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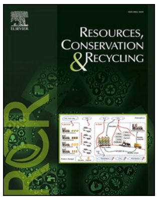

Enhancing life cycle product design decision-making processes: Insights from normal accident theory and the satisficing framework

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ABSTRACT

Life Cycle Assessment (LCA), a computational tool for enabling sustainable product design decision making, faces challenges in the interpretation phase, where conclusions are drawn for improvement recommendations. This necessitate the need to incorporate into LCA management-relevant theoretical underpinnings to strengthen decision-making processes. Comparative LCA case studies of *lead-based* piezoelectric material (*lead zirconate titanate* – PZT) and *lead-free* alternatives (*potassium sodium niobate* – KNN, *sodium bismuth titanate* – NBT), was employed to demonstrate how two theoretical lenses, namely Normal Accident Theory (NAT) and the Satisficing Framework, are used inductively to enhance decision making regarding unintended consequences in the value chain. By operationalising NAT, which has hitherto focused on the consequences of physical accidents, as a life cycle engineering-based methodology, NAT attributes of *interactive complexity* and *tight coupling* was revealed in piezoelectric materials, based on environmental systems' *predictability, observability*, and *applicability.* This led to the introduction of Environmental Impact Accident (EIA) as a new concept, facilitating an early assessment of the associated complexities influencing the sustainability credentials of piezoelectric materials whilst informing mitigation strategies. However, when considering multiple objectives that conflict or trade-off between alternative piezoelectric materials with different environmental and health impacts across the value chain, a conundrum is created but resolved using the Satisficing Framework. The paper concludes by proposing theoretical and practical policy options for incorporating LCA into product life cycle decision making.

1. Introduction

Sustainable materials, products, processes, and technologies can be designed based on the triple bottom line (TBL) concept, covering environmental, social, and economic aspects, but attaining such a feat is challenging. The European Commission (2018), for instance, reported that over 80 % of environmental impact and 90 % of manufacturing costs of a product or process are due to decisions made at the design stage. This necessitates the need for mitigating measures to be taken at this stage, where the technical scope for improvements and optimisation is the greatest (Diaz et al., 2022), but difficult to achieve. Significant efforts have since been geared towards fostering the development of life cycle design strategies, consistent with contemporary needs to redefine sustainability performance (Bendoly et al., 2021; Priyadarshini and Abhilash 2020; Le et al., 2022), and enhance greener product development (Hauschild et al., 2020; Kang et al., 2023). Life cycle design strategy has therefore become one of the main focus areas within life cycle engineering and sustainable manufacturing for meeting net-zero targets (Pahlevan et al., 2021).

Design for environment (DfE) tools like Life Cycle Assessment (LCA), for translating sustainability concepts into the type of quantitative design approaches and performance metrics (Allen and Shonnard 2011) that are applicable in sustainable manufacturing have emerged. LCA is used for evaluating the environmental impacts of products, aiding new development processes. The goal of using LCA is to elicit a triumphant outcome that balances environmental, social, and economic considerations. However, tensions can develop in the practical applications of sustainable products and processes, such as (a) balancing the functional

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aims of the materials or products against the unintended social and environmental consequences (Smith et al., 2021); (b) competing and sometimes conflicting programmes or the identification of which sustainability issues are to be prioritised (Nilsson et al., 2018).

At the interpretation stage of LCA, where conclusions are drawn for improvement recommendations, based on the goal, inventory, impact assessment data and the alternative scenario being considered, there is a lack of management-relevant theoretical underpinnings to enhance decision making regarding unintended consequences in the value chain of sustainable products. Several studies (Go et al., 2015; Brundage et al., 2018; Abubakr et al., 2020; Diaz et al., 2022; da Luz et al. 2018) have contributed to the growth of life cycle product engineering strategies for sustainability, but are not informed by management theories. Pryshlakivsky and Searcy (2021) echoed this remarkable lack of management theory-driven life cycle design, hence the motivation of this paper which lies in facilitating improved environmental sustainability decision making (Hauschild et al., 2020).

This paper therefore demonstrates how two theoretical lenses, namely Normal Accident Theory (NAT) (Perrow 1981, 1999), and the Satisficing Framework (Holt et al., 2009) can be used to enhance decision making at the interpretation phase of LCA. Specifically, informed by LCA results, the paper first draws on NAT, a philosophical or classical approach in organisational sociology parlance, to analyse the broader unintended consequences of representative piezoelectric materials, ascertain whether NAT characteristics are exhibited across their value chain, and whether the notion of Environmental Impact Accident (EIA) as a new concept can be introduced. NAT, which hitherto focused on the consequences of physical accidents, was selected as a theoretical lens, predicated upon the study's assumption that even for greener products, unintended environmental impacts can occur along their value chain. Second, the paper adopts the Satisficing Framework, a pragmatic or normative standard for stakeholder decision making, to address the conundrum created by the unintended consequences of sustainable materials substitution (Sackmann et al., 2018). The use of the Satisficing Framework helps in producing a satisfactory outcome under the widest set of scenarios, providing flexible trade-offs during stakeholders' decision-making processes.

To provide an analytical setting for the intended developments, the paper focuses on material substitution sustainability (Bontempi 2017b), using *lead-based* piezoelectric material (*lead zirconate titanate* – PZT) and *lead-free* alternatives (*potassium sodium niobate* – KNN, *sodium bismuth titanate* – NBT) as case studies. These case studies are topical as specific global policy initiatives and environmental legislation such as the Restriction of Hazardous Substances (RoHS) and EU directives on Waste Electrical and Electronic Equipment (WEEE) have mandated the minimisation of the risks associated with the build-ups of hazardous substances like lead at the disposal sites of electronic wastes (Koruza et al., 2018). Currently, technologies and applications enabled by PZT are exempted and are periodically revised under a window spanning three years (Bell and Deubzer 2018), pending the time that the exemptions would be permanently rescinded, when *lead-free* alternatives becomes viable and market ready (Rödel et al., 2015). Other drivers for material substitution in piezoelectric applications are documented by Ibn-Mohammed et al. (2016). Although both KNN and NBT have emerged as the most promising replacements for PZT, a cradle-to-grave LCA examination of both of these substitute materials reveals potential unintended environmental consequences (Ibn-Mohammed et al., 2016), creating a material substitution conundrum among key stakeholders.

By adopting the two theoretical lenses of NAT and the Satisficing Framework in the context of material substitution sustainability for the first time, this paper extends the frontiers of LCA decision making, reinforcing a deeper understanding of unintended consequences, and developing a robust mechanism for resolving any identified conundrum. Given the policy relevance of the case studies, the policy decision options developed by Lehmann et al. (2015), was drawn upon to propose both theoretical and practical options, for embedding LCA into product life cycle decision making. This facilitates effective policy formulations within the piezoelectric materials community to advance breakthroughs to market opportunities, while ensuring uncompromised environmental integrity.

To elucidate these developments, the rest of the paper is structured as follows. In Section 2, an overview of the literature detailing material substitution and the theoretical lenses adopted is presented. Section 3 provides the research methodology, describing the LCA method alongside the theoretical lenses adopted. In Section 4, the comparative LCA of PZT vs. KNN/NBT are presented and analysed in the context of the two theoretical lenses. The role of policy in enabling LCA integration into materials substitution specifically, and product design in general, are discussed in Section 5, leading to the concluding remarks in Section 6.

2. Literature review

This section reviews the literature, starting with smart materials development.

2.1. Smart materials: meaning, applications and environmental burden

Smart materials constitute non-living systems that combine sensing, actuation, logic and control functions to respond adaptively to the environment to which they are exposed, in a usually repetitive and beneficial manner (Strock 1996). They comprise high-performance materials that are a cornerstone of stricter energy policies regulations across numerous economic sectors, and are part of the smart systems-functional materials, including piezoelectrics, magnetocalorics, thermoelectrics, semiconductors and ionic conductors. To meet key challenges towards global sustainability, these materials have opened up new frontiers that enable the energy-material nexus, thus enhancing the quality of life for billions of people throughout the world (Kirchain Jr, Gregory, and Olivetti 2017). From sustainable construction, sustainable transportation infrastructure, consumer products, to renewable energy systems, the need for advanced functional materials is widely acknowledged (Agrawal and Choudhary 2016; Smith et al., 2019; Akhshik et al., 2022). They are therefore vital to a net zero and circular economy future, given the high growth and development witnessed through their discoveries and applications.

Ibn-Mohammed et al. (2023a) noted that despite their functional use and cross-sector transformational benefits, tensions exist between the potential benefits of these materials and the environmental burden attributed to their manufacturing, widespread usage, and end-of-life scenarios, creating rebound effects. To ensure that they do not exacerbate the existing problems of resource use and pollution caused by rapid obsolescence and disposal of products containing functional materials, gaining an understanding of the impact that their mass production and the associated supply-chain systems have on the environment while developing mitigation strategies, is pertinent. This is even more so, as global policy initiatives and legislation including the RoHS, EU directives on WEEE, and End-of-Life Vehicles (ELV), have mandated the minimisation of the risks associated with the build-ups of hazardous substances at the disposal sites of electronic wastes, leading to increased demand for environmentally benign materials and manufacturing routes (Koruza et al., 2018). Considering these, advances in the development of smart materials must be integrated with life cycle product design engineering principles to ensure sustainable material substitution strategies (Bontempi 2017b), in response to the policy initiatives.

2.2. Material substitution

Materials substitution, which could either be *material for material* or *substance for substance* or *process for process* or even *service for product* constitute an integral factor for innovation and industrial expansion. The most common reasons for pursuing material substitution strategies include improvement in performance of product services, meeting new legal requirements, cost reduction and environmental issues (Jahan et al., 2016; Poulikidou et al., 2015). Materials substitution is also driven by the embodied energy and carbon footprint implications of old vs. new materials (Bontempi 2017a), and the fact that engineering products are subject to continual evolution to meet demands for increased performance whilst lowering manufacturing costs (Farag 2007). Additionally, new and improved materials alongside processes inspired by sustainable material substitution strategy (Bontempi 2017b) can contribute to improved competitiveness (Poulikidou et al., 2015; Maine and Garnsey 2006).

At the industrial level, material substitution is continually sought for different reasons including: **(i)** restrictions imposed on certain material usage, due to their threats to human health and safety, where regulations such as REACH (registration, evaluation, authorization, and restriction of chemicals) and RoHS, are mandating industrial businesses to consider alternative materials (Bell and Deubzer 2018); **(ii)** attaining the limits of essential non-renewable materials (e.g. rare earths elements, lithium, cobalt, phosphorous and indium), as obtainable in high-end technologies (e.g., electric vehicles, fuel cells, solar photovoltaics etc.) that are essential for the growth of the economy (Sovacool et al., 2020); and **(iii)** the need to consider the environmental impact of industrial processes based on complete life cycle evaluations, especially as it pertains to different end-of-life scenarios of products, as emphasised by the WEEE Directive (Cucchiella et al., 2015).

The principle of materials substitution is not entirely straightforward given the numerous barriers that has to be overcome. For instance, the uptake of new materials in existing products is fraught with numerous obstacles such as the processing requirements of new materials, price ratio, substitution costs, and, in some instance, the marginal propensity of the end users to change (Kutz 2015). Other forces against material substitution include organisational policy, lack of guidelines for design and in-service expertise for new materials development, huge cost of redesign and investment required for new equipment and the cost of additional inventory needed for more spare replacements (Farag 2007; Ashby 2005; Childs 2013; Kutz 2015).

Given the above considerations, there is a tendency for materials substitution to be disruptive, thus requiring new business models to realise its full potential. Accordingly, for material substitution to be viable (Kutz 2015; Farag 2007): **(i)** the benefit of implementing a new and untested material must be worth the risk of forsaking the current materials that have stood the test of time; **(ii)** the substitute materials must meet the performance requirements of the specified application; **(iii)** the material substitution cost must not surpass the overall benefits; **(iv)** the costs of refurbishing production equipment and related processes must be within reasonable range; **(v)** the wider implications of substitution are controllable in a wider systems context (e.g. better recyclability, lower cost of waste disposal, commercial viability and material availability now and in the future); and **(vi)** institutional, social, legal, and environmental consequences can be overcome.

To meet the requirements enumerated above, numerous techniques exist for evaluating the consequences of material substitution and design decisions, including ecosystems services valuation (Costanza et al., 1997), environmental cost-benefit analysis (Carolus et al., 2018), risk assessments (Sonnemann et al., 2018), and circularity assessment (Corona et al., 2019). However, these techniques have traditionally been adopted to evaluate the implications of specific actions in specific locations (Cowell et al., 2002). LCA, which constitute a DfE strategy and entails step-wise processes of inventory, impact, and improvement analyses, complements these methods, and have since been identified as a strategic tool that must be embedded into the smart materials design and development decisions. LCA constitutes an important tool for studying and analysing strategies to meet life cycle and environmental challenges throughout a product's value chain and across geographical locations. Its overall goal is to provide guidance to decision makers towards mitigating environmental impact.

Across various functional material types, the LCA of material substitution strategies have been demonstrated in piezoelectric materials (Ibn-Mohammed et al., 2018), perovskite solar cells (Ibn-Mohammed et al., 2017; Gong et al., 2015), high volumetric efficiency capacitors (Smith et al., 2018; Zhang et al., 2022), solid-state batteries (Smith et al., 2021; Zhang et al., 2022), lithium-ion batteries (Sun et al., 2020; Marques et al., 2019), solid oxide fuel cells (Smith et al., 2019; Roushenas et al., 2020), triboelectric nanogenerators (Ahmed et al., 2017; Xu et al., 2023) and thermoelectric materials (Ibn-Mohammed et al., 2023b). However, the LCA framework is characterised by numerous challenges across all phases (Reap et al., 2008b, 2008a). To lay the foundations on how the specific challenges of life cycle interpretation and decision-making conundrum in LCA can be overcome, an overview of the two theoretical frameworks considered is provided in the next two sections.

2.3. *Normal accident theory*

Throughout humanity's history, accidents and disasters have continually been a feature of society, and the complexity and embeddedness of smart technologies have created the need for a greater understanding of accidents and disasters (Leveson et al., 2009). This inspired the concept of Normal Accident Theory (NAT), in efforts to provide explanation of the potential consequences of complex systems and gain a better understanding of the devastating accidents they cause (Downer 2010; Nunan and Di Domenico 2017). The originator of NAT is Charles Perrow, an organisational theorist whose work emerged in 1979 as part of his advisory role to a Presidential Commission to investigate and produce a background report following the nuclear accident that occurred at Three Mile Island (TMI) power station (Perrow 1981, 1999). Perrow (1981) concluded that the accident was caused by system complexity arising from a combination of organisational factors within the power station, rather than by an isolated human error or technical fault (Sills 2019; Nunan and Di Domenico 2017). This prompted the TMI accident to be marked a normal accident as it is inevitable with complex technological systems (Perrow 1981, 1999).

NAT therefore underpins accidents which inevitably occur in systems that are characterised by complexity and interdependencies of constituent system components (Weick 2004). Essentially, NAT can be recognized based on two system characteristics namely **interactive complexity** and **tight coupling** (Sammarco 2005; Pidgeon 2011b), which renders systems prone to accidents. Sammarco (2005) noted that **interactively complex systems** have the potential to produce numerous "branching paths among subsystems" and these interactions can be unplanned, incomprehensible, unexpected, and even unperceivable. **Coupling** is a function of the strength of the interconnectedness between system components (Nunan and Di Domenico 2017). When systems are **tightly coupled**, they have little or no slack, and as such, they quickly respond to and transmit perturbations such that operators are constrained by time or lacking the ability to establish what is wrong, leading to doubtful or inadequate human intervention (Sammarco 2005).

Despite the general appreciation of Perrow's characterisation of complex systems, other studies have recommended a careful interpretation of the theory, as complexity is relative and context-specific in terms of systems development, operations and maintenance, and management (Nunan and Di Domenico 2017). The concept of NAT has also been questioned based on its constrained applicability as it addresses only a restricted category of accidents, notably industrial disasters of unexpected events causing huge damage and loss (Sammarco 2005). It has therefore not been applied to more commonly encountered accidents of narrow scope. NAT addresses safety issues in the context of organisational structures for complex industrial systems including nuclear stations, petrochemical industry plants, oil refinery, and hydroelectric dams, among other examples (Perrow 2011).

Nonetheless, the concept of NAT has been adopted in numerous other studies involving physical accidents such as nuclear power stations

(Perrow 2011; Pidgeon 2011a); aviation and air traffic control systems (Helmreich 1997; Latorella and Prabhu 2000); product development (Habermeier 1990); and supply chain networks (Skilton and Robinson 2009). Most of these studies suffer from the inherent limitations of NAT, pertaining to a lack of refinement in defining and quantifying its related terms and concepts (Sammarco 2005), and are therefore mostly qualitative in nature. Hopkins (1999) identified “the lack of criteria for measuring complexity and coupling” alongside “ill-defined concepts” as significant limitations of NAT. An overview of previous works on NAT based on quantitative measures is provided by Sammarco (2005). To the best of our knowledge, NAT has not been integrated into LCA, a gap filled in this paper.

2.4. *From utility maximization framework to the satisficing framework*

The Utility Maximization Framework (UMF) (Davis et al., 2006), based on the theory of rationality and constitutes the core of neoclassical and ecological economics (Smelser and Baltes 2001; Simon 1991), has previously informed decision making regarding alternative options. UMF is premised on four key assumptions: (i) ‘stakeholders have wants they seek to satisfy’; (ii) ‘these wants lead to preference relations that’ “*satisfy the axioms of transitivity, completeness, and nonsatiation*”; (iii) ‘there are costs, implicit or explicit, associated with the products that satisfy these wants’; and (iv) ‘stakeholders choose a particular course of action by balancing preferences and costs in such a manner as to attain maximum satisfaction’(Kaufman 1990). However, UMF focuses mainly on balancing preferences and costs towards attaining maximum satisfaction (Smelser and Baltes 2001). It is therefore constrained to only maximising profits and is severely limited in handling multi-criteria decision problems (Schwartz et al., 2011).

In resolving complex decision making posed by materials substitution conundrum, the application of UMF is not appropriate due to the varying and diverse interests of different stakeholders across the value chains, with different power attributes (Koh et al., 2012; Genovese et al., 2022), all of whom would not be satisfied if decisions were based solely on profit maximisation. Holland (2002) posited that there is really no choice when decisions are based on the logic of utility maximisation, because the stakeholders involved in the decision-making process are influenced by what the maximisation calculus reveals. As such, the real choice is about selecting between options that do not lend themselves to calculations or, at least, not solely based upon the calculation. Furthermore, UMF does not take into consideration the social context within an overall decision-making strategy (Smelser and Baltes 2001), prompting Simon (1972) to propose the Satisficing Framework as an alternative to UMF, for decision-making strategy.

Decisions in life are generally fraught with ambiguity, where probabilities cannot be implicitly specified due to the uncertainties involved. To enable rational and improved decision making, Herbert Simon – an American scientist and Noble-laureate – in 1956, proposed the concept of satisficing (Simon 1972), a decision-making strategy that focuses on attaining an acceptable or satisfactory solution, as against the optimal solution (Kaufman 1990; Schwartz et al., 2011). Essentially, the concept strives for adequacy rather than perfection and prioritises pragmatism with the expectation that saving on expenditure of time, energy and resources will be achieved (Brown 2004). Simon (1997) explained: “*A decision maker who chooses the best available alternative according to some criterion is said to optimize; one who chooses an alternative that meets or exceeds specified criteria, but that is not guaranteed to be either unique or in any sense the best, is said to satisfice,* (pg. 295)*”*.

Fundamentally, satisficing implies settling for an outcome that is adjudged satisfactory as against striving for the best available outcome (Kaufman 1990). As a strategy, satisficing can include the adoption of a minimalist approach towards achieving the first attainable decision that satisfies basic acceptable outcomes. Instead of maintaining maximum exertion towards the attainment of an ideal outcome, satisficing focuses on pragmatic efforts when confronted with decision-making. Adopting the Satisficing Framework therefore provides guidance and supports broad ecological institutional settings, allowing clear long-term ecological goals to be established, facilitating effective decision making. The Satisficing Framework has been adopted for innovations (e.g. renewable energy technologies, smart materials systems, nuclear technologies etc.) in advanced economies (Courvisanos 2005), facilitating trade-off analysis while providing the needed flexibility to account for structural inefficiencies in stakeholder decision-making processes. To date, this framework is yet to be applied to elicit decision making in LCA, constituting another gap filled by this work.

3. Research methodology

The conceptual framework for the study is schematically depicted in Fig. 1. The first part entails the carbon accounting methodology (hybrid LCA framework) (Section 3.1), for the environmental profile evaluations of representative piezoelectric materials, under a material substitution scenario. The second part entails the extension of environmental sustainability frontiers, using two theoretical lenses, namely NAT (Section 3.2) and the Satisficing Framework (Section 3.3).

3.1. *Life cycle assessment methodology*

LCA is a computational technique that consist of four main phases including: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation (ISO 2006); and it can either be setup as an attributional or a consequential framework (Schaubroeck et al., 2021). Conducting the LCA of functional materials and devices is challenging as it is predicated upon technology maturity and the stage of development, and therefore focuses mainly on upstream emissions of fabrication processes (Weyand et al., 2023). Due to data gaps, the LCA is conducted based on inventory data estimated from laboratory fabrication processes (Ducoli et al., 2023). The process also involves using stoichiometric relationships, engineering heuristics, relevant data from within the literature and proxy values (Piccinno et al., 2016). The LCA methodological framework was adopted to quantify and compare the environmental impacts of *lead-based* (PZT) vs. *lead-free* (KNN and NBT) based on the system boundary, Fig. 2, and include the following steps: (i) gaining an understanding of the piezo materials in terms of raw material requirements and composition, alongside synthesis routes; (ii) systems boundary setting and functional unit specification; (iii) life cycle inventory construction based on physical processes, material and energy flows, and upstream supply-chain data; (iv) life cycle impact assessment across selected environmental indicators; and (v) interpretation.

The hybrid LCA framework, which is a two-step methodology integrating both process-based and environmentally extended input-output (EEIO) LCA frameworks (Suh and Huppes 2005) was adopted. In a hybrid framework, the process-based LCA is used to evaluate individual supply chain inputs within a defined system boundary, and the EEIO evaluates the indirect environmental impacts (Wiedmann et al., 2011). This ensures a more complete system boundary for the environmental assessment (Acquaye et al., 2023). The impact of each supply chain input was calculated using:

$$\text{Process LCA} = \sum_{i=1}^{n} S_p(i) \times E_p(i)$$

$S_p(i)$= The inputs (i) into a product’s supply chain including raw material extraction, production processes, etc.

n=The total number of supply-chain process input (i)

E_p=Emissions intensity across selected environmental indicators

A full description of all the processes and synthesis routes for the piezoelectric materials is provided by Ibn-Mohammed et al. (2016) and Ibn-Mohammed et al. (2018). Data requirement for the Process LCA was based on inventory data for material fabrication and the production routes (Fig. 2). For example, electrical energy consumption during

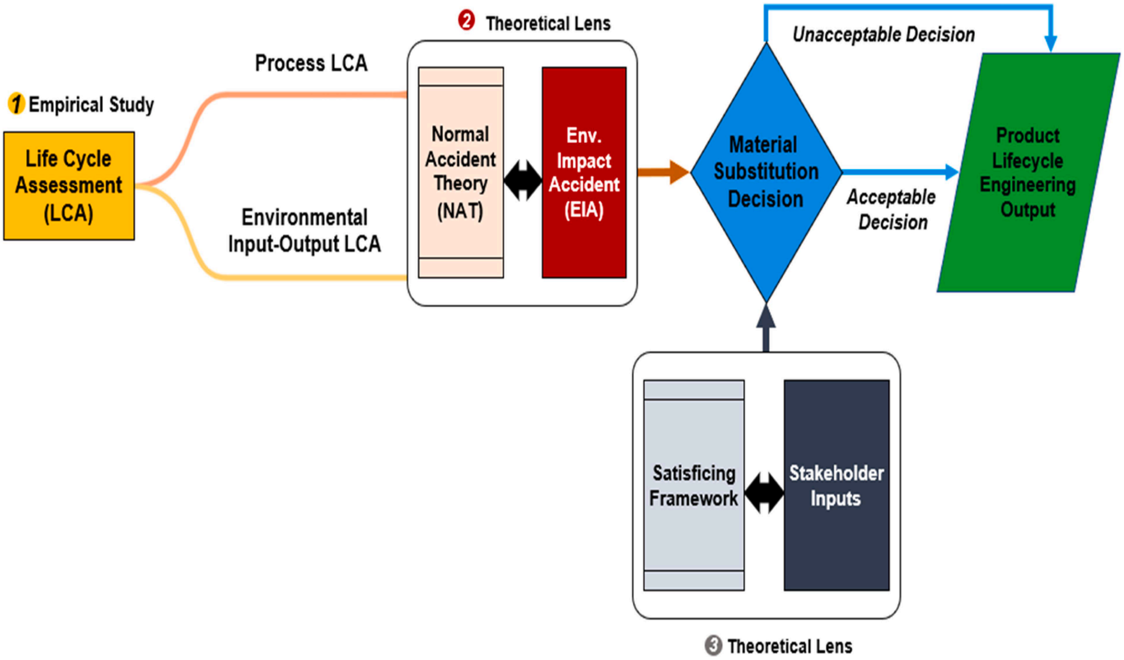


Fig. 1. Conceptual framework detailing the methodological processes and theoretical lenses.

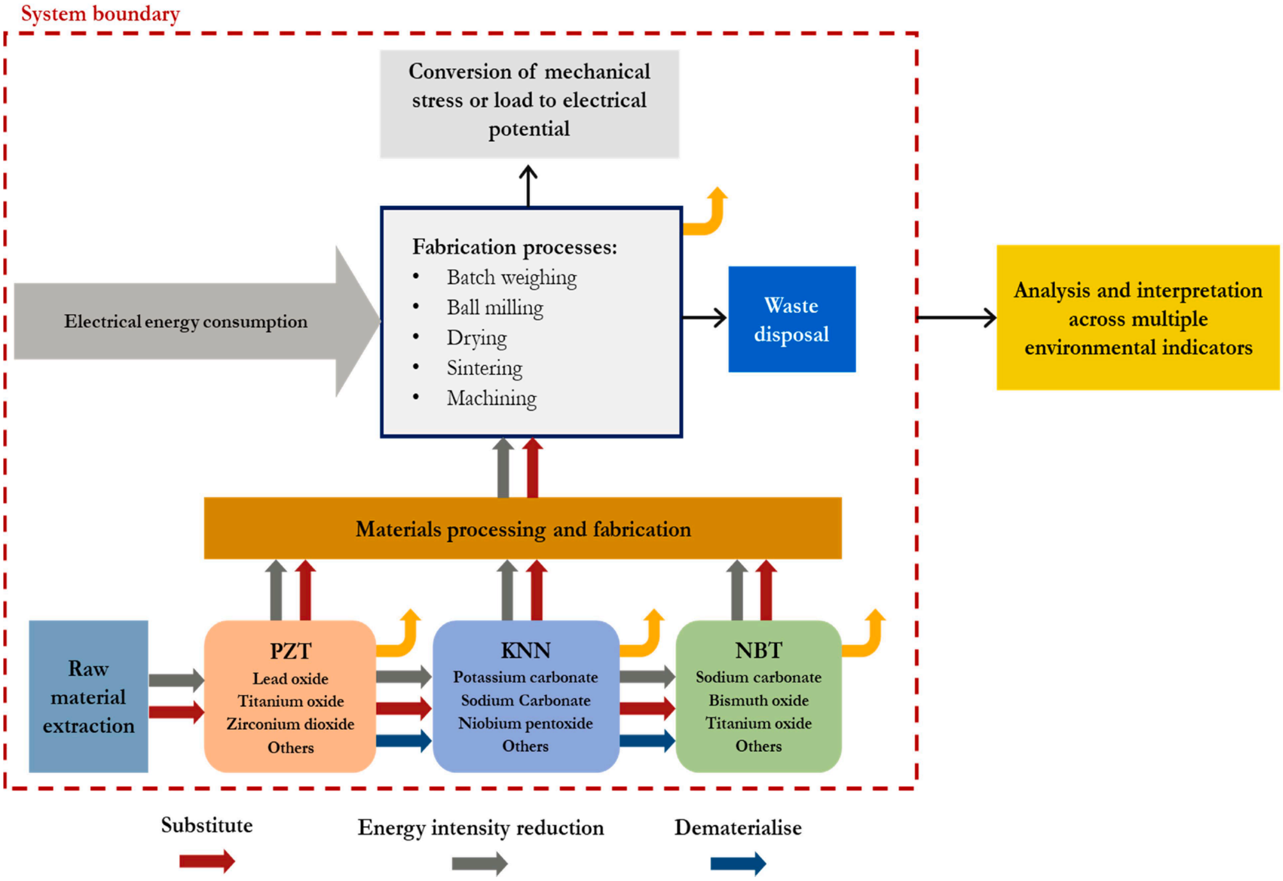


Fig. 2. System boundary setting for the LCA of representative piezoelectric materials.

fabrication was evaluated by multiplying the electrical power rating of a process equipment (e.g., sintering) as specified by the manufacturer by the duration in seconds, during which a specific temperature is maintained for each of the processes. Emissions intensity data were obtained from the Ecoinvent database, and those not available within Ecoinvent were estimated using, stoichiometric relationships, and proxy data.

The EEIO LCA methodology uses country-level economic data derived from input–output trade analysis coupled with industry-level emissions intensities to calculate indirect environmental impacts (Ibn-Mohammed et al., 2014). It simulates the whole supply chain at an economy-wide level, capturing sectoral patterns resulting from production and consumption activities. The EEIO LCA ensures an extended system boundary (Acquaye et al., 2011). The general formulation is given by:

$$\text{EIO LCA} = \mathrm{E}_{\mathrm{io}} \times (I - \mathrm{A}_{\mathrm{io}})^{-1}.\mathrm{y}$$

Where:

A_{io}= Technical coefficient matrix of the input-output model
I= Identity matrix
y= Final demand matrix
E_{io}= Direct emissions intensities derived for each IO industry

The EEIO model was based on an 896 × 896-dimension Input-Output (IO) model, which was constructed from the Supply and Use input-output tables for the UK and the rest of the world (Wiedmann et al., 2011). Data for all environmental indicators are obtained from World Input-Output Database (Timmer et al., 2012) and expanded upon to conform to the 896 × 896 dimension of the MRIO framework. For full description of how the hybrid LCA model was setup in the context of piezo materials, see Ibn-Mohammed et al. (2016) and Ibn-Mohammed et al. (2018).

3.2. *Normal accident theory as theoretical lens for "environmental impact accident"*

As highlighted in Section 2.3, NAT posits that accidents occurrence in some systems is inevitable due to the nature of complex systems, which are **highly interconnected, highly interactive**, and **tightly coupled** (Perrow 1981, 1999). By integrating Perrow's sociological perspective on accidents with insights drawn from the LCA outputs of representative piezoelectric materials, NAT is extended to cover environmental sustainability decision making. Informed by the LCA methodology, the first step is to ascertain whether the system under consideration (i.e., lead-based vs. lead-free piezoelectric materials) exhibits NAT characteristics: **interactively complex** and **tightly coupled**, based on their environmental profile across the entire value chain.

From a NAT's perspective, instances of poor system *predictability, observability,* and *applicability* can induce human errors or worse, disaster (Sammarco 2005). *Predictability*, for example, pertains to unexpected, unplanned, or unfamiliar system behaviours as perceived by the observer. Similarly, complex systems are characterized by transparency, rendering them difficult to comprehend or *observed* by the end user, and *observability* also weakens if the end user is overpowered by information as was the case with the TMI disaster (Perrow 1999). As noted by Sammarco (2005), system ***applicability*** can be negatively influenced by poor ***predictability*** and ***observability.*** In this paper, LCA results are used to determine whether corelation exist or not between NAT's attributes/metrics and the materials systems' *predictability, observability, and applicability* from an environmental impact perspective.

The validation of different hypothesis (Table 1) forms the basis of whether or not a new form of system accident termed *Environmental Impact Accident* (EIA) can be proposed. Operationalising NAT as a life cycle engineering-based methodology with the aim of quantifying the environmental impact of piezoelectric materials enables an early assessment of associated environmental complexities that can influence their sustainability credentials. This ensures informed decisions are made prior to heavy investments in material substitution. Equipped with effective complexity assessment, options can be compared to target the requirements to simplify and measure mitigation efforts. Overall, the use of NAT helps to philosophically elucidate how environmentally sustainable a product is, thus allowing resources to be more carefully redirected.

Table 1
Hypothesis to validate the exhibition of NAT characteristics, adapted from Sammarco (2005).

Hypothesis	Criteria
Is there a correlation between NAT metrics and smart material system observability?	LCA output (EIA)
Is there a correlation between NAT metrics and smart material system predictability?	
Is there a correlation between NAT metrics and smart material system applicability?	
Does increasing complexity decrease system predictability/ observability/applicability?	

3.3. *The satisficing framework for informed stakeholder decision making*

The Satisficing Framework has been applied in diverse fields of study (Barge and Gehlbach 2012), enabling conflict resolutions, by not focusing on maximum utility alone, but also allows for other factors such as ecological/environmental impacts, material circularity potential, social priorities, economic factors and decision trade-offs to be considered (Holt et al., 2009). To assess the satisficing potentials of piezoelectric materials substitutes, the work of Holt et al. (2009), is drawn upon. The authors posited that the ecological framework of Lowe–Kalecki that grants demand-led growth based on sustainability criteria and sets the conditions for investments in innovative technologies to flourish is consistent with the Post-Keynesian Satisficing Framework (Courvisanos 2005). The **three essential benchmarks** (i.e. elements/criteria) that must be achieved to ascertain the "satisficing potential" of an innovative technology such as smart material substitution include (Holt et al., 2009):

- **Criterion 1:** "cumulative effective demand that establishes a strong market share".
- **Criterion 2:** "ecological rules that ensure capital investment is resource-saving with long-run carrying capacities which are sustainable".
- **Criterion 3:** "iterative, flexible and risk-averse investment strategy with democratic control"

These "rules", "elements" or "criteria", enable the continual reassessment of prevailing strategies and promotes further innovation, resulting in a more vigorous and globally competitive programme towards achieving improved environmental sustainability. It is conceived that by adopting the Satisficing Framework, in the context of material substitution scenario, final decisions informed by (i) ecological rules, (ii) the TBL, covering environmental, economic, and social factors, and (iii) trade-off analysis, will engender effective decision making.

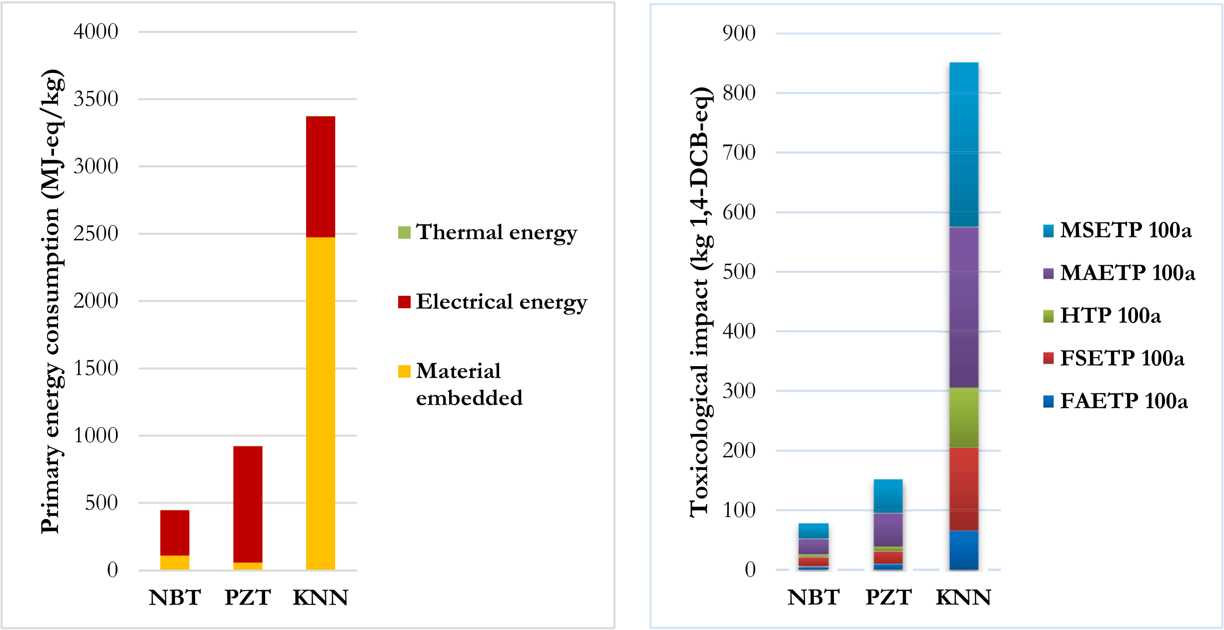
4. Results, analysis and discussion

This section provides the results of the adopted methodological framework.

4.1. *Comparative LCA of the profiled piezoelectric materials*

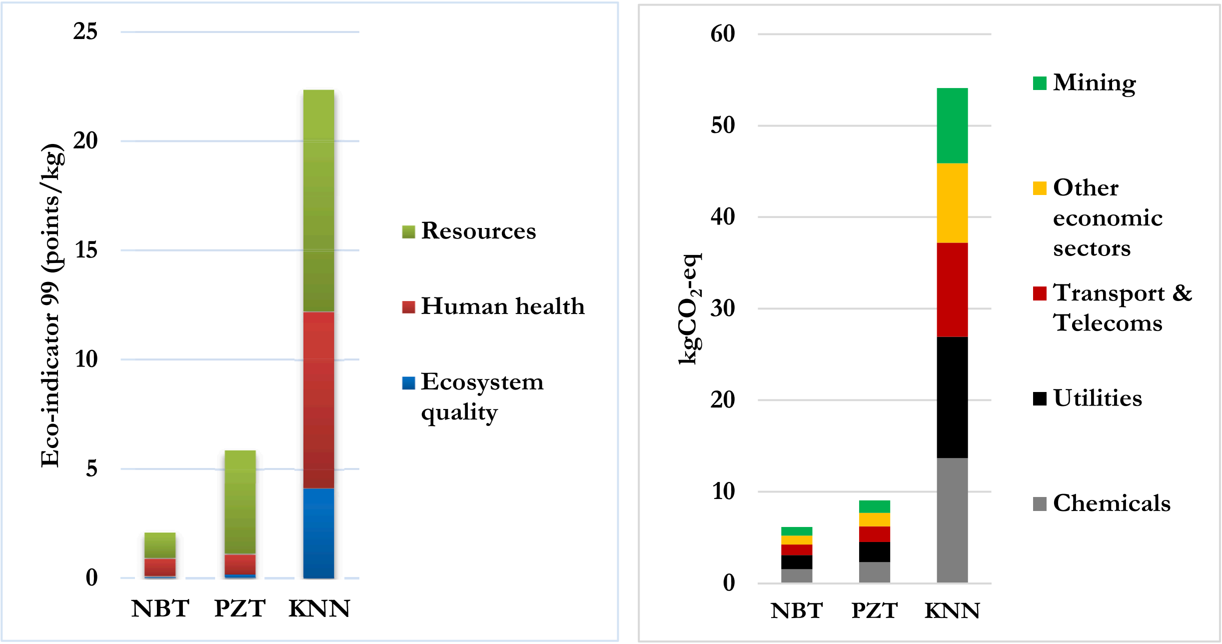
The results of the comparative LCA of *lead-based* (PZT) vs. *lead-free* (KNN/NBT) piezoelectric materials is depicted in Fig. 3. In general, substituting PZT with novel *lead-free* alternatives like KNN and NBT could be deemed friendly to the environment on condition that these new alternatives (i) exert lesser life cycle impact; (ii) has a relatively higher reusable attribute, and (iii) does not require higher energy for its production. However, these characteristics are not met by KNN when compared with PZT across their life cycle, although NBT showed better profile but with a caveat (Fig. 3).

Indeed, KNN across all environmental metrics produced relatively higher life cycle impact due to the series of processes involved in niobium production (a precursor to niobium pentoxide, which is a core



(a) Primary energy consumption

(b) Toxicological impact



(c) Eco-indicator 99

d) EIO upstream GHG per economic sector

Fig. 3. Environmental profile comparison of PZT vs. KNN and NBT piezoelectric materials, based on (a) primary energy demand, (b) toxicological impact, (c) eco-indicator 99 and (d) EEIO upstream GHG. Ecotoxicity potential (ETP), Fig. 3b, are evaluated across five categories namely freshwater aquatic, freshwater sedimentary, marine aquatic, marine sedimentary, and human toxicity.

material in the fabrication of KNN) from the ore stage. In terms of electrical energy consumption during fabrication, KNN is higher due to its high specific heat capacity compared to the other two materials. Expanding on the eco-indicator 99 results (Fig. 3c), KNN exhibited the largest impact across ecosystem, human health, and resources (Fig. 4), due to the presence of niobium pentoxide derived from niobium with extremely intense raw material extraction and refining requirements, causing significant detrimental impact on land, surface and groundwater, and air quality, although niobium and its oxides are innocuous (Ibn-Mohammed et al., 2016). This indicates that the overall damage on the environment has already occurred during mining, prior to the material being adapted for piezoelectric applications. Interestingly, waste disposal of KNN materials shows negligible impact, posing no danger across the remaining life cycle phases.

Fig. 5 shows the detailed eco-indicator 99 profile of PZT with the highest impact emanating from waste disposal associated with lead. Compared to niobium pentoxide in KNN, the impact of lead oxide at the beginning of life (i.e. at the extraction phase) is small but very high at

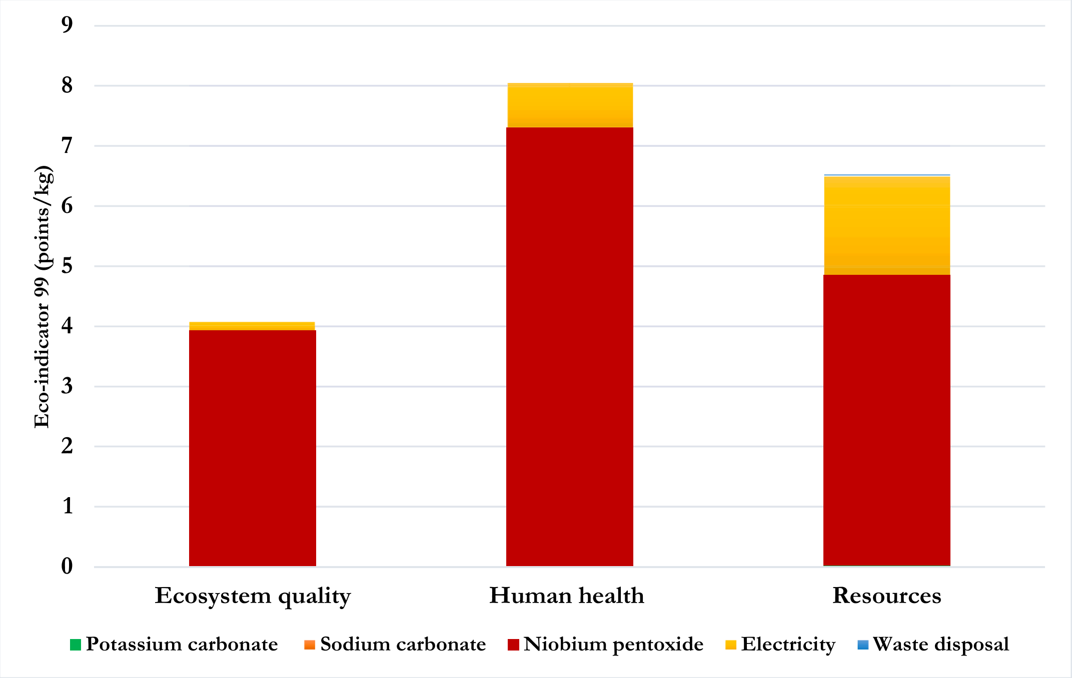


Fig. 4. Detailed eco-indicator 99 results for KNN.

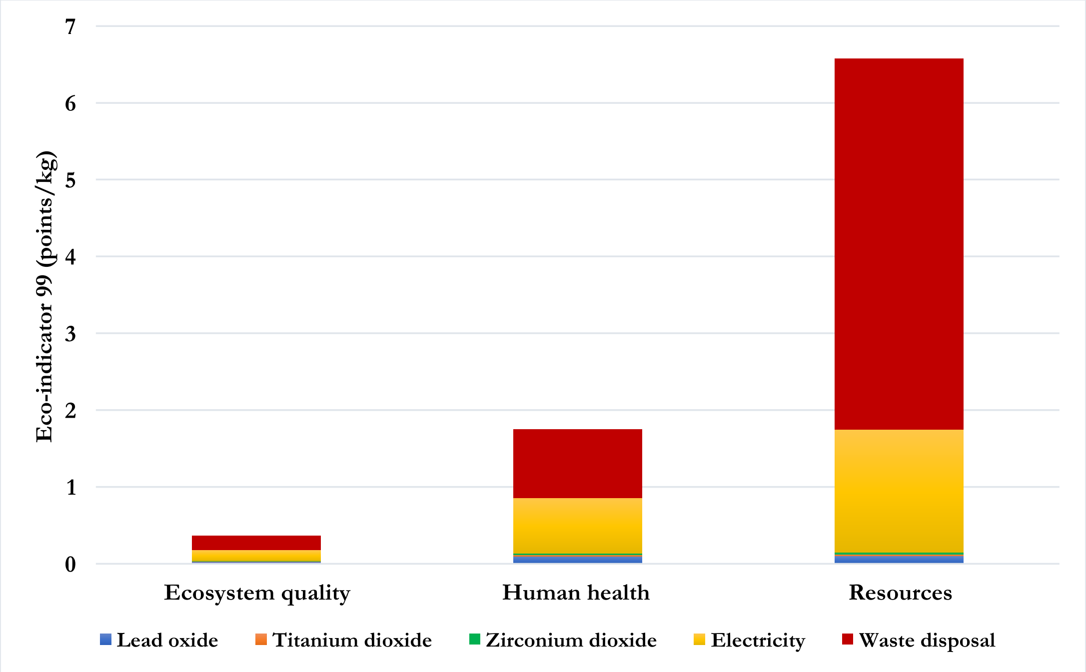


Fig. 5. Detailed eco-indicator 99 results for PZT.

the end of life due to the accumulation of lead in waste disposal of lead-containing products. This indeed, confirmed the fact that the environmental risks posed by PZT as a common application in health-related devices, sound systems and automobile industry among others, is confined to after use disposal and recycling. It is not a common activity to recycle single PZT-containing components. As such, disposing off PZT component is a task of the host system. NBT utilises less energy during manufacturing and consequently minimal total environmental impact, relative to PZT and KNN (Fig. 3), but the major by-product of lead extraction is bismuth (used in its oxide form in NBT). The main difference between lead and bismuth therefore lies in the impact associated with their extraction directly from the earth crust. For full details on the environmental profile of NBT, see Ibn-Mohammed et al. (2018).

Fig. 6 presents a schematic representation of the various impact and material recovery rate of the three different piezoelectric materials at different stages of their value chains. As shown, the most significant environmental impacts associated with KNN occurred at the earlier stages of its life cycle, covering material extraction and refining stages. Equally, because of its higher specific heat capacity and high curie temperature, KNN consumes higher electrical energy during fabrication,

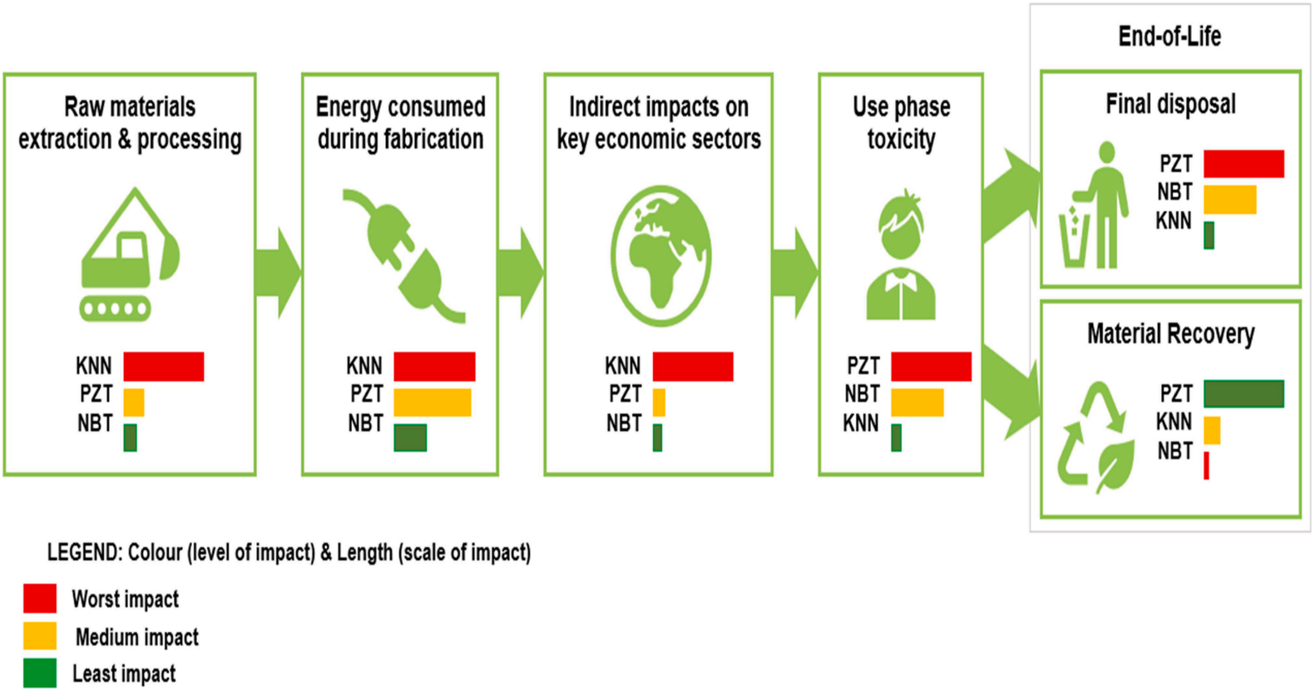


Fig. 6. A schematic representation of the various impact and possible material recovery rate of the three different piezoelectric materials at different stages of their value chains. The relative ratio under each impact category, normalized to 100 % (1), was used to produce the size of the bars, which exemplifies the relative impacts of the piezoelectric materials to one another.

relative to NBT and PZT. PZT's use phase toxicity and end-of-life waste disposal impact surpasses both KNN and NBT.

Each bar in Fig. 6 were scaled based on ratio using the LCA results across the categories considered. For example, under the raw materials and processing impact category, expressed in kgCO_2-eq for each of KNN, PZT and NBT were estimated to be 3373, 921 and 447 respectively. Similarly, the energy consumed during the fabrication of KNN, PZT and NBT are 82 kWh, 78 kWh and 31 kWh respectively. Total indirect impact on each economic sector were estimated in kgCO_2-eq to be 6.15 (NBT), 9.07 (PZT) and 54.09 (KNN). Material recovery data were derived from the literature. It was established that PZT offers better potential relative to KNN and NBT as a result of the higher recycling rate of their key constituent materials inter alia lead, ~75 %; niobium, ~11 % and bismuth ~4 %. The implications of these LCA findings in the context of NAT and the Satisficing Framework are discussed in Section 4.2 and 4.3 respectively.

4.2. Implications of NAT to piezoelectric material substitution

By using the LCA results of PZT vs. KNN and NBT piezoelectric materials, the goal is to ascertain whether these materials systems exhibit NAT attributes but from an environmental standpoint. As highlighted in Section 2.1, smart materials such as piezoelectrics, creates the potential for multiple applications in sensors, actuators, motors, generators, and transducers as part of smart products used in different sectors such as healthcare, automotive, consumer goods, ICT etc., thus constituting a functional part of numerous complex systems. However, as shown in Section 4.1, these materials (most notably KNN) have significant environmental impact. This is not to say that piezoelectric materials and the systems they enable causes normal accidents in the form of physical accidents as with NAT, but despite their functional use and cross-sector transformational benefits, tension is created between socio-environmental impacts and economic benefits.

To make the case that the smart materials systems under consideration exhibit NAT attributes (i.e., **interactive complexity** and **tight coupling**) they are analysed based on LCA results as part of an inductive process. Essentially, the three system variables of **observability, predictability**, and **applicability** (i.e., usability) are used to characterise the piezoelectric materials substitutions outcome, based on how the environmental impact of the individual materials (PZT vs. KNN/ NBT) interacts and cascades throughout the supply chain. Prior to the comparative LCA of KNN and PZT, for example, the associated impact of KNN was neither immediately **predictable** nor **observable** because of a shift of the environmental impact to earlier stages of the life cycle (i.e., raw material extraction and purification processes). This explains why KNN was speculated to have better environmental credentials and are considered "greener" replacements to their PZT-based counterpart, leading to an initial error of judgement within the material science community. However, following the LCA, the unintended consequences of niobium extraction (a key material in its oxide form in KNN) occurring at different stages of the supply chain becomes **observable** (e.g. contamination of rivers and water courses during mining of niobium) (Ibn-Mohammed et al., 2018). Some other environmental accidents such as the potential leaching of radioactive metal like uranium, during the refining phase of niobium are more difficult to **observe**. Table 2 summarises other potential environmental risk (i.e. sources of EIA), location of impact and potential mitigation actions across the KNN's value chain.

For PZT, prior to the LCA results, the human toxicity potential of lead (a key material in its oxide form in PZT), is well established, so it is both **predictable** and **observable**. This is also the case for NBT, although the overall toxicity of lead is higher than that of bismuth. Example of **observable** impact include the possible inhalation of PbO dust during machining in the PZT manufacturing process; and evaporation of bismuth during sintering, posing a more significant problem than the evaporation of lead, resulting in reliability issues in piezoelectric applications (Rödel et al., 2015). Also, given that PZT manufacturing extends to a supply chain that further processes the PZT piezo material into products prior to reaching the end user, the **predictability** of how the toxicity of lead is distributed along the supply chain becomes more difficult to **observe**. Nonetheless, it has been demonstrated that lead-based piezo materials exhibit a high degree of physical integrity and device assembly procedures are subject to local health and safety

Table 2
Environmental and health risks across KNN's value chain.

Process Step	Potential Risk	Location of Impact	Mitigation/ Intervention Actions
Mining	Damage to ferricrete layer of soil during site evacuation	Environment	Stripping and stockpiling of soil extraction
	Change to landform and contamination through leakage of hazardous chemicals	Environment	Deconstruct dam at the end of life of mining
	Contamination of rivers and water courses	Environment	Contain and treat effluent prior to release
	Contamination of groundwater	Environment	Provision of storage facilities for hazardous waste
Concentration	Dispersion of dust particles	Environment	Dispersion modelling for dust level prediction
Refining	Potential leaching of radioactive metal such as uranium	Environment	Storage of such chemicals in facilities with radioactive shielding
	Leaching of radioactive metals into water bodies and acidification of aquatic life	Environment	Disposal of waste to be conducted at offsite facilities. Store and handle hazardous chemicals at leak-proof facilities
Smelting	Potential environmental hazard from waste disposal	Environment	Remedial action and control strategy

Table 3
Environmental and health risks across PZT's manufacturing processes (Bell and Deubzer 2018).

Process Step	Potential Risk	Location of Impact	Mitigation/ Intervention Actions
Batching	Inhalation of PbO dust	Workplace	Localized extraction and installation of dust capturing facilities
Ball milling & drying	Entrainment of PbO or PZT particles in liquid effluent stream	Workplace	Filtering/ remediation of effluent
	Entrainment of PbO or PZT particles in water vapour	Workplace	Localized extraction and installation of dust capturing facilities
Calcination & sintering	Inhalation of PbO vapour	Workplace	Extraction of vapour from furnaces, condensation, and capture of PbO particles
Machining	Inhalation of PZT dust	Workplace	Use of appropriate cutting fluids
Failure of filtering, scrubbing in extraction systems	Increase of airborne and topsoil lead concentration in local environment	Environment	Regular testing, inspection, and maintenance
Failure of filtering of liquid effluent	Unplanned increase of lead concentration entering water treatment plants	Environment	Regular testing, inspection, and maintenance

measures (Bell and Deubzer 2018). Table 3 summarises probable risks (i.e., EIA sources), sites of impact and possible mitigation measures across PZT's value chain.

It is worth recounting that the sites of the impact of PZT is mainly at the factory level during processing but there are also a few key processes that also negatively affects the environment as indicated in Table 3. Despite the toxicity of lead in PZT, there is no concrete research evidence supporting the fact that it has a negative effect on humans during usage (Ibn-Mohammed et al., 2018). Moreover, there are highly recommended protocols, risk assessment procedures, mitigation policies and routine monitoring for levels of lead in the bloodstream of the workforce that have proven effective. It has also been indicated that end users seldom make a direct contact with PZT components, and this reduces the chances of risk to health (Bell and Deubzer 2018).

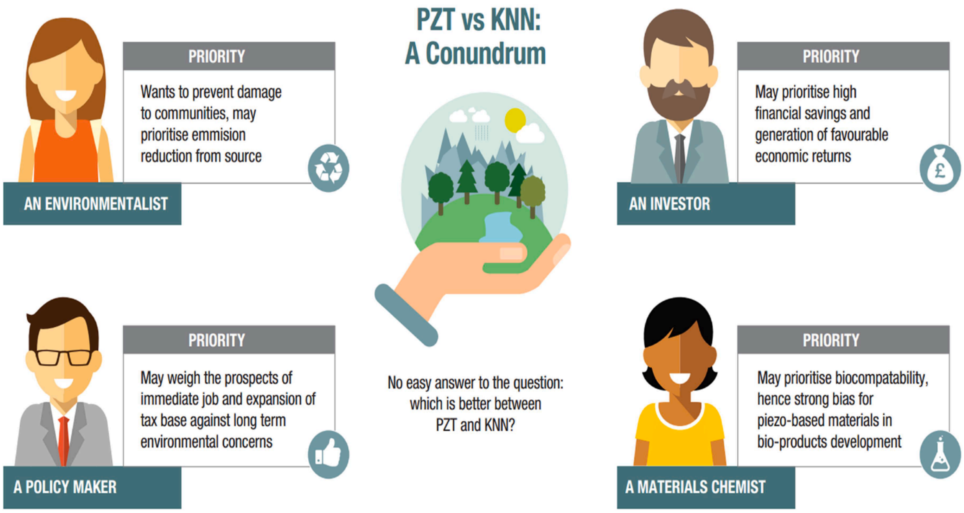
Recognising the fact that NAT focused on the consequences of physical accidents, this paper proposes a new form of system accident termed ***Environmental Impact Accident*** (EIA), to accommodate the complex environmental credentials of piezoelectric materials. Indeed, EIA is akin to NAT given the broader unintended and inevitable environmental consequences along the entire product supply chain (up/downstream) due to replacing toxic PZT with KNN or NBT. It is described as such because, although the known toxic material (lead in PZT) is done away with in the substitute material, other serious environmental impacts are inevitably caused along the supply chain; hence the "accidental tag".

Consequently, it is clear that NAT's attributes of **interactive complexity** and **tight coupling** are exhibited in material substitution of piezoelectric materials as characterised by smart materials system *predictability, observability,* and *applicability*. **Interactive complexity** is reinforced by the fact that piezoelectric materials find applications in every aspect of modern life. As such, segmentation by usage or material performance specifications is demanding and may lead to a mismatch of expectations between industry and legislators in terms of the number of different categories on which legislation can be imposed (Bell and Deubzer 2018). The interaction between all aspects of the environmental profile of piezoelectrics material supply chain, their development and characterisation, regulatory requirements, and the fact that both existing *lead-based* and *lead-free* piezoelectric materials constitute negative externalities at different levels of the production value chain render them **tightly coupled.** Essentially, NAT is extended into EIA, to take into consideration different factors during sustainable material substitution including: i) the magnitude of potential environmental impact and the stage of occurrence within the value chain; ii) interconnectedness of the impact and the stakeholders involved; and iii) uncertainty generated through the replacement of *lead-based* piezo materials with *lead-free* alternatives.

4.3. *Implications of the satisficing framework to piezoelectric material substitution*

In considering mitigation strategies for the EIA risks discussed in Section 4.2, a conundrum is created, triggering significant questions about how LCA outputs can lead to effective decision making. Ibn-Mohammed et al. (2017) highlighted how this conundrum is created during decision-making processes, Fig. 7.

To address the conundrum posed, the 3 criteria identified in Section 3.3, are adopted to assess, and evaluate the relative "satisficing potential" of each piezoelectric material options based on some properties highlighted in Fig. 8. As summarised in Table 4, PZT meets **Criterion 1** as it is the most widely adopted, constituting an integral part of the global piezoelectric materials and devices market. This is also confirmed by its impressive Herfindahl-Hirschman Index (HHI) profile, a measure of its market concentration and competitiveness, (Fig. 8). PZT partly meets **Criterion 2** (from an ecological perspective), since it has overall best profile in terms of sustainability, material and substitution costs, and availability of raw materials (lead is one of the most produced metals in the world). However, the toxicity of PbO in PZT is still a source of major concern especially at its end of life as indicated by its REACH



Wants to prevent damage to communities, may prioritise emmision reduction from source

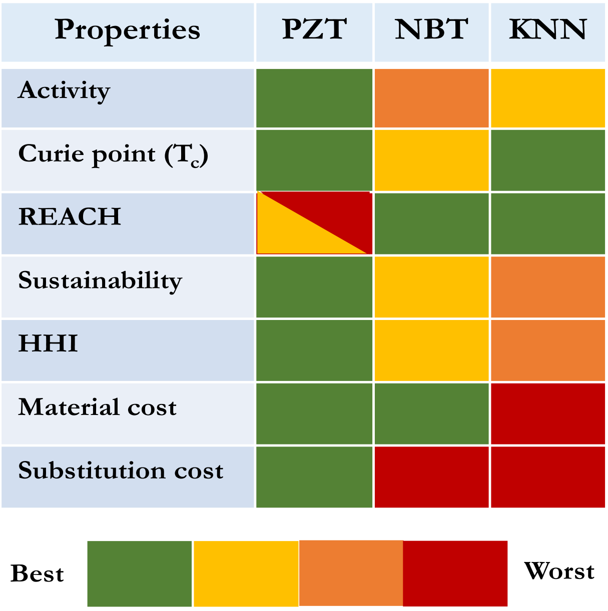
May prioritise high financial savings and generation of favourable economic returns

May weigh the prospects of immediate job and expansion of tax base against long term environmental concerns

May prioritise biocompatability, hence strong bias for piezo-based materials in bio-products development

No easy answer to the question: which is better between PZT and KNN?

Fig. 7. A graphical representation of the puzzle presented through the LCA results of *lead-free* (e.g. KNN) against *lead-based* (PZT), based on assumed viewpoints of four dissimilar stakeholders. Adapted from Ibn-Mohammed et al. (2017).



Properties	PZT	NBT	KNN
Activity	🟩	🟧	🟨
Curie point (T_c)	🟩	🟨	🟩
REACH	🟨🟥	🟩	🟩
Sustainability	🟩	🟨	🟧
HHI	🟩	🟨	🟧
Material cost	🟩	🟩	🟥
Substitution cost	🟩	🟥	🟥

Best 🟩 🟨 🟧 🟥 Worst

Fig. 8. Typology of three piezoelectric materials, adapted from Bell (2016).

profile in Fig. 8. PZT meets **Criterion 3,** commanding a huge market and is well understood, encouraging investments through piezoelectric applications. In fact, the piezoelectric device market is forecasted to grow from $23.5 billion in 2016 to $31.3 billion by 2022, at a compound annual growth rate (CAGR) of 4.9 % between 2019 and 2022 (Research and Markets 2018).

NBT does not currently meet **Criterion 1** because its potential of transitioning from laboratory to market is still currently being explored. They have shown promise in terms of high-temperature and high-power applications as well as mechanical reliability but are not market ready as reflected by its HHI profile, Fig. 8. To fast-track their market readiness, more research efforts is still required to gain a better understanding of secondary characteristics including electrical/mechanical properties, fatigue and machinability (Koruza et al., 2018). NBT partially meets **Criterion 2** from an ecological point of view due to overall lower material costs and from a REACH perspective. However, its substitution cost is very high, with a moderate profile in terms of overall sustainability. NBT has the potential to meet **Criterion 3** given that avenues for new materials with properties better than PZT for select applications are opening, and by extension encourage investments at the application levels.

Lastly, KNN presently does not adequately meet **Criterion 1** for similar reasons to NBT, but as a result of their high Curie temperature, they have attracted interests from producers and manufacturers of bulk materials and multilayer actuators (MLAs). Additionally, KNN is compatible with cheaper nickel (Ni) internal electrodes for MLAs, with Ni furnishing high electromigration resistance and stability on exposure to high applied electric fields (Kawada et al., 2009), dissimilar to its competitor NBT which needs a complex non-standard metallisation solutions or the use of inert noble metals (e.g. Pt and Ag-Pd) (Kobayashi et al., 2013). Thus, KNN is emerging as the leading possible alternative to PZT for piezoelectric applications, leading to a pathway for market penetration. KNN also does not meet **Criterion 2** on the basis of ecological consideration due to the enormous environmental effects associated with niobium extraction, a precursor to niobium pentoxide, as highlighted in Section 4.1.

KNN's profile covering its HHI, sustainability, material, and substitution costs (Fig. 8) are not quite adequate. However, by adopting strategies in Table 2, possible environmental and health risks embedded within their supply chain can be mitigated. Similar to NBT, KNN has sufficient positive attributes to match **Criterion 3**, considering the opportunity for novel materials with properties and attributes better than PZT. This is particularly true for high-temperature applications like control actuation in aero-engines to promote fuel efficiency. The development of lead-free alternatives for direct living tissue sensor implantation in medicine and the health industry generally represent interesting potential market for KNN.

It is worth noting that presently, none of the piezoelectric substitutes could be "drop-in" alternatives for PZT for a specific proprietary variant or grade because of electrical properties (e.g., electronic drivers and amplifiers) electromechanical properties (e.g., device design) alongside

Table 4
Summary of the satisficing potentials of piezoelectric materials. .

Satisficing criteria	PZT (Lead-based)	NBT (Lead-free)	KNN (Lead-free)
Criterion 1	Satisfactory	Not yet satisfactory	Not yet satisfactory
Criterion 2	Quite satisfactory	Partially satisfactory	Potentially satisfactory
Criterion 3	Satisfactory	Potentially satisfactory	Potentially satisfactory

financial expenses associated with re-design and approvals (Bell and Deubzer 2018). In cases where piezoelectric properties of PZT are evenly matched with some lead-free alternatives, other important physical characteristics including elastic and dielectric properties and temperature dependence will be different with increased cost and implementation implications. Indeed, the expenditure associated with the redesign of transducers is likely to cost a maximum of £100,000 per one item and more relatively complex systems such as the ink-jet heads may require investment above £1 m. All of these factors within a Satisficing Framework must be considered when decisions regarding material substitution strategies are being made.

5. Policy and LCA integrations

This section discusses the role of policy in enabling LCA integration into product development, alongside policy options recommendations based on the piezoelectric materials case studies.

5.1. *Role of policy in enabling LCA integration into life cycle product design*

Policy can play significant role in promoting the integration of LCA into life cycle product development processes through:

i. *regulatory mandates*, by mandating LCA as a requirement for specific types of industries or products to assess their environmental impact prior to market entry (Lehmann et al., 2015);
ii. *standards and guidelines*, through the establishment of standardised methodologies and protocols for conducting LCAs, rendering the calculation steps much easier to perform and interpret, thus ensuring consistency and comparability across various industries and products (Chang et al., 2014);
iii. *incentives*, by providing financial incentives including tax credits, subsidies or grants for companies that adopts eco-friendly practices and embed LCA into their product development processes (Lehmann et al., 2015; Sala et al., 2021), thus encouraging business investment in sustainable practices;
iv. *research and development support*, via funding of research and development efforts focused on enhancing LCA methodological approaches, tools, and databases (Vinodh and Rathod 2010), thus contributing to the continuous improvement and advancement of LCA practices (Hetherington et al., 2014);
v. *education and training,* through investments in educational programmes and training initiatives to facilitate understanding and proficiency in carrying out LCA (Piekarski et al., 2019), thus motivating practitioners to effectively apply it in product development;
vi. *collaboration and partnerships,* through encouraging collaboration among stakeholders including industry, academia, government agencies, and NGOs (Nakano and Hirao 2011), fostering knowledge sharing, best practices, and innovation in LCA implementation (Testa et al., 2022); and
vii. *transparency and reporting requirements,* by promoting transparency in reporting LCA results, rendering information available to consumers (Cooper and Fava 2006).

Indeed, by defining requirements for disclosing environmental impacts on product labels or in marketing materials, consumers can make environmentally informed decisions. Nonetheless, there are numerous barriers to policy implementation to overcome, and would require robust stakeholder engagement for qualitative and quantitative data collection and techno-economic analysis of policy decision options. This creates an opportunity for a future direction of this work.

5.2. *Policy options for embedding LCA into piezoelectric materials development*

To recommend policy options for embedding LCA into piezoelectric materials development specifically and other products in general, the work of Lehmann et al. (2015) that focused on the automotive sector and identified four different structural components that are combined in a pair-wise fashion and prioritised, is drawn upon. The structural elements to define any viable policy or legislative option as identified by Lehmann et al. (2015) are summarised in Table 5. It shows different categories of enforcement, which can either be *mandatory* or *voluntary*, alongside different levers based either on *product performance* or *process improvements* requirements. It also shows different approaches to the adoption of LCA based on its complete consideration or just imbibing the concept of life cycle thinking, as well as the roles of market, be it to gain *access* or serve as an *incentive*.

Through different permutation and combination of the structural elements in Table 5, varied policy options were established as schematically illustrated in Fig. 9. The first possible policy option as shown in Fig. 9, is one that is *mandatory*, based on *product performance*, is *directly* informed by *complete LCA*, and differentiated by *market access*. Using this same logic which traced out policy option 1 from Fig. 9, a total of eleven policy options emerged. The authors noted that for voluntary policy options, the “market access” feature is not expected as they are not legally binding and are only meant to induce indirect effects on the markets. The identified policy options were prioritised by the authors using three conditions including the (i) rigorous nature of the implementation (informed by the nature of enforcement and lever); (ii) rigorous nature of LCA adoption (i.e. the extent of its adoption); and (iii) stakeholder acceptance (i.e., the extent to which stakeholders were willing to implement LCA).

Table 5
Structural components for defining policy options, alongside their characteristics.

Structural components	Characteristics of policy option	Description of policy option
Category of enforcement	Mandatory (with regulatory oversight)	Legally binding policy with defined requirements such as setting target/limit values that must be met.
	Voluntary (“Soft” legislations)	Non-legally binding policy but anticipates indirect effects.
Levers	Performance	Policy stipulates product requirements and if unfulfilled, the product undergoes redesigning.
	Process	Policy specifies company-level process requirements for process optimisation and improvements.
Adoption of LCA	Direct (complete LCA)	Policy directly stipulates LCA-informed targets/limits, mandating the communication of the complete LCA outputs.
	Indirect (life cycle thinking)	Back-end adoption of LCA or LCA results to inform policy development and formulation such as setting target values for processes.
Market role	Market access	Policy specifies minimum requirements (e.g., threshold values) for transitioning products to market. Generally, “market access” is leveraged for the exclusion of products/processes/services with low performance from the market.
	Market incentive	Policy specifies a framework (e.g., standards or criteria) for supporting environmentally-friendly products. “Market incentive” is usually targeted at the promotion of between 10 and 20 % superior products/processes/services, through the use of Eco labels, for example.

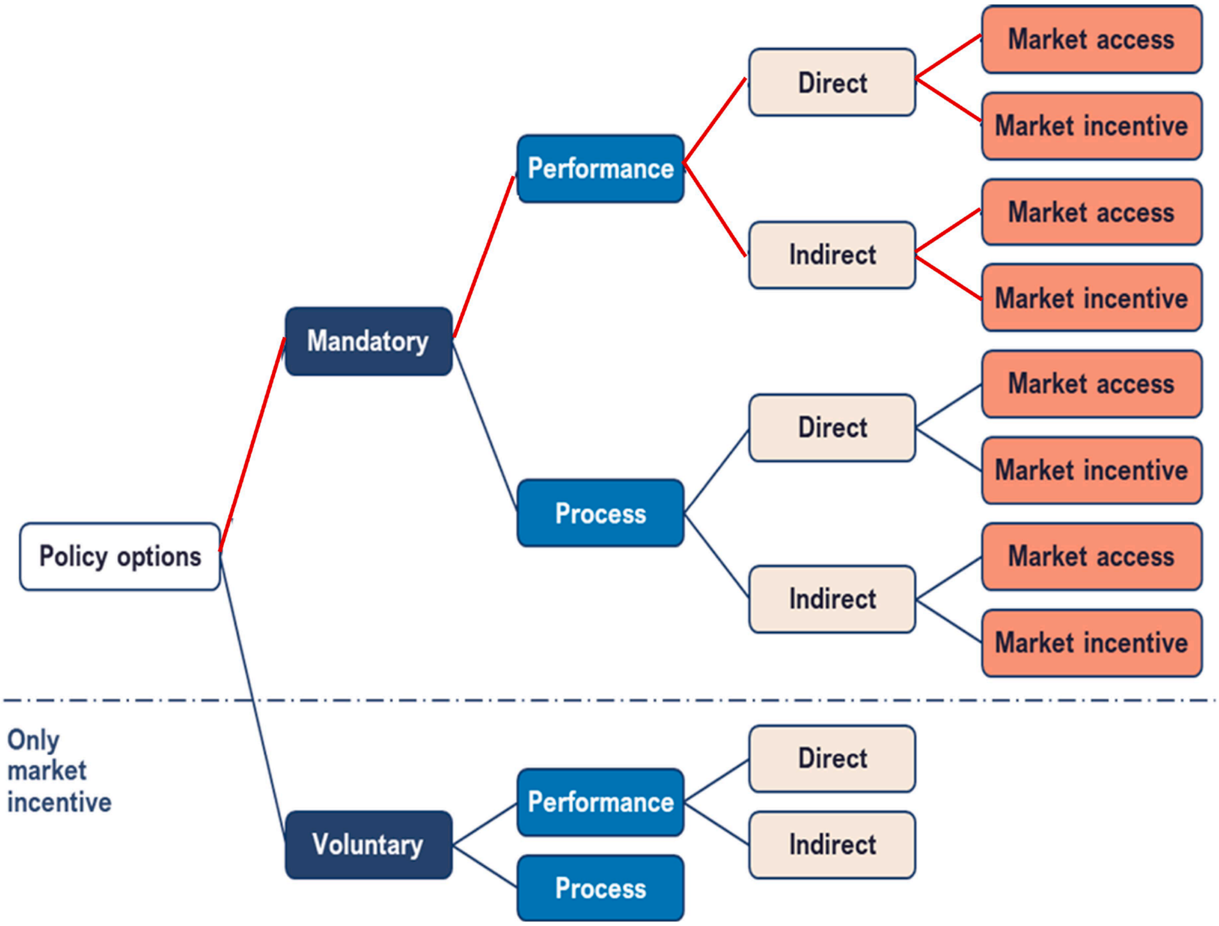


Fig. 9. 11 emerged policy options for embedding LCA in legislations as a strategy for enhancing sustainable life cycle product engineering, adapted from Lehmann et al. (2015).

Lehmann et al. (2015) conducted strengths, weaknesses, opportunities, and threats (SWOT) analysis based on a number of criteria including technical requirements, methods, models, tools, data, quality assurance and communication to analyse the options. This was further complemented by relevance, acceptance, credibility, easiness, robustness (RACER) analysis (Hernandez and Cullen 2019). Different policy options require different solutions for implementation. Based on their particular features as informed by SWOT and RACER, four policy options, namely: *mandatory-performance-direct, mandatory-performance-indirect, mandatory-process-direct,* and *voluntary-performance-direct*, differentiated by *market role* were prioritised.

For instance, the "*mandatory-performance-direct"* policy option is the most stringent option for embedding LCA into policy regulations for product development, compared to the less stringent "*mandatory-performance-indirect*", which does not require full LCA to be conducted, but can be regarded as an intermediate step for legislation informed by full LCA. If the lever is based on the technical aspects of process-based policies rather than product-based, then the invoked policy option is "*mandatory-process-direct"* or "*mandatory-process-indirect"* both of which can be regarded as a transitional pathway for LCA adoption to inform performance-based legislations, although the latter is weaker. The *voluntary-performance-direct* and *-indirect* policy options can also be based on product performance and process improvements, but are considered "soft" legislations, although the "direct" version is the strongest policy option, which can be initially implemented to mitigate resistance against mandatory legislations (Lehmann et al., 2015).

This selected portfolio of options and a knowledge of their merits and demerits can facilitate the development of how LCA principles can be embedded into piezoelectric material substitution decision making. Given that piezoelectric materials are used in sensors, actuators, motors, generators, and transducers as part of smart products used in different sectors (e.g., healthcare, automotive, consumer goods, ICT etc.), the *mandatory-performance-direct* and *-indirect* policy option are therefore adjudged applicable. Currently, policy decisions within the piezoelectric market are fraught with uncertainties as the decision to replace lead-based piezo (e.g., PZT) with lead-free alternatives (e.g., KNN and NBT) are periodically revised, with the view that the exemptions granted to PZT would be permanently rescinded, when lead-free alternatives become viable and market ready. However, this policy position is not effective as PZT continues to be the most utilised material across the piezoelectric material market. Recommendations, both theoretical and practical, based on the *mandatory-performance-direct* and *-indirect* policy option are therefore proposed in Tables 7 and 8. Current legislations and the necessity for new regulations for lead-based piezoelectric materials, and their associated objectives are also provided by Bell and Deubzer (2018).

6. Conclusion

By using the material substitution scenarios of PZT vs. KNN and NBT piezoelectric materials, it was illustrated, for the first time, how two theoretical lenses, namely NAT and the Satisficing Framework, are used inductively to enhance decision making at the interpretation phase of LCA. This is applicable to all aspects of any sustainable material substitution strategy fraught with a conundrum.

Informed by LCA results, NAT was first drawn upon, to characterise the broader unintended and inevitable consequences of piezoelectric materials substitutions. By operationalising NAT as a life cycle

Table 7

Mandatory-performance-direct policy option for piezoelectric materials.

Market role	Theoretical/practical example of policy legislation
Access	Mandating piezoelectric materials/products developers to demonstrate through full LCA that life cycle CO_2 emission or toxicity do not surpass the defined limit value set through legislation. For example, a toxicity limit based on a given concentration (μg/m^3) in a product containing PZT may be imposed. Mandating developers to declare the origin and environmental impact of niobium, a precursor to niobium pentoxide as part of KNN's value-chain manufacturing process. Mandating the recycling of individual PZT components to prevent their disposal alongside the host system. Mandating developers to define the risks associated with the manufacture, use, and disposal of PZT. Mandating e-waste recycling through a balanced mixture of controlled disassembly and raw materials extractions.
Incentive	Mandating piezoelectric materials/products developers to demonstrate life cycle CO_2 emission or toxicity profile in the form of an eco-label. This may trigger possible market advantage if purchasing decisions are informed by environmental credentials of piezo products.

Table 8

Mandatory-performance-indirect policy option for piezoelectric materials.

Market role	Theoretical/practical example policy legislation
Access	Mandating piezoelectric material manufacturers to show evidence that CO_2 emission or toxicity profile in the use phase of piezo-based products do not exceed a set value. For example, Xg CO_2 emissions/ product in use phase or in the manufacturing phase
Incentive	Mandating piezoelectric material manufacturers to demonstrate/ publish emission information which occurs in the relevant phase (e.g. sintering or drying or calcining), based on appropriate label.

engineering-based methodology, NAT attributes of **interactive complexity** and **tight coupling** was revealed in piezoelectric materials, based on environmental systems' *predictability, observability,* and *applicability.* This led to the introduction of Environmental Impact Accident (EIA) as a new concept, facilitating an early assessment of the associated complexities influencing the sustainability credentials of piezoelectric materials, thus informing mitigation strategies. Equipped with effective complexity assessment, options can be compared to target the requirements to simplify and measure mitigation efforts. However, in exploring the mitigation options for such EIA when considering multiple objectives that conflict or trade-off between alternative piezoelectric materials with different environmental and health impacts across the value chain, a conundrum is created. Consequently, the Satisficing Framework was adopted to resolve the EIA-induced conundrum, using the three crucial benchmarking elements based on ecological/environmental impacts.

Finally, given the policy relevance of the case studies presented, policy options, both theoretical and practical, for embedding LCA into product life cycle decision making is proposed. This was based on different categories of *mandatory* or *voluntary* enforcement, characterised by product requirements specifications as a prelude to gain *market access* or drive *market incentives*. This enables effective policy decision making within the piezoelectric materials community when translating material development breakthroughs into market and commercial opportunities, while ensuring uncompromised environmental integrity.

CRediT authorship contribution statement

T. Ibn-Mohammed: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **F. A. Yamoah:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **A Acquaye:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **K. Omoteso:** Writing – review & editing. **S.C.L. Koh:** Writing – review & editing, Resources.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Additional information

This paper is not accompanied by supplementary information.

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