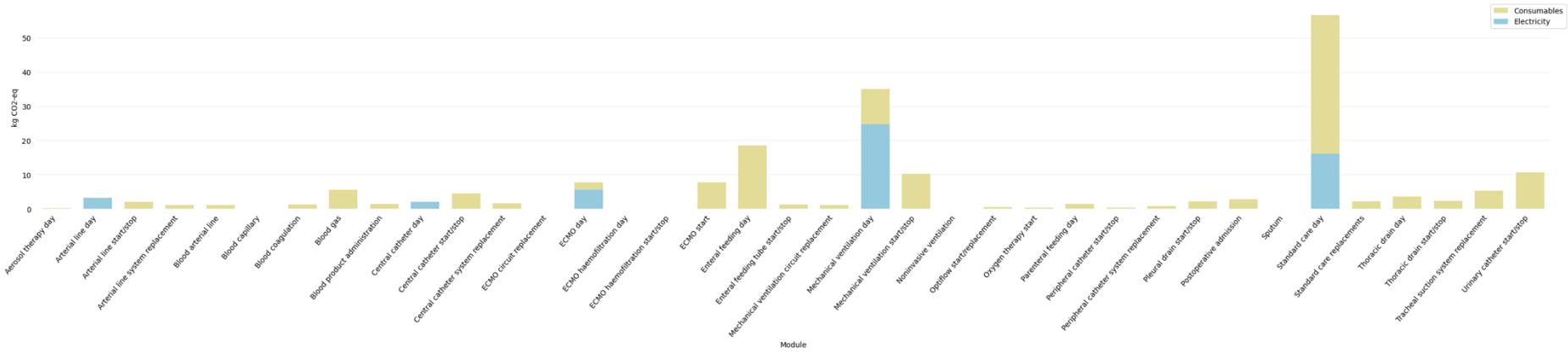
Appendix

Appendix A. Emission factors

Material name in product database	Emission factor (kg CO2-eq/kg)	Emission factor description	Source
Glass	1.906	Borosilicate glass	Idemat V2-3
Cotton	1.006	Cotton, market mix	Idemat V2-3
Electronics	10.584	PCB board, empty	Idemat V2-3
Aluminium	8.679	Aluminium, virgin	Idemat V2-3
Copper	3.817	Copper, virgin	Idemat V2-3
Silver	123.699	Silver, virgin	Idemat V2-3
Tin	16.769	Tin, virgin	Idemat V2-3
Viscose	1.5	Viscose, biobased	Idemat V2-3
PVC	2.25	PVC, market mix	Idemat V2-3
Polypropylene	1.63	Polypropylene	Idemat V2-3
Polyethylene	1.87	LDPE	Idemat V2-3
Silicone	7.28	Silicone rubber PDMS	Idemat V2-3
Stainless steel	5.098	Stainless steel 304, world average	Idemat V2-3
Natural rubber	1.39	Natural rubber	Idemat V2-3
Nitrile rubber	3.57	NBR nitrile rubber	Idemat V2-3
Medication (proxy)	0.006	Ultrapure water RoW	EcoInvent 3.10.1
Petrolatum	Not available	-	-
Hydrogel	Not available	-	-

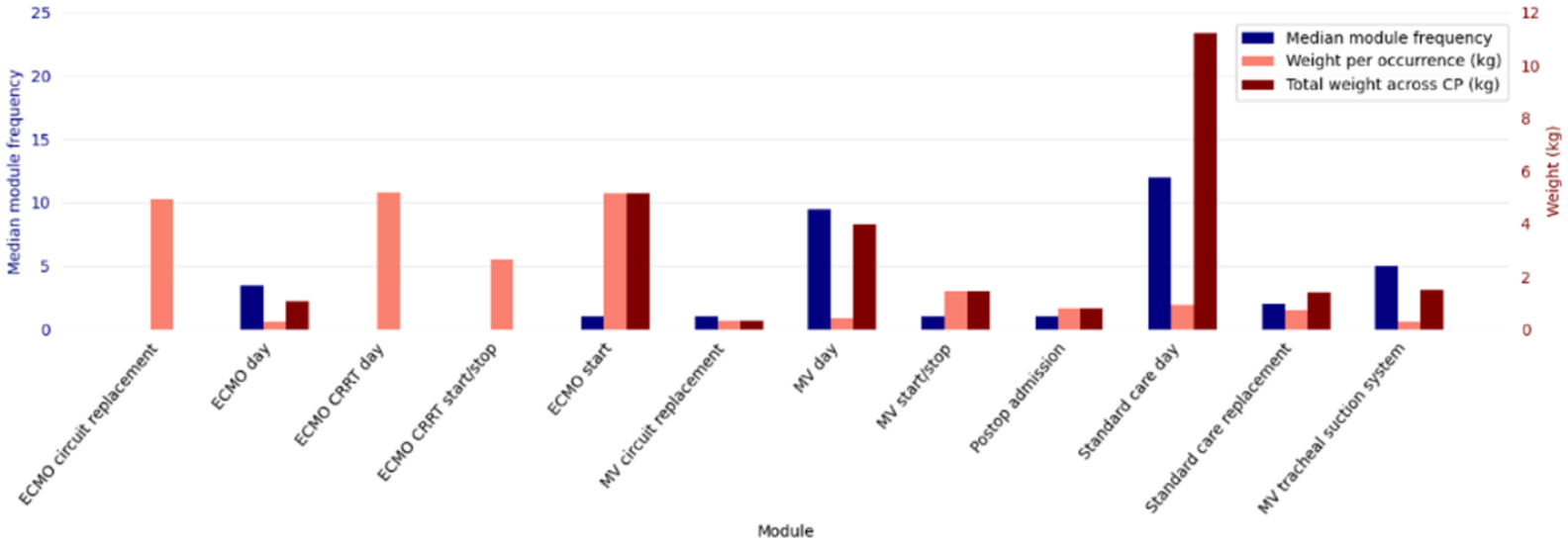
Appendix B.

Impact per module per occurrence in kg CO_2-equivalent)



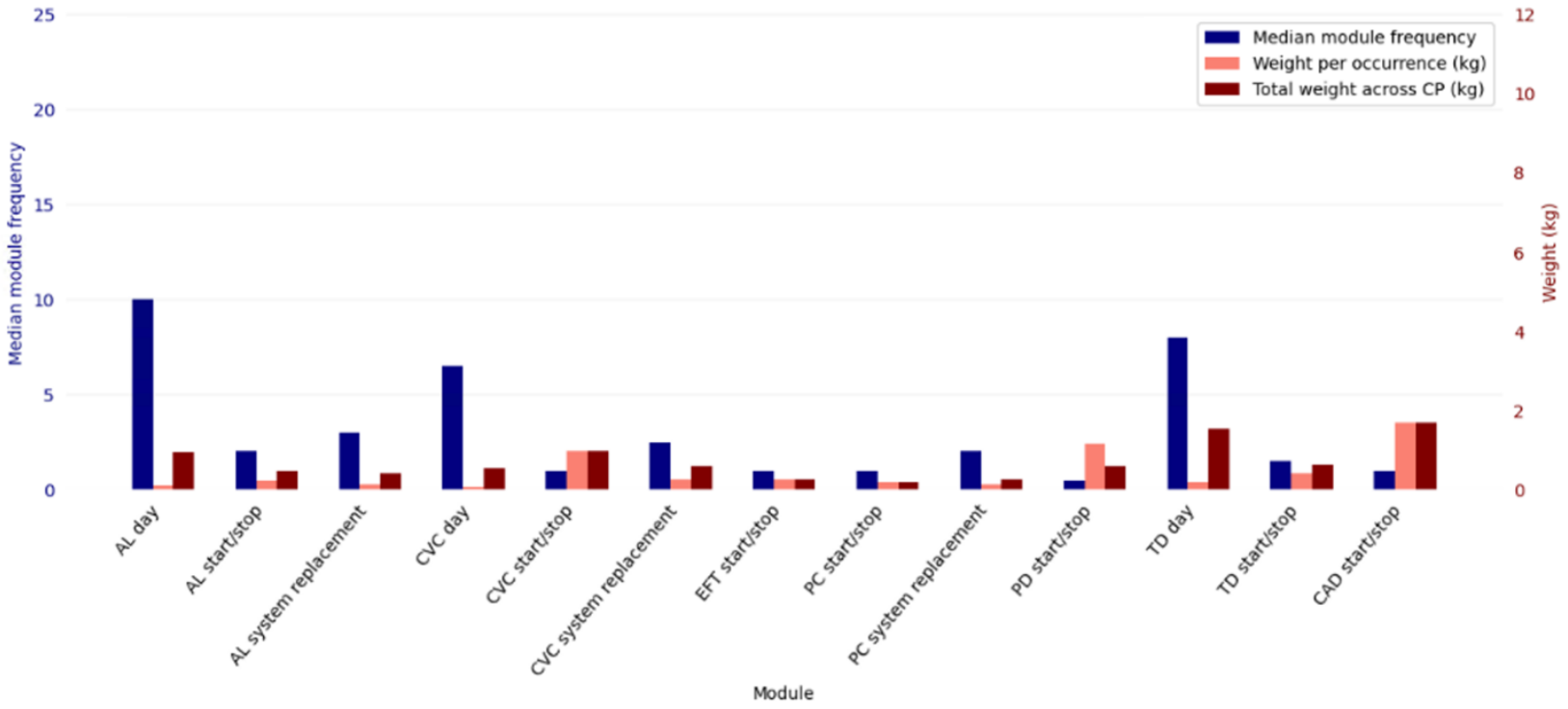
Appendix C. Frequency and weight per module

Appendix C1. ECMO, mechanical ventilation and standard care



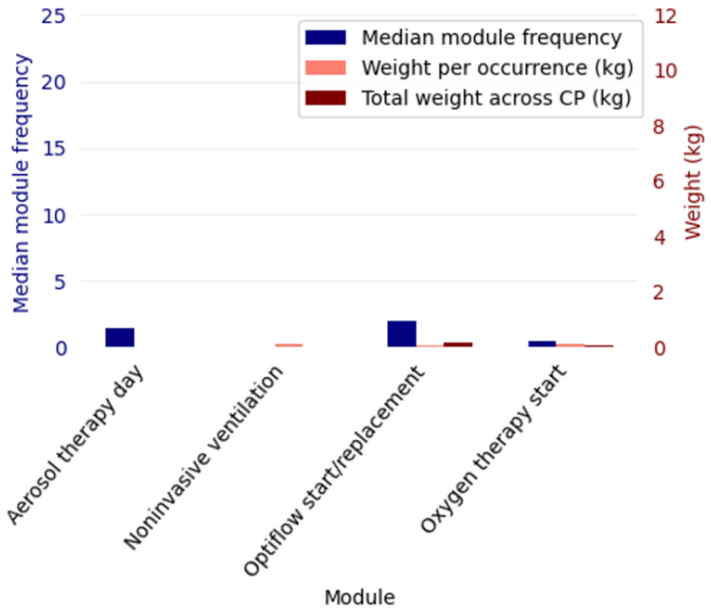
ECMO = extracorporeal membrane oxygenation; CRRT = continuous renal replacement therapy; MV = mechanical ventilation; Postop = postoperative

Appendix C2. Catheters



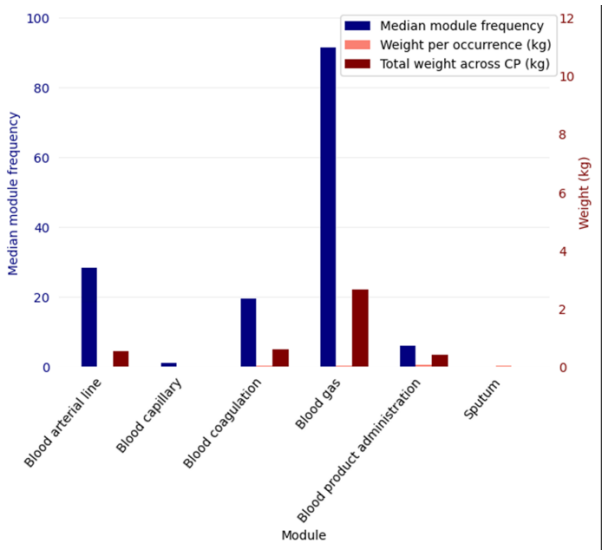
CP = clinical pathway; AL = arterial line; CVC = central venous line; EFT = enteral feeding tube; PC = peripheral line; PD = pleural drain; TD = thoracic drain

Appendix C3. Non-invasive ventilatory support



CP = clinical pathway

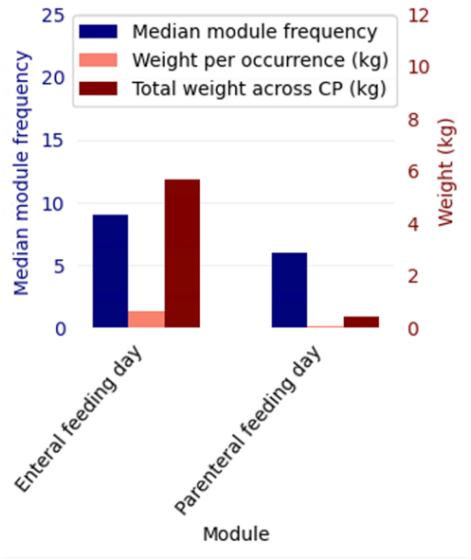
Appendix C4. Lab diagnostics and blood products



CP = clinical pathway

Appendix C5. Nutrition

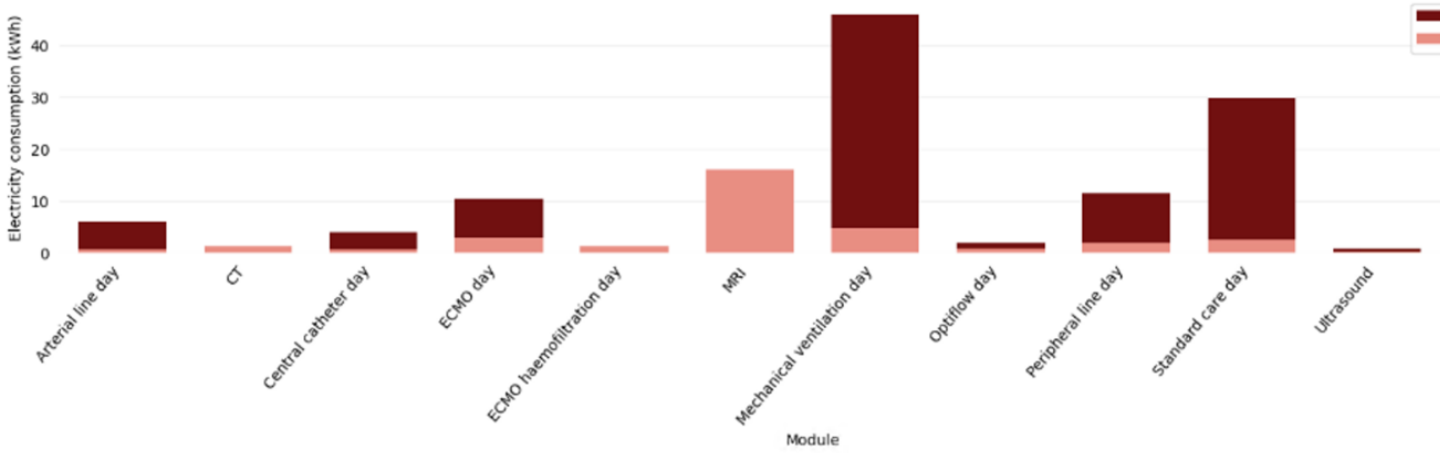
NB: y-axis on the lab diagnostics graph is 4x longer than the other graphs.



CP = clinical pathway

Appendix D.

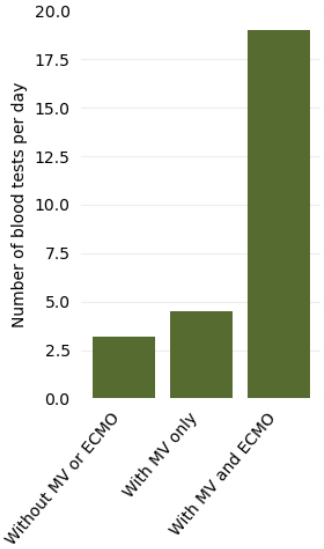
Energy consumption of modules and radiology (per occurrence and median across the clinical pathway in the patient cohort)



CP = clinical pathway; CT = computed tomography; ECMO = extracorporeal membrane oxygenation; MRI = magnetic resonance imaging

Appendix E.

Relationship between number of blood tests per day and general level of care



MV = mechanical ventilation; ECMO = extracorporeal membrane oxygenation