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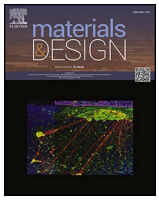

CM3D: A circular materials Multi-Criteria Decision-Making tool for medical devices

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ABSTRACT

The Circular Economy (CE) is fundamental to reducing healthcare's environmental impact. Moving toward a CE requires closing, narrowing and slowing the flow of materials, parts and products involved in the healthcare system. Materials are critical to medical device circularity. Currently, manufacturers' material selection processes focus on cost, logistics, manufacturing and regulation. However they neglect the latter phases of the product life-cycle, impeding the move towards circular materials and products.

We propose a tool for 'circular material selection' in medical devices, using the Multi-Criteria Decision Method (MCDM) to evaluate potential materials. While widely used in other sectors, MCDM is limited in medical devices. The Circular Materials MCDM for Medical Devices (*CM3D*) addresses this gap and considers the entire product life cycle. Stakeholders informed selection of circular evaluation criteria, with the VIKOR algorithm used to rank material alternatives to identify an ideal 'circular' candidate.

A case study demonstrates CM3D's practical application in laparoscopic scissor blades and handles. CM3D provides objective assessment of candidate materials and identifies a tungsten carbide coating for scissor blades and stainless steel for handles, aligning with research literature. Future work will apply CM3D to other medical devices and consider wider implementation within multi-component design cycles.

1. Introduction

Despite its vital role in society, the healthcare sector has a more challenging relationship with the 'health' of the planet. Its mechanisms consume huge quantities, estimated at 100 billion metric tons in 2019 [1]. Only 8.6 % was recirculated back into the economy, generating enormous quantities of greenhouse gas emissions (4.4 % globally) and expel vast amounts of waste directly to incineration and landfill [2,3]. The UK's National Health Service (NHS) adds 530,000 to 1 million tons of annual solid waste annually [4]. This number represents a large portion of the global annual medical waste, estimated at 5.9 million tons. This paradox underscores the urgent need to dramatically improve the healthcare industry's environmental impact.

Sustainability in healthcare is a multi-faceted area in which greenhouse gas emissions and the associated target of achieving 'Net Zero' receive the most attention, as exemplified by ambitious initiatives like the NHS Green Plan. However, there is a growing recognition that reducing resource use and emitted waste are equally important considerations. The most significant waste hotspots in healthcare are hospital operating rooms and intensive care units, which are also the most resource-intensive [5]. An audit revealed that a single operating theatre in the UK NHS produces an estimated 2.3 tons of solid waste annually, with an average of 7.87 kg generated per procedure, equivalent to a week's waste from a household of four [3].

Recently, the Royal College of Surgeons of England, in collaboration with the UK Health Alliance for Climate Change, released the seminal 'Green Surgery' report, the first time a medical association has made a comprehensive and detailed commitment to sustainability [5]. It recognises the reliance of the NHS (and other healthcare systems) on a 'linear economy' of single-use products and the direct consequence of resource depletion, waste and high greenhouse gas emissions [6]. More profoundly, it states that addressing these challenges to meet current policy targets (e.g. NHS NetZero) requires more than incremental change but a fundamental shift towards a circular economy. These

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conclusions are echoed in numerous other studies to minimize healthcare-related waste and reduce carbon emissions [3,7–12].

1.1. Establishing a circular materials selection process for medical devices

Circular Economy (CE) is a principle that limits resource use and impacts on the ecological system [11]. CE approaches are as follows. (1) Narrow the materials flow loop by reducing the quantity of the material. (2) Slowing the loop by sterilising, reusing or repairing. (3) Closing the loop by refurbishing or recycling the medical device at the end of life (EoL) [3].

Material choice plays a crucial role in supporting circularity for medical devices [13]. Materials determine a medical device's durability and ability to be recirculated, remanufactured, refurbished, or recycled [13]. Unfortunately, material selection is a lengthy, complex, expensive process that requires interdisciplinary knowledge [14]. It is interwoven as a critical part of the design process and often involves evaluation of non-commensurable and competing criteria, such as cost vs. performance [15]. Typically, medical device manufacturers select materials predominantly based on criteria relating to early phases of the product lifecycle (i.e. Production and Use), focusing on cost, supply-chain availability, regulatory requirements, and functional performance [14]. However, this precludes later phases of the lifecycle and provides no means to capture the potential value of 'circularity' during materials selection. Thus, there is a need for new tools that can help better guide a 'circular' materials selection process by considering criteria across the full product lifecycle.

1.2. Multicriteria decision method (MCDM) and material selection for medical devices

The general stages in materials selection for medical devices are (1) identifying requirements/criteria (2) identifying potential materials (3) scoring the potential materials against criteria and (4) ranking to identify an 'optimal' material choice [16–19]. A range of methods are available for pre-screening and identification of potential materials, including Expert Opinion [20], Materials Property ('*Ashby*') plots [16], Knowledge-Based Systems (KBSs) using artificial intelligence [21], questionary methods [14], and Case-Based reasoning (CBR) [22]. However, the most crucial and complex stages are recognised as Scoring and Ranking potential materials to find an 'optimal' solution [14]. Here, it is important to recognize that identifying an 'optimal' choice across multiple criteria necessarily implies a need for compromise because it is unlikely that one material will out-perform all others across every criterion being considered [23].

MCDM was selected as the core method in this work because it is widely recognised as a well-established technique for robust decision making in multi-criteria systems. It has been used extensively outside the field of materials selection [24]. In this context, it brings a number of benefits in comparison to other established material selection techniques. Compared to Ashby plots, MCDM inherently handles multiple conflicting criteria (i.e., cost vs. performance) and offers flexibility in incorporating both subjective and objective scoring [14]. Considering KBS, MCDM offers a more flexible definition of criteria for specific applications and is not restricted to data accessibility [25]. Compared to expert opinion, MCDM provides more objective judgment with less bias attributed to objective and measurable criteria [26]. Lastly, considering CBR, which typically uses solutions based on past problems, MCDM is better at preventing incorrect generalization [14]. A final benefit of MCDM is that it provides a scored ranking of alternatives, rather than a discrete 'best' option, thus providing the decision maker with some flexibility [14].

MCDM has seen increasing use and is the most widely used material selection framework because it accommodates conflicting criteria with different units of measurement [27]. MCDM also facilitates scoring and ranking to appraise the proposed alternatives [27]. MCDM has been widely implemented in medical devices for materials or whole device selection. Notable applications of MCDMs include the selection of materials for; reusable and disposable lumbar arthrodesis kits [8], dental crowns [24], pulmonary heart sensors [28], dental instruments [9] and electrocautery appliances [29].

However, the above MCDM examples are focused on specific applications, limiting their translation and do not consider factors of circularity. Work by Mesa et al [13] demonstrates the potential of embedding circularity in materials selection by creating a framework named the extended material circularity (EMC) approach [13]. However, while the framework includes circularity criteria, it is not focused on medical devices and it is targeted at minimising carbon emissions across lifecycle stages, rather than wider goals of circularity [13].

1.3. Research gap

No existing MCDMs specifically cover the application of the circular economy to medical devices. Other potentially relevant MCDMs employ highly specific criteria prohibiting their translation to medical devices and considerations of circularity. There is a clear need for an MCDM tool that considers CE criteria across the complete medical device lifecycle phases and enables robust materials selection to promote circularity.

1.4. Research focus

This paper reports the development and evaluation of an MCDM framework to promote materials selection for circular medical devices. The framework is named CM3D (The Circular Materials MCDM for Medical Devices) and considers the complete medical device lifecycle, from 'cradle' to 'grave'phases. Our approach is based on using MCDM for the assessment of conflicting criteria to facilitate robust materials selection for circular medical devices.

The paper is organised as follows: Section 2 reports the development of the CM3D in collaboration with expert stakeholders, Section 3 evaluates the CM3D in a case study to select materials for reusable laparoscopic surgical scissors, Section 4 discusses the CM3D tool and specific outcomes from the case study, with overall conclusions in Section 5.

2. Development of the circular materials MCDM for medical devices (CM3D) framework

The CM3D framework was developed as part of the UK Engineering & Physical Sciences Research Council (EPSRC) funded 'ReMed' project, a multidisciplinary activity whose remit is advance research into *'a circular economy for small medical devices'* (https://www.remed.uk/). ReMed involves close collaboration with key stakeholders in the small medical device industry, which has acted to inform this research and ensure our outcomes are relevant and appropriate to industry and academia. This section describes the conception and development of CM3D from this foundation and realising a final implementation.

2.1. Approach and scope

The inception of CM3D occurred as the outcome of a medical devices industry stakeholder meeting on 22nd June 2023, which aimed to explore industry needs related to circular medical devices. Participants included stakeholders across the sector, including materials suppliers, medical device manufacturers, regulatory consultants, medical device re-processors and re-manufacturers, and representatives from UK National Health Service (NHS) procurement and policy teams. Research moderators worked with stakeholders to identify key needs, from which a consensus emerged that a) material selection in medical devices is a complex process b) industry require tools to help guide and promote the selection of more 'circular' materials for medical devices. These facets apply to both prospective device design phases and retrospective device revisions.

This provided a starting point for a focussed review of the literature, summarised above, which highlighted the knowledge gap and opportunity for development of an MCDM-based selection framework for circular materials. A concept was then developed for CM3D which employs a multi-stage approach, as shown in Fig. 1, with selection criteria spanning the entire device life cycle. The life-cycle was divided into 5 stages; Stage 1 generates a set of potential materials, Stage 2 identifies relevant criteria to use in assessment and comparison of materials, Stage 3 weights the criteria according to their perceived importance, Stage 4 then scores each potential material against the criteria and applies the MCDM algorithm to rank the materials, concluding with analysis and interpretation of these results in Stage 5 to identify a single preferred material.

Implementing a universal framework which covers all types of medical devices is challenging, because their lifecycles may differ significantly (e.g. with respect to variations in design, use, safety, and regulation). The scope of this work is on 'small medical devices' (aligned to our ReMed project), generally described by Class I and Class IIa devices (MHRA, UK MDR) or Class I and II devices (FDA), which are low to medium risk and have transient contact with human tissue.

The CM3D toolset is designed to be used by development teams with product material knowledge. It should be used to identify where improvements can be made in material sustainability while not impacting medical device performance.

A second stakeholder engagement phase was then convened to develop the CM3D framework. 16 expert stakeholders were invited to participate to provide expertise across the device lifecycle. In brief, this included three materials supply experts, four medical device manufacturers, two medical device remanufacturers, one regulatory expert, five medical device designers, and representation from a medical device trade body. Further information on our stakeholder engagement strategy and membership is provided in the Supplementary (B and C) information. Each stakeholder participated in an interactive online workshop on 22nd July 2024 with outcomes informing the development of each stage in the CM3D framework, as described in the subsequent parts of this section.

2.2. CM3D stage 1: Pre-selection of materials

The CM3D framework's first stage entails selecting a set of prospective materials, defined as 'alternatives' in MCDM terminology, that will be assessed using the MCDM process. Generation of materials alternatives is considered beyond the scope of this paper because it is highly dependent on regional supply chains, company-specific intellectual property, and the application of device-specific expert knowledge to identify candidate materials from large databases based on their

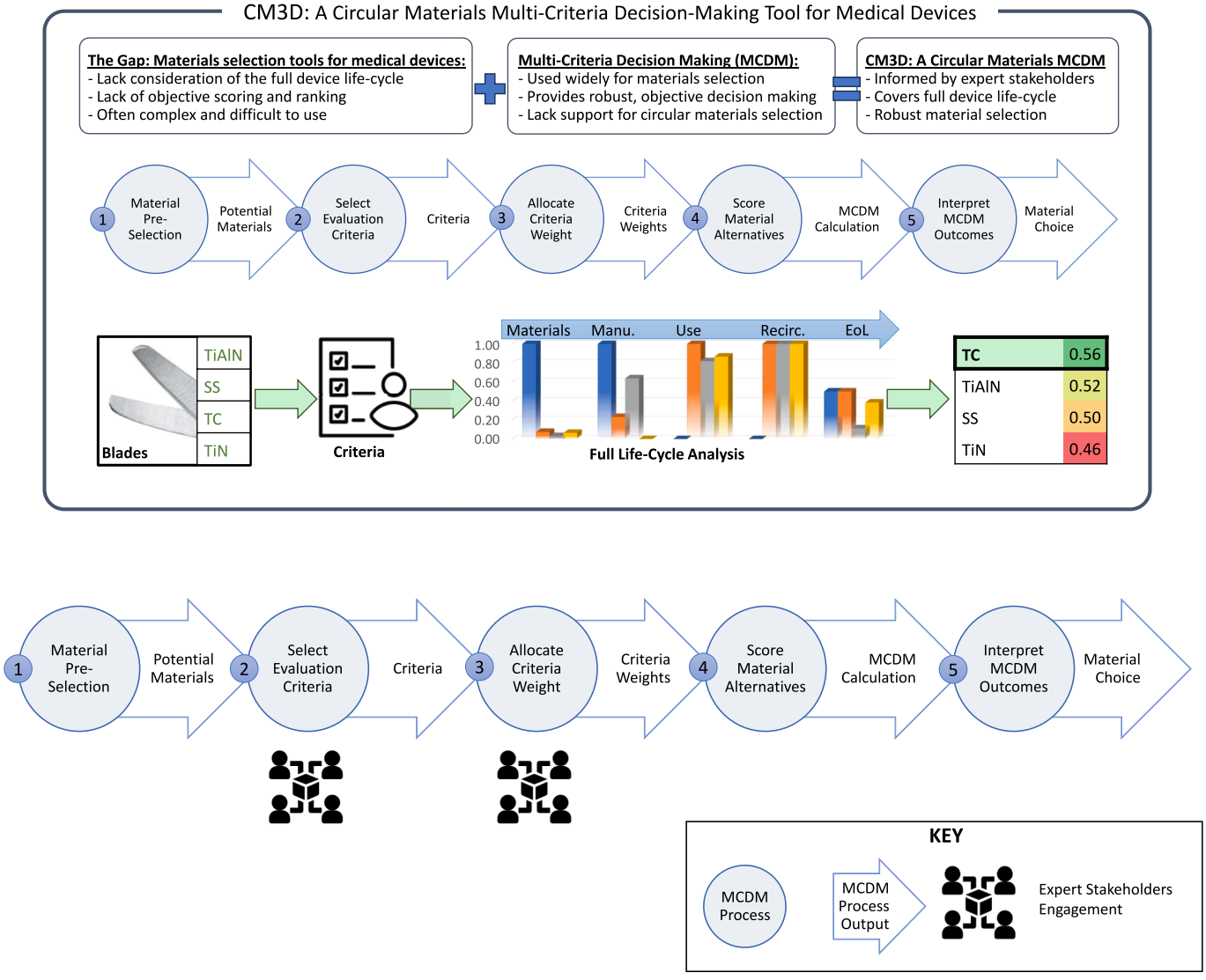

Fig. 1. The development of the circular materials MCDM for medical devices (CM3D).

properties (e.g. Ansys Granta EduPack™) [30]. In the context of medical devices, a key factor used to screen potential materials is their compliance with medical device regulations, encompassing factors such as safety and material standards, which will vary depending on the device Class, and covered by standards such as ISO 13485 and local regulations [31]. At this pre-selection stage, evaluation is a screening process where materials either pass or fail. The outcome from this stage is thus a list of potential materials that meet the preliminary screening (e.g., are compliant with relevant medical device regulations) and can now need to be ranked.

2.3. CM3D stage 2: Selection of proposed criteria

A circular materials decision-making (DM) process should comprehensively cover raw materials resources, production process, energy consumption, economic cost, reuse and recycling, and waste management [32]. Therefore, the selection criteria in the CM3D framework are designed to span the complete medical device lifecycle and are divided into five key phases as described in ISO 14971 (Risk Management in Medical Devices) [33]. The lifecycle phases are shown in Fig. 2; (1) materials supply (cradle), (2) Manufacturing (gate), (3) use, (4) recirculation (circulate), and (5) end of life (grave). The materials supply phase considers factors relating to extraction and processing of raw materials into a form ready for manufacture. The manufacturing phase considers how the processed materials are transformed into a medical device. The use phase then considers criteria relating to functional use of the medical device. The recirculation phase focuses on factors relating to the ability to reuse the medical device. Lastly, the end-of-life phase involves factors that determine the potential future opportunity for the material mass after it ceases to be a medical device.

Criteria were identified for each phase using a multi-stage process. Firstly, a literature review was used to identify potential criteria from relevant studies [13,32,34–40] (available in Supplementary A). The criteria were then reviewed to determine the availability and quality of data sources necessary to objectively score prospective materials in each area. For example, high quality information is readily available on end-of-life environmental impact factors (Ecoinvent, https://ecoinvent.org/database/). Finally, expert stakeholders reviewed and ranked the prospective criteria (in the interactive online workshop) and identified criteria not suited for inclusion in the main MCMD process. These criteria include scarcity, global production, toxicity, and blended percentage. Scarcity was related to abiotic depletion potential, which data is not readily available. Therefore, scarcity was transferred to the pre-selection checklist because it implies a similar meaning to renewability. Global production was removed, considering the stakeholders' suggestion that raw materials should be locally sourced when feasible. Toxicity was also moved to the pre-selection checklist because it needs to be considered firsthand before selecting alternative materials. The toxicity level must meet the regulatory requirements and chemical legislation. The blended percentage refers to parts made as a composite that may impede circular reprocessing or End of Life strategies (e.g. fusing two polymers may prohibit recycling) and which was adopted in the pre-selection checklist.

The finalized criteria from this process are shown in Table 1. Each lifecycle phase has four criteria, each rated highly important by stakeholders, to give a total of 20 areas of assessment. The stakeholder group considered this provided a pragmatic arrangement that captured key aspects of material selection without being too complex to implement in practice. It is notable that some criteria have relevance in multiple lifecycle phases [19,24]. For example, *'cost'* is important in terms of *raw material cost* [24], *cost of manufacturing* [19], *commercial value* (related to profit), the *cost of cleaning and sterilising* [41], and the *cost of recycling* [41]. Similarly, *'resource use'* is relevant at each stage, providing a flexible description that can recognise factors such as energy, personnel, time and material needs. Other criteria are necessarily phase specific, for instance the resource associated with production of raw material feedstock. The selected criteria are discussed in the subsequent sections.

2.3.1. Materials

The 'Materials' lifecycle stages consist of the following sub-criteria: cost of raw materials, quantity, renewability, and production resource.

Cost (of Raw materials) in (GBP/Kg) is an important commercial consideration. Sources: a) Ansys Granta Edupack. b) Material suppliers.

Quantity in (Kg/unit) depends on material density and physical attributes (so it yields the desired functional properties) to minimise mass and thus narrow material loops. Sources: a) device designs

Renewability (production in tonnes/year) is an environmental sub-criterion at the materials stage. Fossil fuel-based materials lead to resource depletion. Choosing renewable sources, i.e., bio-sources or abundant materials would ensure sustainability. Sources: a) Ansys Granta Edupack.

Resource for production can be water consumption (L/Kg) and power consumption (Watt/Kg) to process raw materials. Other measured indicators are the equipment and chemicals used to extract raw materials. Sources: a) Ansys Granta Edupack, b) Ecoinvent software.

2.3.2. Manufacturing

The 'Manufacturing' stage sub-criteria are specified as follows.

Cost of manufacturing (GBP/unit) facilitates different manufacturing methods, which results in different costs. Source: manufacturers.

Machinability (number of units of devices produced per hour, feed rate, or cutting speed) measures the ease with which a machine manufactures materials. Sources: a) Ansys Granta Edupack, b) manufacturers.

Manufacturing Efficiency (the number of output/wastes generated) measures the production efficiency. The minimum waste generated aligns with 'narrowing the loop'. Source a) manufacturers.

Resource for Manufacture (power or electricity (Watt)/Unit produced), and equipment required. Sources a) Ecoinvent, b) manufacturers.

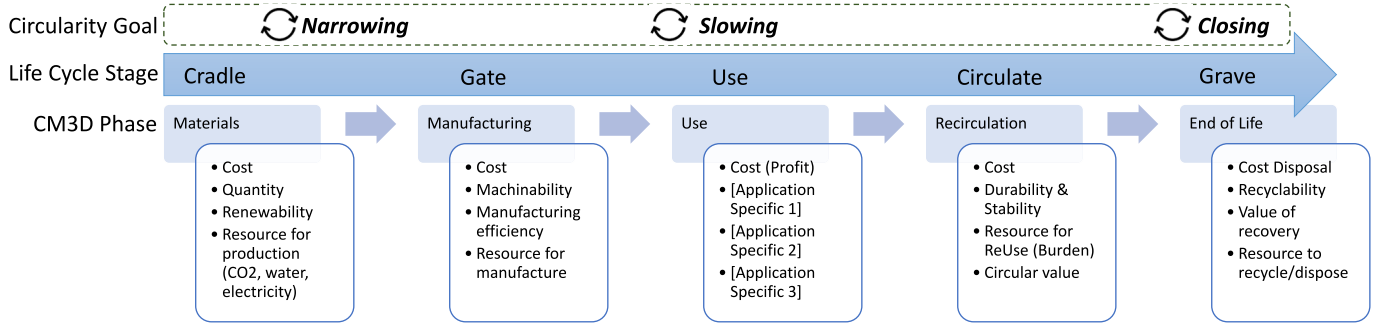

Fig. 2. Criteria are grouped based on Life Cycles. The whole life cycle of medical devices consists of materials (cradle), manufacturing (gate), use, recirculation (circulate), and end of life (grave).

Table 1
The finalized criteria for the circular material MCDM for medical devices (CM3D), the measured indicators, and the resources.

Life Stages	Criteria	Source	Measured Indicators	Units
Materials Supply	Cost (of material)	Edupack	Price	GBP/Kg
	Quantity	Manufacturers guidelines	Amount/unit	Kg
	Renewability	Edupack	Annual world production	Tonnes
	Resource for Production	Edupack	Equipment, chemical, water, power consumption	L/kg (water)
Manufacturing	Cost (of manufacture)	Manufacturers guidelines	Price (PVD, 3d printing, casting or injection moulding)	GBP/unit
	Machinability	Manufacturers guidelines	Unit Produced/hours	Units
	Manufacture Efficiency	Manufacturers guidelines	Output/Waste	%
	Resource for Manufacture	Manufacturers guidelines	Equipment, chemical, water, electricity consumption, energy (casting)	MJ/Kg
Use	Cost (value of part)	Manufacturers guidelines	Price	GBP/unit
	Application specific #1	Edupack	App Specific	App Specific
	Application specific #2	Edupack	App Specific	App Specific
	Application specific #3	Edupack	App Specific	App Specific
Recirculation	Cost (of re-circulation)		Equipment, chemical, water, electricity consumption	GBP/unit
	Durability & Stability		Retain function after multiple use and sterilization	Number of use and sterilize?
	Resource for ReUse (Burden)		Personnel, time constraints, equipment	0–9 scale
	Circularity Rating		9 = Reuse; 7 = Reprocess; 5 = Remanufacture; 3 = Recycle; 0 = not Recoverable	0–9 scale
End of Life	Cost (of disposal)	Materials Safety Datasheet (MSDS)	Hazardous? The ease to be disposed	GBP/unit
	Recyclability	Edupack	Recycle fraction in current supply	%
	Value of Recovery		Price drop of scrap material	GBP/Kg
	Resource to Recycle/ Dispose		Personnel, time constraints, equipment, energy	MJ/Kg

2.3.3. Use

The 'Use' stage sub-criteria are specified as follows.

Cost (value of part) (GBP/Unit) is related to profit per part. Source: a) manufacturers.

Application specific 1, 2, and 3 are to accommodate different types of medical devices. For example, laparoscopic scissors blades need less friction for cutting, while the handle must have sufficient fatigue resistance for opening and closing many times. The CM3D allows users to choose the three most crucial application-specific criteria. The application-specific criteria ensure prolonged device functionality, thus 'slowing the loop.' Source a) Ansys Granta Edupack, b) manufacturers.

2.3.4. Recirculation

The sub-criteria are specified as follows.

Cost of Recirculation (GBP/unit) includes cleaning, disinfection, and sterilisation procedures, estimated to be around 0.4 GBP/instrument [42]. The criteria are crucial to reduce the risk of cross-contamination [41] and ensure 'closing the loop.' Source: a) manufacturers, b) nurse.

Durability and Stability (0–10 scale) measure the capacity to be reused while maintaining materials' qualities through cleaning and sterilisation. It can be determined by durability testing or observation of chemical and morphological changes when exposed to the elevated temperatures or harsh chemicals used in decontamination and or sterilisation. Increased durability and stability prolong service life and hence 'slow the loop.' Sources: a) Ansys Granta Edupack, b) experimental report.

Resource for Reuse (Burden) (0–10 scale). (Time, equipment, and staff required/unit for cleaning and sterilising). For example, ultrasonic cleaning was reported to take 5–20 min, while medical device disassembly and reassembly can take 10–30 min [43]. The sterilisation in autoclaves is expected to last at least 1 h and can only contain a limited number of equipment trays [43] Sterilisation, disassembly, and reassembly take nurses' time and might delay surgical procedures [42]. Less resources for reuse can ease recirculation, thus 'closing the loop'. Sources: a) clinicians, b) reprocessing companies.

Circularity Rating (0–10 scale), with the following scales.

9 = Re-Use
7 = Reprocessed
5 = Remanufactured
3 = Recycled
0 = Dispose Only

2.3.5. End of life

Cost (of Disposal) (GBP/unit) depends on different disposal methods. The NHS specified the disposal guidance [4]. Waste can be categorised into seven hierarchical levels: 1. prevention, 2. correctly segregate, 3. recirculate/back into use, 4. recycle, 5. generate for energy sources, 6. dispose, and 7. in the ground landfill [4]. The smaller the scale, the better it is to prevent disposal or end up in landfills. The disposal treatments are divided into high temperature/incineration, alternative treatment, i.e., chemical or mechanical treatments, and offensive waste [4]. The offensive waste can be treated equally as municipal waste, which can be combusted as an energy alternative. To reduce disposal cost, reducing the total quantity of waste, i.e., by reducing packaging, reducing the miles of disposal, and extending materials' durability.

Recyclability (% recycled in the current supply) represents the potential for recycling. Source: a) Ansys Granta Edupack.

Value of Recovery (GBP changes/Kg) indicates how much value changes after materials are recovered, i.e., recycled. Ensuring that the value of recovery surpasses the cost and resources required to recover them is crucial. Source: a) material suppliers / preprocessors.

Resource to Recycle/Dispose (0–9 scale) depicts how easy materials separation is. Many materials consist of composites or mixtures (blended), which prevent recycling. Previous works have utilised similar criteria, such as 'the ease of disassembly' [38]. However, this criterion is more design-related than materials-related (i.e., dependent on joining and or fastening methods). The term 'resource to recycle/dispose of' is materials-related because it can accommodate relevant measures such as %blended. Source: a) materials suppliers, b) manufacturers.

2.4. CM3D stage 3: Allocation of criteria weights

Criteria weighting in CM3D represents the relative importance of

each criterion toward the overall goal, an aspect that is critical in obtaining appropriate scoring and ranking [13,44]. Here, we consider the process for assigning weights and the opportunity to alter weight profiles depending on the type of medical device.

2.4.1. Selection of a criteria weighting method

Criteria weighting can be obtained by different methods, spanning subjective, objective, and combined weighting methods [44]. Comprehensive recent reviews consider the respective merits of different weighting techniques as employed in MCDMs [45], a brief summary follows. Subjective weighting requires a group of experts or stakeholders' opinions explicitly specifying importance [45]. Common examples of subjective methods include direct ranking, point allocation, Delphi and stepwise weight assessment ratio analysis (SWARA) [44].

Direct ranking involves stakeholders assigning a numerical judgment of importance to criteria, which are then normalised [46]. The Delphi method is similar but employs a multi-stage process with large groups (ca. 30–50) over multiple feedback sessions, finding a wide group consensus [47,48]. Conversely, objective weighting, exemplified by methods like the analytical hierarchy process (AHP), involves a matrix-based assessment to observe interactions between criteria to form a pairwise matrix [24,27]. The technique is widely used in MCDMs but becomes increasingly complex and time-consuming as the number of criteria increase [49,50].

In this research, we selected the direct ranking method because it provides a pragmatic and robust means of enabling direct contributions from our expert stakeholders within reasonable time-constraints that would have precluded the more time-intensive Delphi approach and or complexity of pair-wise comparison required from objective methods like AHP.

2.4.2. Allocation of weighting

Stakeholder weighting was assigned during an online interactive workshop on 22nd July 2024 as part of the ReMed project (see Section 2.1). A briefing was given to explain all the selected criteria (Table 1), after which each stakeholder independently scored the importance of the criteria on a 0–9 scale according to three different product types: (1) Single use (e.g. medical syringe), (2) Circular (Low Value) (e.g. surgical scalpel), and (3) Circular (High Value) (e.g. laparoscopic scissors). This approach was adopted from stakeholder feedback in recognition that the criteria weightings will differ significantly depending on these attributes. For example, for a single use product, the importance of material cost may be higher than for a high-value reusable product used over multiple cycles. This results in three distinct weighting 'profiles', reflecting the relative importance of criteria in different types of products. Normalisation of each profile was then conducted using a linear scaling such that the sum of criteria was '1′ across all five life stages.

2.4.3. Weight profile of the criteria for CM3D

The weight allocations from the stakeholder group were consolidated to produce a single set of weights by taking the mean for the criteria in each profile (after confirming a normal distribution in each case). The outcome of the criteria weighting process is summarised in Fig. 3, with full details in Supplementary B. The standard deviation of the weight across stakeholders was low, indicating a general agreement. The finalized (chosen and removed criteria are depicted in Table 2.

The bar chart and the spider plot represent the criteria weight importance across five life cycle phases for three scenarios: 1. Single use, 2. Circular (low value), and 3. Circular (high value).

It is evident that while the 'Circular (Reusable)' scenarios have similar weight profiles for circular (low) and circular (high), single-use differs, with greater emphasis on Manufacture (particularly cost) and markedly less on recirculation since this is not generally a consideration.

2.5. CM3D stage 4: The MCDM calculation algorithm

2.5.1. Selection of the MCDM algorithm

In general, MCDM consists of six stages (1) defining assessment criteria, (2) choosing materials alternatives, (3) normalisation of the decision matrix, (4) calculation of a weighted normalised decision matrix, (5) computing distances to an ideal solution, and (6) ranking alternatives [51]. Stages 3–6 constitute the MCDM 'algorithm', in which the most commonly used approaches include TOPSIS, VIKOR, PROMETHEE, and ELECTRE [24].

Of these, VIKOR and TOPSIS are distance-based MCDM and involve fewer steps, reducing computational time [24]. Both PROMETHEE and ELECTRE use pairwise comparisons in their weighting, which is time-consuming and reduces its practicality [24]. TOPSIS identifies the best and worst solutions but does not consider the relative importance of the distances, which may be a concern in this context where criteria are not equally weighted, non-commensurable, and conflicting (e.g., cost vs. performance) [15]. Accordingly, CM3D is based on VIKOR (VlseKriterijuska Optimizacija I Komoromisno Resenje) which was developed to allow compromise solutions according to decision maker's preferences [52]. The VIKOR compromise solution accommodates both the "maximum group utility" and quantifies the individual regret of the "opponent" [15,52]. Compromise is often required during material selection as each alternative may have distinct advantages and disadvantages [14,39]. Compromise also reflects decision-making established by mutual concessions [15]. VIKOR accommodates trade-offs explicitly by using concordance (S values), discordance (R-value), and overall value (Q) [15,52]. Like other MCDMs with non-commensurable criteria, VIKOR accommodates different criteria units by normalization steps. Normalization is carried out to eliminate units and makes all criteria dimensionless, achieved by dividing the score by its maximum value

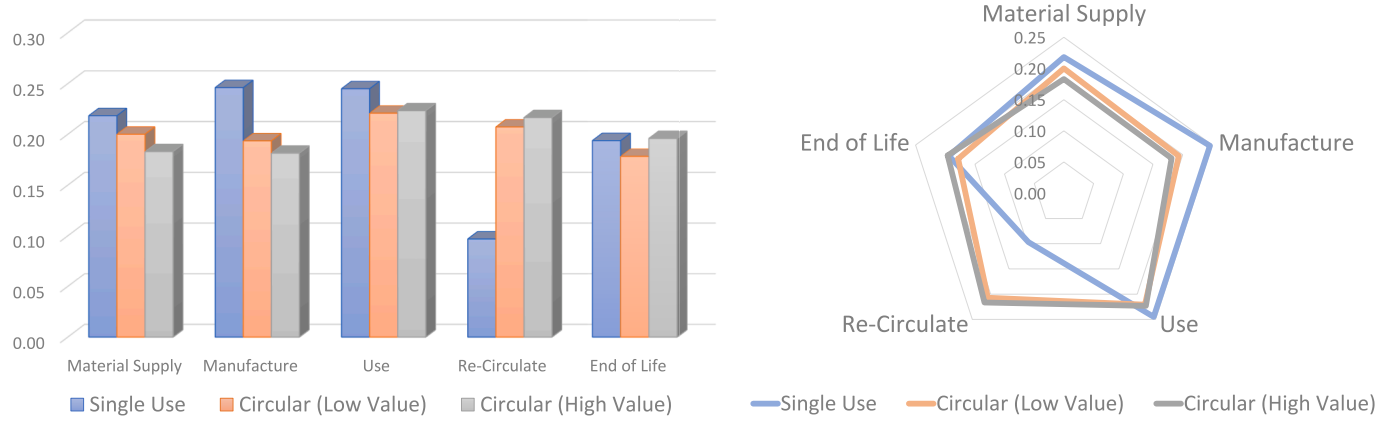

Fig. 3. Visual summary of the three criteria weight profiles determined through stakeholder consultation for the cm3d tool. plots show the combined weighting of the five lifecycle stages.

Table 2
Weight importance of various criteria according to stakeholders for three different scenarios.

		Score (0–9) Profiles								
		Single Use			Circular (Low Value)			Circular (High Value)		
		Mean	STD	Median	Mean	STD	Median	Mean	STD	Median
Material Supply	**Cost (of material)**	7.93	0.96	8.00	6.60	1.72	6.00	4.93	2.19	4.00
Material Supply	**Quantity**	6.93	2.02	8.00	6.40	1.35	6.00	5.47	1.51	5.00
Material Supply	**Renewability**	5.00	2.88	5.00	7.79	1.19	8.00	7.93	1.53	8.00
Material Supply	**Resource for Production**	6.87	1.88	8.00	6.64	1.55	6.00	6.87	1.81	8.00
Manufacture	**Cost (of manufacture)**	7.93	1.71	8.00	7.07	1.49	7.00	5.87	1.55	6.00
Manufacture	**Machinability**	7.47	1.60	8.00	6.60	1.88	7.00	6.00	1.89	6.00
Manufacture	**Manufacture Efficiency**	7.73	1.53	8.00	6.73	1.03	7.00	6.79	1.48	7.00
Manufacture	**Resource for Manufacture**	7.00	1.69	8.00	6.13	1.13	6.00	6.33	1.50	6.00
Use	**Cost (value of part)**	6.00	2.17	6.00	6.27	1.91	6.00	6.73	1.94	8.00
Use	**Application specific #1**	9.00	0.00	9.00	9.00	0.00	9.00	9.00	0.00	9.00
Use	**Application specific #2**	8.00	0.00	8.00	8.00	0.00	8.00	8.00	0.00	8.00
Use	**Application specific #3**	7.00	0.00	7.00	7.00	0.00	7.00	7.00	0.00	7.00
Re-Circulate	**Cost (of re-circulation)**	3.53	3.38	2.00	7.07	1.67	7.00	7.00	1.65	8.00
Re-Circulate	**Durability & Stability**	2.73	2.05	3.00	6.73	1.75	7.00	8.13	1.19	9.00
Re-Circulate	**Resource for ReUse (Burden)**	2.67	2.85	2.00	7.60	1.45	8.00	7.13	1.73	8.00
Re-Circulate	**Circularity Rating**	2.93	3.24	2.00	7.00	1.60	7.00	7.53	2.33	9.00
End of Life	**Cost (of disposal)**	6.40	2.82	7.00	5.20	2.46	5.00	6.00	2.59	7.00
End of Life	**Recyclability**	5.67	2.94	7.00	6.67	1.29	7.00	7.33	1.45	8.00
End of Life	**Value of Recovery**	5.80	2.48	6.00	6.36	0.93	7.00	7.00	1.52	6.50
End of Life	**Resource to Recycle/ Dispose**	5.87	2.45	7.00	6.21	1.31	6.00	6.64	1.69	6.00
		23.734			24.44			26.97		
	Profile Total	122.47		127.00	137.07		137.00	137.70		143.50
		Single Use			**Circular (Low Value)**					**Circular (High Value)**
	Material Supply	0.22		0.23	0.20		0.19	0.18		0.17
	Manufacture	0.25		0.25	0.19		0.20	0.18		0.17
	Use	0.24		0.24	0.22		0.22	0.22		0.22
	Re-Circulate	0.10		0.07	0.21		0.21	0.22		0.24
	End of Life	0.19		0.21	0.18		0.18	0.20		0.19
	SUM of normalization	**1.00**		**1.00**	**1.00**		**1.00**	**1.00**		**1.00**
Remove to Pre-Selection Criteria										
Material Supply	Scarcity									
Material Supply	Global Production									
End of Life	Toxicity									
End of Life	Blended %									

[52].

2.5.2. Implementation of VIKOR algorithm in CM3D

VIKOR classifies each criterion as either 'profit' (higher values are better) or 'cost' (lower values are better). Examples of 'profit' values include renewability and mechanical properties, such as modulus or fracture toughness. Examples of cost criteria include material costs or mechanical properties, such as friction. A summary of our step-wise implementation of VIKOR in CM3D is provided here, with further details available in the original publication [51]. An example of CM3D, implemented in Excel, is provided as a digital Supplementary C (CM3D).

The 'profit' and 'cost' classifications by VIKOR accommodate contradicting criteria. Determination of the 'profit' and 'cost' value for each alternative (j). j = 1, 2, ……..J;

$$\text{For 'profit' criteria: } f_j^* = \max f_{ij} \text{ and } f_j^- = \min f_{ij} \tag{1}$$

$$\text{For 'cost' criteria: } f_j^* = \min f_{ij} \text{ and } f_j^- = \min f_{ij} \tag{2}$$

Based on the above definition of 'profit' and 'cost,' there will be three calculated values as follows:

1. S_i = is defined as a summation of weighted regret [49,53], quantifying the regret for not choosing the ideal material alternative according to each criterion. S_i is divided into S^* which reflects the best value and S^- which reflects the worst value. Min S_i also indicates maximum group utility "majority rule" [15]

$$S_i = \sum_{i=1}^{n} W_i(f_{ij} - f_j^*)/(f_{ij} - f_j^-) \tag{3}$$

2. R_i = is The 'maximum regret' [49,53], measuring the distance/ difference between one alternative and the ideal alternative within one specific criterion. Min R_i indicates minimum individual regret of the ''opponent'' [15]. R_i is divided into R^* which reflects the best value and R^- which reflects the worst value

$$R_i = \max_i W_i(f_{ij} - f_j^*)/(f_{ij} - f_j^-) \tag{4}$$

3. Q_i = defined as the VIKOR index (0–1 scale) [49,53], combines ''majority rules'' and individual regrets of the ''opponent''. Q_i The calculation below can be calculated with the v value set to 0.5

$$Q_i = v\left(\frac{S_i - S^*}{S^- - S^*}\right) + (1 - v)\left(\frac{R_i - R^*}{R^- - R^*}\right) \tag{5}$$

The variable 'v' is defined as the weight of the strategy for maximum

group utility and '1-v' is the weight of the individual's regret [52]. 'v' is 0.5 when consensus is reached and < 0.5 when obtained with a veto [52]. In this study, '*v*' was determined by consensus and defined as 0.5. A smaller Q value means a better choice and a smaller distance to the ideal alternative material [53]. The final Q value is the average of each Q value calculated from individual Si and Ri values in each lifecycle. The four alternative materials were ranked according to the smallest overall Q value. The smaller the overall Q value, the closer to the ideal alternative. However, to visualize an intuitive ranking process, the final scoring uses 1- Q_i value of each alternative material. In this case, the optimum choice with no regret will be scored as '1'.

Finally, to assess the stability of the decision-making process, the value of Q for each alternative can be compared to the respective *Si* and *Ri* values [52]. Since the CM3D accommodates five life stages, each proposed material alternative has five individual *Si* and *Ri* values. The individual Q value demonstrates the performance of an alternative material in each lifecycle, while the overall Q value demonstrates the total compromise that will inform the final decision.

2.6. CM3D stage 5: Interpreting the MCDM outcome

CM3D allows for analyses of material alternatives according to 1) each stage of the lifecycle and 2) overall performance across the lifecycle, as shown in Fig. 3. The overall performance is determined by ranking the material alternatives from best to worst according to the magnitude of Q.

3. Case study

To evaluate the efficacy of CM3D, and illustrate how it can be implemented, a case study is presented concerning the selection of materials for a laparoscopic surgical scissor. A commercially available reusable laparoscopic scissor (H XX-533–50, HERMANN, Germany) was selected, representative of a medium–high value reusable instrument, which is supplied to the UK NHS and available internationally. Fig. 4 shows the typical components of reusable laparoscopic scissors, comprising a handle, blade assembly, and outer shaft.

3.1. Methods

Here, we consider the use of CM3D to identify preferred materials for a) the scissor handle, b) the blade coating, comparing these to the currently available commercial version as a baseline. The handle and blade components are considered independently, each with a different set of application-specific evaluation criteria and corresponding material alternatives.

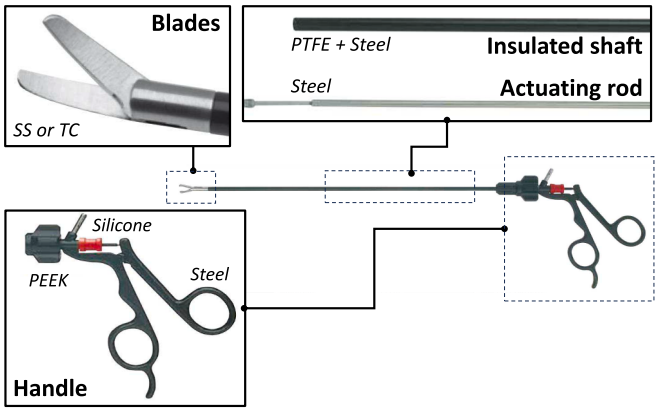

Fig. 4. Laparoscopic Scissors Circular (High Value).

3.1.1. Stage 1: Pre-selection of materials

3.1.1.1. Handles. The baseline handle is made from Polyether ether ketone (PEEK), providing a robust material compatible with steam sterilisation and chemical cleaning agents. Proposed alternative materials were identified as:

1. Medical-grade stainless steel (SS306) to extend lifespan and thus 'slow the loop'
2. Polyethene terephthalate (PTFE) is a widely used material for surgical tools that protects from friction and is highly inert when exposed to chemicals [54], allowing cleaning and sterilising, hence 'closes the loop'.
3. Ultra-high molecular weight polyethylene (UHMWPE) is widely used for its chemical resistance and low wear, which allows cleaning and sterilisation which also 'closes the loop' [55].

3.1.1.2. Scissor blade. The baseline blade material is hardened stainless steel (SS306) enabling steam sterilisation of the cutting edge. In this context, CM3D was used to evaluate additional inserts or commercial coatings on the blades, firstly to extend their lifetime, secondly to improve performance by reducing inter-blade friction. Alternative options were identified as:

1. Tungsten carbide inserts (TC) sintering in a vacuum furnace [56].
2. Titanium aluminium nitride (TiAlN) using plasma vapor deposition (PVD)
3. Titanium nitride (TiN) using PVD

3.1.2. Stage 2: Selection of Application-Specific criteria

In addition to the general criteria detailed in Fig. 2, application-specific criteria (in the Use Phase) were defined for the two components based on key functional requirements. For the blades, the criteria were friction, Youngs' modulus, and hardness, factors that promote extended life and performance [57]. For the handle, they were fatigue strength, Young's modulus, and fracture toughness [58], promoting the ability to support the load over repeated opening and closing cycles during use.

3.1.3. Stage 3: Allocation of weight

The criteria weighting profile selected for this case study was 'Circular (High value)'. This was augmented with weights for the application-specific criteria. For the blades, these were defined as friction (rated 9/9), modulus (8/9), and hardness (7/9) while for the handles fatigue strength (9/9), modulus (8/9) and fracture toughness (7/9).

3.1.4. Stage 4: Criteria scoring and MCDM calculations

The material alternatives were scored for the handle and blade components across all criteria using the designated data sources shown in Fig. 3. The scores are summarised in Table 2 and elaborated in Fig. 3.

The calculations of the VIKOR algorithm, described in Section 2.5.2, were implemented within a spreadsheet (Microsoft Excel v2402). An interactive version of the spreadsheet is provided in the digital Supplementary C; a static version is shown in Table 3).

Scoring the handle material alternatives used the primary sources indicated in Table 3. However, scoring the blade alternatives required additional information from the literature because the proposed materials were not available in the primary sources. Information on *Durability* [Reprocessing Stage] was determined from the literature [59] and linearly scaled from 0 to 9 (with 9 being the most durable alternative). This complements research reporting that TC inserts can extend the life of surgical instruments by up to 2.5x [60], while ceramic-based titanium coatings can extend life by up to 4.5–6.5x [61]. Stability is a complex factor affected by changes in thickness, chemical composition, structure, and morphological changes, with instability leading to cracks, decay, or

Table 3
Scoring of alternative materials for laparoscopic blades and handle.

		Alternative #1	Alternative #2	Alternative #3	Alternative #4
		SS	**TC**	**TiAlN**	**TiN**
Material Supply					
Cost (of material)		4.77	21.80	18.40	13.90
Quantity	Custom	3.00	3.00	3.00	3.00
Renewability		810 x 10^8	0.044 x 10^8	15 x 10^8	14.5 x 10^8
Resource for Production		140.00	144.00	256.00	256.00
Manufacture					
Cost (of manufacture)		80.00	90.00	110.00	110.00
Machinability		8.00	8.00	8.00	8.00
Manufacture Efficiency		8.00	8.00	8.00	8.00
Resource for Manufacture	Custom	80.00	90.00	70.00	90.00
Use					
Cost (value of part)		80.00	80.00	100.00	100.00
Application specific #1	Friction	0.23	0.03	0.06	0.06
Application specific #2	Modulus	210.00	670.00	438.00	525.00
Application specific #3	Hardness	87.00	3200.00	2700.00	2500.00
Re-Circulate					
Cost (of re-circulation)		8.00	2.00	2.00	2.00
Durability & Stability		2.00	9.00	9.00	9.00
Resource for ReUse (Burden)		9.00	1.00	1.00	1.00
Circularity Rating		5.00	9.00	9.00	9.00
End of Life					
Cost (of disposal)		8.00	8.00	8.00	8.00
Recyclability		39.00	32.50	45.00	65.10
Value of Recovery		0.92	5.00	1.69	1.69
Resource to Recycle/Dispose		7.00	8.00	8.00	8.00
		Alternative #1	**Alternative #2**	**Alternative #3**	**Alternative #4**
		SS	**PEEK**	**PTFE**	**UHMWPE**
Material Supply					
Cost (of material)		4.77	44.90	10.30	1.30
Quantity	Custom	3.00	3.00	3.00	3.00
Renewability		810 x 10^8	7 x 10^3. 00	200 x 10^3	61 x 10^3
Resource for Production		140.00	1600.00	480.00	61.00
Manufacture					
Cost (of manufacture)		80.00	100.00	100.00	100.00
Machinability		8.00	8.00	8.00	8.00
Manufacture Efficiency		8.00	9.00	9.00	8.00
Resource for Manufacture	Custom	80.00	90.00	90.00	90.00
Use					
Cost (value of part)		90.00	100.00	100.00	100.00
Application specific #1	Fatigue Strength	307.00	47.00	20.70	19.80
Application specific #2	Modulus	205.00	3.95	0.55	0.96
Application specific #3	Fracture Toughness	100.00	31.00	7.00	8.00
Re-Circulate					
Cost (of re-circulation)		2.00	5.00	5.00	5.00
Durability & Stability		2.00	3.00	3.00	6.00
Resource for ReUse (Burden)		2.00	6.00	6.00	6.00
Circularity Rating		9.00	3.00	3.00	6.00
End of Life					
Cost (of disposal)		8.00	7.00	7.00	7.00
Recyclability		39.00	1.40	0.74	8.90
Value of Recovery		0.92	8.50	11.30	1.30
Resource to Recycle/Dispose		7.00	9.00	9.00	9.00

wear, limiting longevity [62]. Published experimental studies were therefore used to determine scores for stability, i.e., wear resistance, which depends on Young's moduli match between coating and substrate [59]. The Titanium-Nitride coatings improved the wear resistance up to 6.5x compared to bare SS [59]. Based on this data, SS scored much lower than the ceramic coatings ('2′ for SS, '9′ for the ceramic coatings).

At the end-of-life stage, the disposal cost was assumed to be the same for all alternative materials, assuming incineration as medical waste, and thus scored '8′. The cost of disposal (assuming recycling) is lower for SS because it is a single type of alloy (scored as 7) while the other alternatives involve composites requiring separation, thus scoring higher at 8. Finally, the Recovery Cost was taken from the price difference between virgin and scrap materials.

3.1.5. Stage 5: Analysing CM3D outcome for circularity

To provide insight into CM3D's outcomes, the material alternatives are analysed to consider both their overall performance and the respective performance in each of the lifecycle stages.

Furthermore, a bounded Material Flow Analysis (MFA) was used to provide insight into how each of the material alternatives affected instrument circularity. MFA provides an intuitive approach to understanding the flow and magnitude of materials in a product over time, which has been adopted in previous studies [9,11]. In this case study, the MFA compares the baseline material (SS blades and PEEK handle) with the top-ranked material alternatives selected by CM3D. A simplified MFA was conducted, with component weights and material types determined through product analysis and neglecting packaging (assumed consistent between scenarios). The MFA is then visualized as a Sankey diagram. The data and calculations used in the MFA analysis are provided in Supplementary D.

3.2. Results

The CM3D process successfully ranked the material alternatives for

the blade and handle components, enabling a 'best' alternative to be identified in each case. The outcome of the ranking process is summarised in Fig. 5 and Supplementary C, with commentary in the following sections.

3.2.1. Blades

The overall ranking of material alternatives for the blade is determined from *Q* in Table 4a (n.b. lower is better), finds Tungsten Carbide (TC) to be the best 'compromise', maximising utility *Si* while minimizing regret *Ri*. It is notable that the baseline material (SS) is not the lowest ranking material. Further insight into the relative performance of each material can be obtained by looking at each stage of the lifecycle, shown in Fig. 5a. Here, it is evident that the performance profile of SS differs significantly from the coatings; it ranks highest in raw materials and manufacturing stages since it is the cheapest option, abundant, requires minimal resources to extract, and can be efficiently manufactured. However, in later stages, it ranks lower during Use and Recirculation stages because the functional properties (e.g. friction) are inferior and less durable (impacting longevity) in comparison to the material alternative coatings.

3.2.2. Handle score analysis

The CM3D ranking for handle material alternatives, as shown in Fig. 5b, finds Stainless Steel to be the best compromise by a clear margin compared to UHMWPE, PTFE, and PEEK (the baseline). Table 4b indicates that the Q value of SS has the best score in most lifecycle stages, while the Q values of the polymer candidates are clustered around similar, but inferior, values. The Q values correspond well with each *Si* and *Ri* value, indicating good stability of the results. Inspecting their rating across the life cycles (Fig. 5b) shows that SS outperforms the polymeric options in almost all aspects of materials, manufacturing, recirculation, and EoL, despite the material and manufacturing costs being higher.

Table 4a
CM3D outcomes of material alternatives for the blade components. Si value (maximum group utility), Ri value (regret), and Q value (compromise).

Blade Alternatives Outcomes	SS	TC	TiAlN	TiN
Materials	Si = 10.32	Si = 22.19	Si = 24.29	Si = 23.28
	Ri = 5.50	Ri = 7.93	Ri = 7.79	Ri = 7.79
	Q = 1.00	Q = 0.07	Q = 0.03	Q = 0.07
Manufacturing	Si = 9.90	Si = 11.13	Si = 10.79	Si = 12.20
	Ri = 5.63	Ri = 6.33	Ri = 5.87	Ri = 6.33
	Q = 1.00	Q = 0.23	Q = 0.64	Q = 0.00
Use	Si = 22.65	Si = 2.52	Si = 6.11	Si = 5.51
	Ri = 9.00	Ri = 1.35	Ri = 2.77	Ri = 2.25
	Q = 0.00	Q = 1.00	Q = 0.82	Q = 0.87
Recirculation	Si = 23.81	Si = 2.54	Si = 2.54	Si = 2.74
	Ri = 7.13	Ri = 1.75	Ri = 1.75	Ri = 1.75
	Q = 0.00	Q = 1.00	Q = 1.00	Q = 1.00
EoL	Si = 20.46	Si = 16.32	Si = 19.54	Si = 17.28
	Ri = 6.00	Ri = 6.64	Ri = 6.64	Ri = 6.64
	Q = 0.50	Q = 0.50	Q = 0.11	Q = 0.38
Overall	**(1-Q) = 0.50**	**(1-Q) = 0.56**	**(1-Q) = 0.52**	**(1-Q) = 0.46**

4. Discussion

The aim of this research was to develop a tool to aid in the selection of materials for 'circular' medical devices. Our focus was ensuring that the resultant tool was appropriate for use by the medical device industry

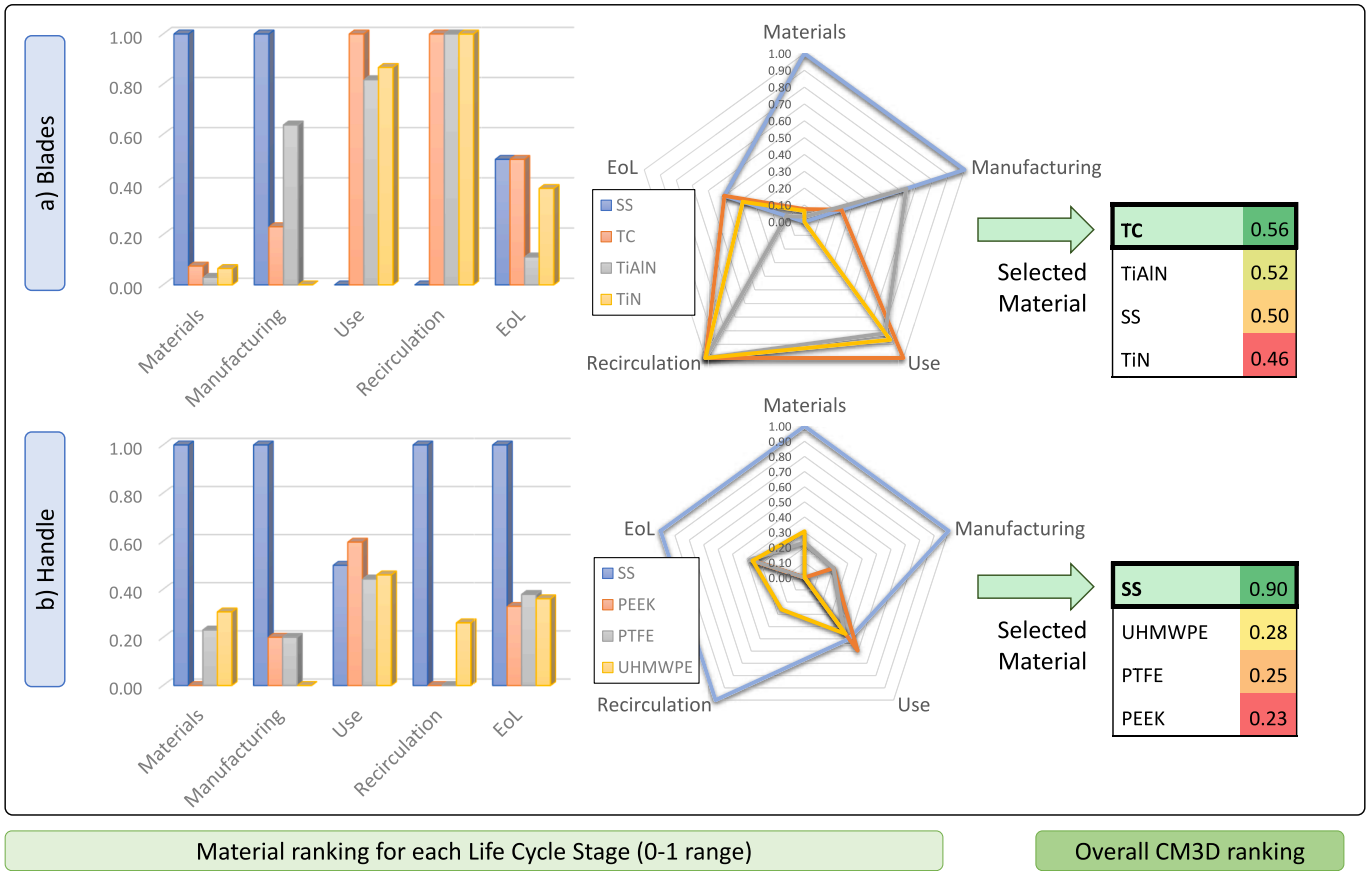

Fig. 5. Using CM3D to evaluate materials for two components of a laparoscopic scissor showing: a) The blade in which Tungsten carbide (TC) scored the highest, followed by Titanium aluminium nitride (TiAlN), Stainless Steel (SS), and Titanium Nitride (TiN) b) The handle in which Stainless Steel scored the highest, followed by ultra-high molecular weight polyethylene (UHMWPE), polyethylene terephthalate (PTFE), and polyether ether ketone (PEEK).

Table 4b
CM3D outcomes of material alternatives for the handle components. Si value (maximum group utility), Ri value (regret), and Q value (compromise).

Handle Alternative Outcomes	SS	PEEK	UHMWPE	PTFE
Materials	Si = 6.62	Si = 25.20	Si = 13.84	Si = 16.62
	Ri = 5.50	Ri = 7.93	Ri = 7.93	Ri = 7.93
	Q = 0.00	Q = 1.00	Q = 0.69	Q = 0.77
Manufacturing	Si = 11.08	Si = 12.20	Si = 12.95	Si = 12.20
	Ri = 5.63	Ri = 6.33	Ri = 6.33	Ri = 6.33
	Q = 0.00	Q = 0.80	Q = 1.00	Q = 0.80
Use	Si = 9.67	Si = 14.05	Si = 14.98	Si = 15.10
	Ri = 9.00	Ri = 7.85	Ri = 7.96	Ri = 7.98
	Q = 0.50	Q = 0.40	Q = 0.54	Q = 0.56
Recirculation	Si = 10.60	Si = 23.22	Si = 16.64	Si = 23.22
	Ri = 5.42	Ri = 7.13	Ri = 7.13	Ri = 7.13
	Q = 0.00	Q = 1.00	Q = 0.74	Q = 1.00
EoL	Si = 17.60	Si = 20.70	Si = 23.75	Si = 19.09
	Ri = 6.43	Ri = 7.07	Ri = 6.64	Ri = 7.19
	Q = 0.00	Q = 0.67	Q = 0.64	Q = 0.62
Overall	**(1-Q) = 0.9**	**(1-Q) = 0.23**	**(1-Q) = 0.28**	**(1-Q) = 0.25**

and that it can provide an objective assessment of key criteria across the device lifecycle. From the literature it was evident that MCDM provides a robust framework to meet these needs, but that it is highly dependent on the selection of appropriate 1) criteria 2) weighting and 3) scoring [45]. Accordingly, the tool was co-developed with a group of expert stakeholders. As a result, CM3D is intended as a pragmatic tool, combining knowledge and techniques from literature with real-world feedback from the medical device industry. This was instrumental in several respects. Firstly, criteria were selected such that they could be supported by robust and readily available information and were relevant to the medical device industry. This precluded some criteria that required complex analysis (i.e. an LCA) or new investigations, instead favouring the use of trusted databases where possible. Secondly, stakeholders highlighted that the relative importance of criteria would differ depending on characteristics of the medical device. In this instance of CM3D, devices were classified according to their usage and value (Single-use, Reusable Low Value, Reusable High Value), each with an associated weight profile. However, other characteristics could also be considered including 'device complexity', 'production volume' and 'device classification', which were recognised during co-development discussions. Finally, stakeholders highlighted the importance of providing a concise and cogent summary, abstract from the complexity of the MCDM calculation process. This aspect is addressed through implementation as a 'standard' spreadsheet (see Supplementary), providing an accessible means to use CM3D without recourse to specialised software or complex post-hoc analysis.

Despite growing attention and research activity on the circular economy in healthcare, and medical technology, there are relatively few tools available to guide material selection to promote circularity. Previous similar MCDM studies offered partial evaluations, i.e., only on sustainability aspects such as carbon emissions, power, or water consumption, or only the performance, manufacturing, or economic factors. Other studies covered all but did not focus on the circularity of medical devices [32]. CM3D represents the first tool to comprehensively cover key aspects of circularity across the device lifecycle. Consultation with our stakeholders highlighted that tools of this nature have value across design, commercial product development and 'maintenance'. During conceptual design and new product development, it can be used to prospectively identify and explore the merits of different candidate materials and how they align with circularity. Once a design has been confirmed, the tool can be used in Device Verification and Validation to evidence material selection as part of a Technical File. Lastly, the tool can be used to inform retrospective materials optimisation of extant devices to improve their circularity, for example through material substitution during repair or refurbishment without redesign.

The weighting profiles determined in collaboration with expert stakeholders, summarised in Fig. 3, provide insight into definitions of 'circularity' in medical device material selection. Full weightings per criteria are presented in the supplementary information. For the *'Reusable High Value'* scenario, Durability and Stability were ranked most important, followed by Renewability and Circularity Rating. These align with expectations that a circular medical device will be robust and capable of long-term use. For the *'Reusable Low Value'* scenario, the emphasis shifts toward Renewability followed by Resource for Re-Use, which is apposite since if this value is high, it would surpass the device value and prohibit (commercially viable) recirculation. In contrast, in the *Single-Use* scenario, the Cost of Material and Cost of manufacture, followed by Manufacturing Efficiency are ranked most important, with markedly less consideration after the Use phase.

The chosen criteria of the current CM3D remain 'general' to accommodate different pathways while focusing on the materials selection aspect. For example, if some medical devices are incinerated or others are recycled (mechanically or chemically), both are covered under the category of 'resources of disposal.' Alternatively, if some medical devices require sterilization using an autoclave while others necessitate gamma irradiation, this will be addressed by the 'resource of reuse' aspect. It is essential to recognize that the circular economy pathway is not fixed and a variety of options may be possible. Therefore, CM3D provides users with the opportunity to score and compare different strategies in an objective manner.

The case study evaluated the efficacy of using CM3D to conduct a retrospective analysis of reusable laparoscopic scissors, focusing on the handle and blades. This represents a context where the design is relatively constrained (for functional and ergonomic reasons) but there is freedom to explore alternative materials. At CM3D Stage 1, material alternatives were identified for each component using expert knowledge and the literature, identifying a range of commercially available options for assessment. In Stage 2, function-specific criteria were selected for each component, related to the component requirements. It is notable that while Stage 2 necessarily requires expert knowledge, it is focused on functional design criteria, (readily available knowledge within a company developing medical devices), rather than requiring expertise in areas of 'sustainability' or circularity, which are instead leveraged using the predetermined criteria within CM3D in the next stage. At Stages 3 and 4, most criteria could be scored directly from established databases (e.g. EcoInvent); however, in some instances, information was not available for the blade materials and required additional research. This introduces a potential source of subjectivity (appropriate selection of sources), which could be mitigated through documentation to enable external validation. CM3D successfully ranked material alternatives. These outcomes differ from typical commercial offerings because CM3D focuses on circularity. For the scissor blades SS is a typical material, low-cost, abundant, and easy to manufacture. However, the coating alternatives (TC, TiAlN, TiN) bring significant enhancements to enhance lifespan (slowing loops) and increasing performance. The ability to refurbish blades by reapplying a coating also improves the ability to repair, increasing service life (closing and slowing loops). CM3D provides a balanced assessment of these non-commensurate factors, highlighting TC as the best overall candidate. Similarly, for the handles, PEEK is a widely used material that has a relatively low cost and is readily manufactured. However, CM3D ranked SS as the ideal choice, which can bring significant benefits by enabling servicing and repair for recirculation (closing and slowing loops), and high-value material recovery through recycling at End of Life (closing loops). Furthermore, the output of CM3D produces spider plots to visualize the characteristics of different material alternatives across the life cycle stages. This provides a useful means for the decision-maker to get a holistic view of the relative merits of alternatives. For example, the relative importance of different life cycle stages may differ according to product type. Equally, it allows decision makers to examine trade-offs between different life cycle stages.

Although the case study uses a theoretical approach which requires future experimental validation, the outcomes highlight the potential value of this approach and align with experimental studies reported in the literature. Wang et al. reported that TC coated cutting tools exhibited enhanced cutting performance, reduced wear rate and extended lifetime in comparison to SS [63]. Considering the handle material, both PEEK and SS have excellent properties suited to manufacture and use (e.g. thermal and chemical resistance, fatigue strength). However, at EoL the use of PEEK can prohibit recycling due to low value of recovery material degradation [64], and reduced mechanical properties [65] after repeated use cycles. Whereas SS remains a valuable and viable commodity for recirculation, and its durability upon sterilization can be further enhanced, i.e., by using coolant during machining [66].

The work presented here represents an initial implementation of CM3D, providing a foundation for continued research. As such, it is important to recognise current limitations. The core of CM3D is the MCDM, which provides a robust mechanism for multi-variable decision making. However, there is recognition that in some contexts, algorithms can suffer from rank reversal problems (changing the number of material alternatives results in changes in rank order). This predominantly affects TOPSIS and COPRA but was also identified in VIKOR [32]. Recently, the R-VIKOR algorithm was reported to mitigate against this effect [67]. Accordingly, future work will assess the sensitivity of CM3D to rank reversal and, thus, if an alternative or improved algorithm is necessary. The effectiveness of an MCDM is also a function of the attributed importance weightings, which differed significantly between the three categories used in CM3D. The current categorisation represents a simplification of a multi-factorial situation based on stakeholder feedback. Future work will more rigorously explore this aspect, considering how factors, including production volume and device class, effect weightings. Finally, the current implementation of CM3D considers component parts using a single material. In reality, multi-material components are common in medical devices, and future research will extend the CM3D framework to consider these hybrid cases. This is particularly important since it is often challenging to separate materials in hybrid components at end of life, making recycling prohibitive and impeding circularity.

5. Conclusions

A clear need was established for improved tools to aid materials selection for circular medical devices, particularly in forms relevant to the medical device industry. In co-development with expert stakeholders, the CM3D tool was developed to address this need. The tool is based upon the MCDM VIKOR algorithm to provide robust decision-making. A set of criteria that span the product lifecycle were selected, together with associated weights of importance, designed to recognize and promote principles of circularity in the decision-making process.

The case study established that CM3D was able to effectively rank material alternatives for laparoscopic scissor blades and handles. The results showcase the function of CM3D as a pragmatic tool for selecting materials for medical devices at the industry scale.

Future work will involve validating the CM3D outcomes in other scenarios, such as high-volume or low-volume medical devices. The current CM3D considers individual medical device components in isolation. Future research will seek to integrate CM3D within the design cycle for multi-material and multi-component devices.

CRediT authorship contribution statement

Zahrina Mardina: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rory P. Turnbull:** Writing – review & editing. **Shahin Rahimifard:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Richard Bibb:** Writing – review & editing, Supervision, Funding acquisition. **Peter Culmer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zahrina Mardina reports financial support was provided by united kingdom research and innovation (UKRI). Peter Culmer reports financial support was provided by united kingdom research and innovation (UKRI). Shahin Rahimifard reports financial support was provided by united kingdom research and innovation (UKRI). Richard Bibb reports financial support was provided by united kingdom research and innovation (UKRI). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matdes.2025.114015.

Data availability

Data will be made available on request.

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