



# Inconsistencies in handling of multifunctionality in the environmental footprint of electric vehicle batteries: a cross-industry analysis

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## Abstract

**Purpose** With the increasing importance of sustainable development, reflected in various policies, life cycle assessment (LCA) guidelines for different industries and materials have emerged in recent years, mainly linked to batteries and their raw materials. This paper analyses the inconsistency between different industries' LCA guidelines, their practical implications and the potential way forward.

**Methods** In this publication, we analyse LCA guidelines for four key battery raw materials, namely lithium, nickel, cobalt and copper. We linked the materials to their relevant applications and industries, focusing on the multifunctionality handling in the different industries. The analysis considers two types of multifunctionality handling: co-production and recycling end-of-life treatment. We determine the consistency within and between applications and industries, as well as along supply chains from the material to the product, and analyse the implications of inconsistencies quantitatively and qualitatively. Based on the analysis results, we discuss key consistency checks needed in the future and potential pathways towards more consistency based on an influence–interest analysis of the involved industries regarding potential standardisation processes.

**Results and discussion** The analysis shows inconsistencies in the multifunctionality handling within and between applications and industries, as well as along supply chains. The discrepancies can lead to a variation of the climate change impacts per kilogram of material of up to a factor of five. Potential developments towards more consistency could be driven bottom-up by the metal associations or top-down by the different industries or as a combination of both. Attention is needed regarding the upcoming mandatory LCA guideline for batteries in the EU market. For overall consistency, international industries would need to align with this guideline. Until consistency is reached, transparency on methodological aspects, potential inconsistencies and their implications is crucial.

**Conclusions** Multifunctionality handling is only one relevant consensus aspect for which this comparison must be made between various applications and industries. Other aspects are, for example, electricity modelling and impact assessment methods. An extension of this work is needed to cover all potential inconsistencies and guide future standardisation. This could be supported by further analysis of possible pathways and the development of guidance for a consensus process towards standardisation.

**Keywords** Allocation · Battery material · Electric vehicles · End-of-life allocation · Multifunctionality · LCA guidelines · Standardisation

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## 1 Motivation and introduction

The European Union (EU) implements systems and incentives towards a sustainable and resilient energy and mobility transition through regulations such as the EU Batteries Regulation and the Critical Raw Materials Act (CRM) (European Parliament and European Council 2023; European Parliament and Council of the European Union 2024). A key aspect of the EU Batteries Regulation is the carbon footprint reporting by 2025, followed by thresholds which represent maximum allowable carbon footprints that batteries may not exceed to enter the EU market by 2028 (European Parliament and European Council 2023). Mandatory carbon footprint declarations and thresholds require a standardised way to perform the life cycle assessment (LCA), enabling a fair comparison of producers and products. Therefore, in the past years and ongoing, different stakeholder groups have developed LCA guidelines for batteries and electric vehicles (EV) to shape the way the LCA is done in the future (e.g. Bonell et al. 2024; Catena-X Automotive Network E.V. 2023; Duce et al. 2013; European Commission 2024; Global Battery Alliance 2023).

One topic that is frequently addressed but still lacks standardisation is the treatment of multifunctionality throughout the product life cycle (Beylot et al. 2024; Eltohamy et al. 2024). A production system or process is considered “multifunctional” when it produces or treats multiple products or services (DIN EN ISO 14044 2006). In the life cycle of an EV battery, different situations of multifunctionality occur: (i) co-production of primary and secondary raw materials, (ii) multifunctional use stage with applications such as vehicle-to-grid or second use of batteries and (iii) multifunctionality at the end of life (EoL) with the recycling of batteries.

Multifunctionality requires special attention when performing an LCA study. The modelling of multifunctionality poses challenges, as the LCA method is based on determining the environmental impact of a product based on its function, which is not straightforward with multifunctionality (Hauschild et al. 2018; Husmann et al. 2024). Various guidelines and scientific publications address the handling of multifunctionality in the battery life cycle (Eltohamy et al. 2024; Husmann et al. 2024; Lai et al. 2021; Santero and Hendry 2016).

Guinée et al. stated already two decades ago: “There is no ‘correct’ way of solving the multifunctionality problem, even not in theory. There are, however, demands one can make to solving the problem, like that solution should be consistent in itself, and that it should be consistent with main methodological principles” (Guinée et al. 2004, p. 33). This underlines that the handling of multifunctionality

is a topic that needs harmonisation and not the development of further methods. This harmonisation is ongoing in various battery and vehicle initiatives, as well as some material-specific guidelines. However, these isolated standardisation efforts can lead to inconsistencies between applications and industries and therefore to over- or underestimated environmental impacts at the system level, as well as to considerable efforts for suppliers to provide environmental footprints for their materials across different industries. These inconsistencies between industries are currently not addressed.

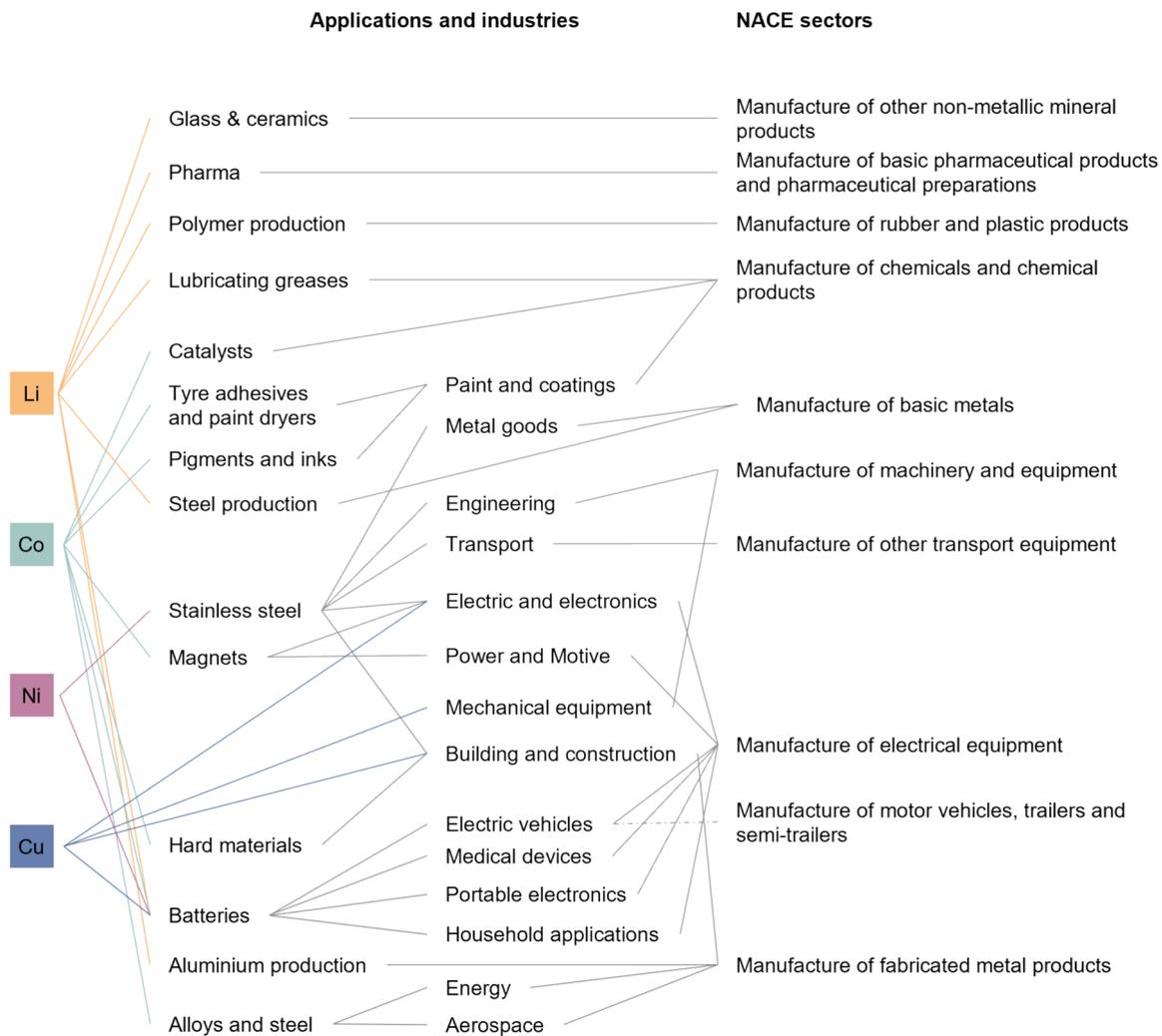
Therefore, this paper analyses the inconsistency between different industries’ LCA guidelines, what it means in practice and the potential way forward. For four relevant battery materials—lithium, nickel, cobalt and copper—their main applications and relevant industries are identified based on previous analyses (SCRREEN 2022a, b, c, d). For these industries and applications, LCA guidelines are searched and analysed. This work updates and extends previous review work (Eltohamy et al. 2023, 2024; Husmann et al. 2024). The EoL allocation and handling of general multifunctionality are analysed for all guidelines, and the consistency in and between applications and industries is determined. This is followed by a qualitative and quantitative analysis of the implications of different guidelines and standards before discussing the key consistency checks and potential paths towards more consistency.

## 2 Methods

### 2.1 Analysed materials and their applications

The global applications of lithium, nickel, cobalt, and copper were analysed and linked to NACE sectors based on previous analysis (SCRREEN 2022a, b, c, d). The simplified overview of applications, industries, and sectors in Fig. 1 shows the complexity of the market for metals.

Lithium is used in diverse applications, with batteries currently dominating the global demand for lithium with 71% (SCRREEN 2022c). This includes non-rechargeable (mainly for household applications and medical devices) and rechargeable batteries (for portable electronic devices). The most extensive end use of batteries is in electric vehicles (EV), due to large battery sizes. Furthermore, lithium is used in glass and ceramics, lubricating greases, polymer production, casting powder in the steel industry, and further applications such as pharmaceutical products and aluminium (alloy) production (SCRREEN 2022c). Future outlooks forecast that the energy transition will drive the demand for lithium and, more explicitly, batteries (Energy Transitions Commission 2023).



**Fig. 1** Simplified overview of applications of lithium, cobalt and nickel and copper and to which NACE sectors they belong based on (SCRREEN 2022a, b, c, d). The sector of manufacture of motor vehicles,

trailers and semi-trailers is added (dotted line) to show the link of batteries and vehicles

More than half of the global cobalt production is used for batteries, of which about half is used in EVs. Cobalt-containing products generally end up with a large share in the portable electronics and the automotive industry. Further relevant applications are power and motive, paint and coating, energy, aerospace, construction, and chemicals. Recently, cobalt demand for batteries has grown compared to other applications (SCRREEN 2022a). Batteries will likely drive future demand; however, not all will be used for vehicle electrification but also in consumer electronics (Energy Transitions Commission 2023).

Batteries only make up 7% of the global first uses of nickel. The production of stainless steel highly dominates the demand for nickel. Nickel in steel is used in various applications such as engineering, metal goods, transport, electrical and electronics, and building and construction

(SCRREEN 2022d). While the demand for nickel in batteries might increase compared to other applications, batteries are unlikely to become the most relevant application as the nickel demand is expected to be driven by several energy transition technologies and other industries. Nickel is also relevant in several energy transition technologies besides batteries, such as hydrogen, nuclear, and wind power (Energy Transitions Commission 2023).

Copper has a wide range of end uses. The main applications of copper are electric and electronic applications (power circuits, wires used for electric energy supply from power plants, motor windings in electrical motors and connectors in computers), mechanical equipment (such as sleeve bearings and other forged parts), buildings (in wiring, pipes and fittings, electrical outlets, switches and locks) and automotive and transport (SCRREEN 2022b). The widespread

application of copper shows that its demand is not driven by batteries for EVs. Furthermore, it is also unlikely that this will change in the future. Future copper demand is expected to be driven by a wide range of energy transition technologies and conventional products (Energy Transitions Commission 2023).

Given the widespread use of these materials across multiple applications and industries, many companies and supply chain actors may have differing perspectives on the preferred approach to handling multifunctionality for their product systems. Especially because they might use different forms of the substances (e.g. nickel sulphate in batteries and nickel class 1 in the nuclear industry), sources of the raw materials may be different or change over time (e.g. laterite vs. sulphide mining).

## 2.2 Analysed guidelines and best practices

Based on the relevant applications and industries presented in Section 2.1, LCA guidance documents were identified (see Fig. 2). The complete list can be found in the SI in Table S1–1. The review targeted not only European but, more generally, also global guidelines. In total, 24 guidance documents were identified. For lithium, copper and cobalt, material-specific guidance documents exist, developed by metal associations (Cobalt Institute 2023; International Lithium Association Ltd (ILiA) 2024; Vaccari and Tikana 2017). Additionally, one scientific publication aimed to harmonise LCA practices in the metals and mining industry and, therefore, targets all materials analysed in this publication (Santero and Hendry 2016). Most guidance documents are available for batteries and vehicles. This reflects the ongoing development and harmonisation efforts and the regulatory pressure from the EU Batteries Regulation. Four guidance documents for batteries were identified; one is currently in the draft stage. Of these four documents, three are developed by or on behalf of the European Commission (Andreasi Bassi et al. 2023; Bonell et al. 2024; European Commission 2024). The fourth one is developed by an industry organisation (Global Battery Alliance 2023). For vehicles, seven guidelines were identified. These were developed by industry and/or academia (CATARC 2022; Catena-X Automotive Network E.V. 2023; Duce et al. 2013; Moréac-Njeim et al. 2025; PFA 2022; RISE 2019; VDA 2022). Material

associations also developed guidance documents for aluminium and steel (European Aluminium, 2023; Worldsteel Association 2017). For chemicals, guidance documents from different industry initiatives were found (American Petroleum Institute (API) 2023; Together for Sustainability 2024). Product category rules (PCR) were developed for pharmaceutical applications, constructions and electronics, two by the international environmental product declaration (EPD) system and one by a research organisation (EPD International 2019, 2024; Siegert et al. 2019). For electronics, a further guidance document by an industry organisation was found (Electronic Components Board Japan Electronics and Information Technology Industries Association 2008). The guidance document for plastics originates from the Joint Research Centre of the European Commission (Nessi et al. 2021). The analysis shows the variance of stakeholders involved in developing guidance documents.

## 2.3 Approaches for handling multifunctionality

Different approaches exist to solve multifunctionality throughout the life cycle of a battery: (i) subdivision, (ii) system expansion/substitution and (iii) allocation (see Fig. 3). Subdivision refers to solving the multifunctionality by dividing the multifunctional process into sub-processes that can be linked to one function (DIN EN ISO 14044 2006). Two different interpretations exist for system expansion. The system is expanded to include all additional functions when applying system expansion in the traditional sense. It would, therefore, change the functional unit of the system (Husmann et al. 2024). When interpreted as substitution, the additional functions are subtracted from the system (Finkbeiner 2021). While these two interpretations are conceptually different, their results are compatible (Eltohamy et al. 2024). Allocation refers to partitioning a process's environmental impacts among different products. An allocation factor ( $a$ ) is used to allocate impacts to one product or the other. The allocation factor can be based on physical properties, such as mass, or other properties, such as economic value (DIN EN ISO 14044 2006).

Following the ISO standard, these approaches are combined in a specific hierarchy: first, allocation should be avoided with subdivision or, if not possible, system expansion. If allocation cannot be avoided, it shall be performed based on physical

**Fig. 2** Number of guidelines identified for applications and industries with an overview of materials used in these

	Battery	Vehicle	Chemicals	Plastics	Steel	Pharma	Aluminium	Electronics	Construction
Li	x	x	x	x	x	x	x		
Ni	x	x			x			x	x
Co	x	x	x		x	x		x	x
Cu	x	x						x	x
	4	7	2	1	1	1	1	2	1

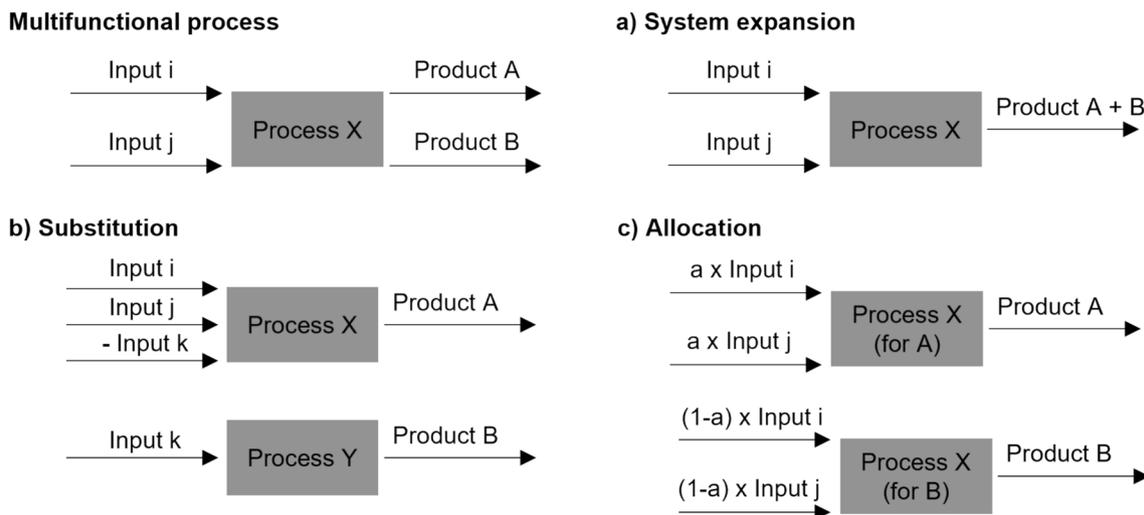


Fig. 3 The main different approaches to handle multifunctionality are system expansion (a), substitution (b) and allocation (c)

properties and, if not possible, based on other properties such as the economic value (DIN EN ISO 14044 2006).

### 2.4 Approaches for solving multifunctionality at end-of-life recycling

The recycling process at the EoL has two main functions: (i) producing secondary materials and (ii) waste treatment. There are different approaches to handling the multifunctionality at EoL. In the guidelines analysed, three different ones are mentioned: (i) cut-off, (ii) avoided burden and (iii) the circular footprint formula (CFF). These methods split the environmental impacts differently over the battery life cycles (Fig. 4).

The cut-off method allocates the environmental impacts of the recycling process to the secondary materials produced. This means that the recycling process at the EoL is excluded from the life cycle of the battery that gets recycled (Product A). The battery using the recycled material (Product B) carries the environmental burdens of the recycling process (Nordelöf et al. 2019). The cut-off point typically describes the point until which the EoL is modelled. In this approach, recycling is treated as a production process of secondary material.

Avoided burden is the application of the principle of substitution to recycling. With avoided burden, recycling is modelled as a waste treatment process. The environmental impacts allocated to the battery that gets recycled (Product

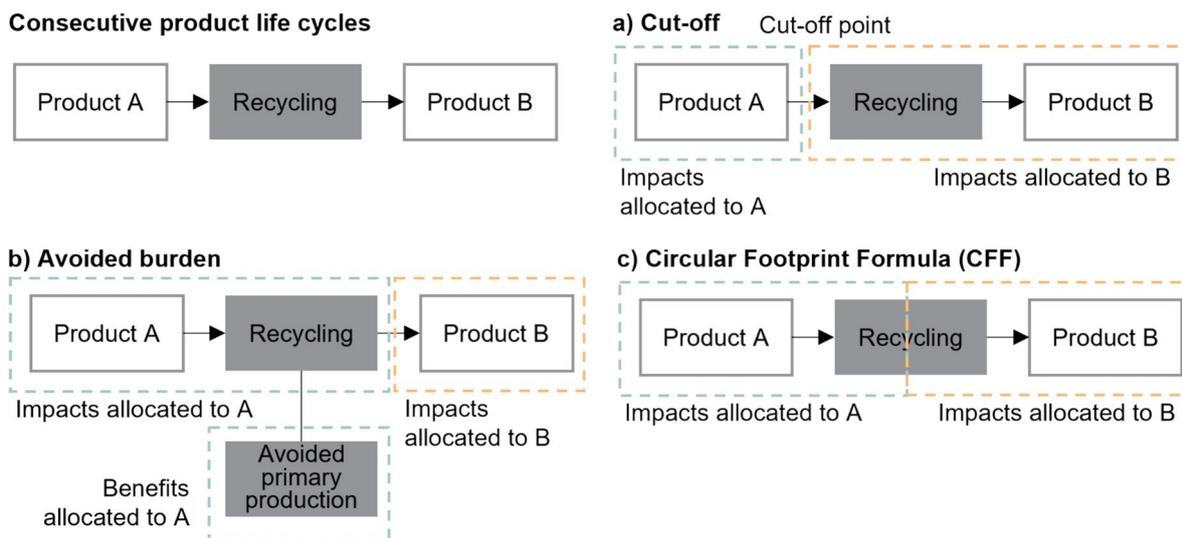


Fig. 4 The main approaches to the EoL allocation are cut-off (a), avoided burden (b) and the circular footprint formula (CFF) (c)

A) are the impacts of the recycling minus the impacts avoided from the primary production with the recycled material. Therefore, the benefits of recycling are allocated to the battery that gets recycled (Allacker et al. 2017; Ekvall et al. 2020; Nordelöf et al. 2019). The resulting net environmental impact of recycling is the difference between the impacts of secondary and primary production. However, this one-to-one displacement is an assumption, and the dynamics of demand and supply have to be studied to determine whether secondary production actually decreases primary production (Geyer et al. 2016). Otherwise, applying avoided burden will likely overestimate the recycling benefits in most real-world cases. The battery using the secondary materials (Product B) gets them burden free.

The CFF is a hybrid approach between cut-off and avoided burden, introduced for batteries by the product environmental footprint category rules for high specific energy rechargeable batteries for mobile applications (PEFCR) (Bonell et al. 2024). The environmental impacts and benefits of recycling are split between the battery that gets recycled (Product A) and the battery using the secondary material (Product B). The CFF includes several aspects, such as the materials quality, recovery rates and demand factors based on market conditions (Bonell et al. 2024).

### 3 Results

#### 3.1 Guideline analyses

##### 3.1.1 Guidelines for solving multifunctionality at end-of-life recycling

When the recycling at EoL was included, it was handled either by following one of the allocation approaches

described in Section 2.4 or no EoL allocation was needed (see Fig. 5). The cut-off approach is the most applied. It is recommended by the material-specific guidelines for lithium and cobalt, by one battery and one vehicle guideline, as well as by guidelines from the chemicals, pharmaceutical, aluminium, construction and electronics industries. However, the cut-off points may vary, as also identified in earlier reviews (Eltohamy et al. 2023; Nordelöf et al. 2019), which influence the impacts of one product life cycle. The second most used approach is avoided burden, which is recommended by Santero and Hendry for all metals (Santero and Hendry 2016), by the Cobalt Institute for non-cobalt waste flows (Cobalt Institute 2023) and by one vehicle guideline (Duce et al. 2013). Some publications highlight that the metal mining sector supported the avoided burden approach, considered as reflecting material quality and deemed more relevant to the environmental modelling, decision-making and policy discussions around metal recycling (Norgate 2013; Santero and Hendry 2016). However, these documents do not discuss the material quality linked to EoL allocation. Recently, developed material guidelines for lithium and cobalt might indicate that this preference of avoided burden has shifted. The CFF is used for batteries and plastics. Notably, the CFF is only recommended by guidance documents developed by or on behalf of the European Commission in support of EU policy making. However, it has to be noted that different versions of the CFF exist: (i) one on the product level (e.g. in the PEFCR), (ii) one on the material level (e.g. in the draft of the Delegated Act) and (iii) one adapted to production scrap recycling (e.g. in the draft of the Delegated Act). Different versions of the CFF and potentially different default values can hinder the consistency and comparability of the results. Only the steel industry states that because of closed-loop recycling, no allocation is needed.

**Fig. 5** Approaches for EoL allocation in different applications and industries

	Cut-off	CFF	Avoided Burden	No EoL allocation needed	Out of scope
Material guidelines Li	1	-	1	-	-
Material guidelines Cu	-	-	1	-	1
Material guidelines Ni	-	-	1	-	-
Material guidelines Co	1	-	2	-	-
Battery	1	3	-	-	-
Vehicle	2	-	1	-	4
Chemicals	2	-	-	-	-
Plastics	-	1	-	-	-
Steel	-	-	-	1	-
Pharmaceutical	1	-	-	-	-
Aluminium	1	-	-	-	-
Electronics	1	-	-	-	1
Construction	1	-	-	-	-
<b>Total</b>	<b>11</b>	<b>4</b>	<b>6</b>	<b>1</b>	<b>6</b>

Six guidelines, the majority for vehicles, consider EoL out of their scope.

### 3.1.2 Guidelines for solving multifunctionality beyond end-of-life

Various hierarchies were identified for handling multifunctionality besides the EoL allocation (see Fig. 6a). These hierarchies combine the approaches to handle multifunctionality, as described in Section 2.3, in different ways. Hierarchy A is as follows: (1) subdivision, (2) system expansion/substitution, and (3) allocation. Hierarchy B skips the step of system expansion/substitution, while hierarchy C skips the step of subdivision. Hierarchy D only foresees allocation, and hierarchy E only system expansion. In hierarchy F, subdivision and system expansion are combined into a single step. Notably, only hierarchy A follows the ISO hierarchy, while all other hierarchies deviate from it, mostly by omitting or

combining subdivision and system expansion. Only one hierarchy excludes allocation.

Hierarchy A and B are the most applied ones. Hierarchy A is recommended by the lithium- and cobalt-specific guidelines, as well as the battery, vehicle and chemicals industry. Some guidelines for batteries, vehicles and chemicals also recommend hierarchy B, along with guidelines for electronics and construction. Santero and Hendry recommend hierarchy C for lithium, nickel, cobalt and copper (Santero and Hendry 2016). All other hierarchies are only recommended by one guideline, and five guidelines do not provide any guidance on multifunctionality handling. As for the EoL allocation, the four guidelines developed by or on behalf of the European Commission provide the same recommendation (Hierarchy B).

To handle multifunctionality, the details alongside the provided hierarchies are crucial. These include whether clear guidance is provided when to move from one step in the

#### a) Multifunctionality hierarchies

	Hierarchy A	Hierarchy B	Hierarchy C	Hierarchy D	Hierarchy E	Hierarchy F	Process specific rules	No specific rules
	(SD-SE-A)	(SD-A)	(SE-A)	(A)	(SE)	(SD/SE-A)		
Material guidelines Li	1	-	1	-	-	-	-	-
Material guidelines Cu	-	-	1	-	-	-	1	-
Material guidelines Ni	-	-	1	-	-	-	-	-
Material guidelines Co	1	-	1	-	-	-	-	-
Battery	1	3	-	-	-	-	-	-
Vehicle	3	1	-	1	-	-	-	2
Chemicals	1	1	-	-	-	-	-	-
Plastics	-	-	-	-	-	1	-	-
Steel	-	-	-	-	1	-	-	-
Pharmaceutical	-	-	-	-	-	-	-	1
Aluminium	-	-	-	-	-	-	-	1
Electronics	-	1	-	-	-	-	-	1
Construction	-	1	-	-	-	-	-	-
<b>Total</b>	<b>7</b>	<b>7</b>	<b>4</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>5</b>

#### b) Allocation: Price ratios and price averages

	Price ratio				Price average			
	>4	>5	>1-	undefined	10-year	5-year	5- or 10-year depending on product	
							undefined	undefined
Material guidelines Li	1	-	-	1	2	-	-	-
Material guidelines Cu	-	-	-	1	2	-	-	-
Material guidelines Ni	-	-	-	1	1	-	-	-
Material guidelines Co	1	-	-	1	2	-	-	-
Battery	2	-	2	-	1	1	2	-
Vehicle	1	1	-	-	-	2	-	-
Chemicals	-	-	-	1	-	-	-	1
Electronics	-	-	-	1	-	-	-	1
Construction	-	-	-	1	-	-	-	1
<b>Total</b>	<b>5</b>	<b>1</b>	<b>2</b>	<b>7</b>	<b>8</b>	<b>3</b>	<b>2</b>	<b>3</b>

**Fig. 6** Multifunctionality handling in different applications and industries. **a** shows the different multifunctionality hierarchies applied. The hierarchies combine subdivision (SD), system expansion (SE) and allocation (A) in different forms. **b** shows the details on applying

allocation. Here, only guidelines are included, which (i) have allocation as part of their hierarchy and (ii) provide any specific guidance on allocation

hierarchy to the next. This mainly concerns whether system expansion or substitution is a feasible option and when to use allocation based on physical properties or economic value. This analysis reveals that most guidelines provide no (explicit) guidance on applying system expansion or substitution. This is also supported by a previous review (Eltohamy et al. 2023).

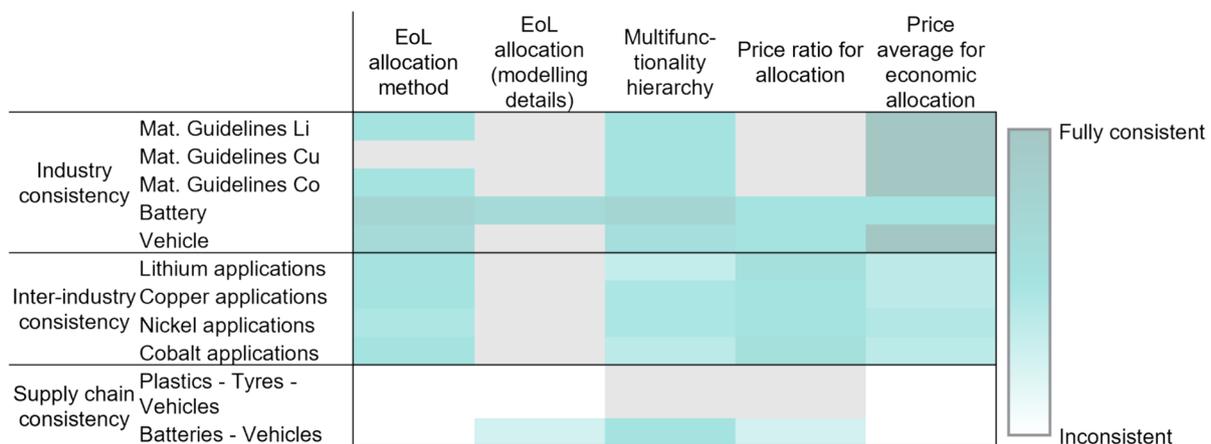
Of the guidelines with allocation as part of their hierarchy, three do not provide further guidance on allocation, and four more only give very generic guidance, such as that allocation based on physical properties is preferable (see Fig. 6b). Santero and Hendry (relevant for all materials analysed) state that allocation based on mass or metal content only applies to metals with similar values. Otherwise, economic allocation shall be used. However, “similar values” are not explicitly defined (Santero and Hendry 2016). The remaining guidelines state that economic allocation shall be applied when the ratio of the prices of the co-products is above a certain threshold. This threshold varies between larger than 4 (five guidelines for lithium, cobalt, batteries and vehicles), larger than 5 (one vehicle guideline) and larger than 10 (two battery guidelines).

A further question is how to determine the prices of products. Three guidelines leave that open. All material-specific guidelines and one battery guideline demand a 10-year global average, and one battery and two vehicle guidelines request a 5-year global average. Depending on the product, two battery guidelines have a 10- or 5-year global average. The chemical and plastics industry guidelines do not provide specific details on applying the allocation. While the allocation details are mainly further specified in the material-specific, battery and vehicle guidelines, the specific recommendations vary within and between applications and industries. The detailed guideline analysis results can be found in the SI in Table S2-1.

### 3.2 Consistency on different levels

The analysis in Section 3.1 revealed that various approaches are applied in different guidelines. Often, no dominant approach could be identified. To further evaluate the discrepancies, we analysed the level of consistency reached (i) within applications and industries which have more than one guideline with detailed guidance on the relevant aspects, (ii) between all applications and industries using lithium, nickel, cobalt or copper, respectively, and (iii) consistency in supply chains (see Fig. 7). Consistency within and between applications and industries was calculated as the ratio of how often the most dominant approach is recommended and the number of all recommendations. For the consistency along supply chains, this was further refined with the following scale: inconsistent means that the approach of the upstream industry is not at all applied in the downstream industry, mainly inconsistent means that the most dominant approach in the upstream industry is applied in the downstream industry but not as the dominant approach; for partly consistent, the upstream and the downstream industries have the same most-applied approach. For mostly consistent, the upstream shall be consistent in its recommendation, which shall also be the most dominant approach in the downstream industry. For full consistency, both industries would always recommend the same approach.

Regarding the EoL allocation, the recommendations for batteries are best aligned as three out of four guidelines recommend the CFF, and two of these three provide the same version of the CFF. For vehicles, only three guidelines provide recommendations for the EoL allocation, which is the cut-off approach in two cases. The further alignment is unclear as details on the cut-off point are mostly unspecified. The two guidelines, each targeting lithium and cobalt, provide two different recommendations for the EoL allocation;



**Fig. 7** Consistency within applications and industries if more than one detailed guideline was available, inter-industry consistency and supply chain consistency. A grey cell indicates that an analysis was not feasible

for copper, only one guideline gives a recommendation. Concerning the multifunctionality hierarchy, the battery industry is again the best-aligned one, with mostly consistent guidance. However, the consistency decreases to partly consistent for the price ratio and the price average. While the multifunctionality hierarchies in the material-specific guidelines are not well aligned with only partly consistency, they each recommend the same period for the price average. The higher level of alignment in the battery industry compared to other applications is due to the fact that three of the four guidelines were developed by or on behalf of the European Commission to support policy-making, and this development occurred quite recently. However, they do not all recommend the same price ratio and period for the price average. Upon examining all guidelines regarding the various materials, it becomes clear that they are highly inconsistent in terms of the EoL allocation and the multifunctionality hierarchy.

While lithium, copper, nickel or cobalt production is the beginning of all supply chains, some identified applications are also part of the same supply chains. Lithium is used in polymer production, which ends mostly in tyres for vehicles, and the main end use of lithium-ion batteries (LIB) is also Evs. We, therefore, also analysed how consistent the guidelines are for plastics and vehicles, as well as batteries and vehicles. This analysis shows the largest inconsistencies. The polymer and battery guidelines are primarily developed by or on behalf of the European Commission; therefore, the CFF is recommended, which is not the dominant approach for vehicles. The guideline on polymers recommends a multifunctionality hierarchy, which is not applied for vehicles and does not provide any further guidance. The most recommended hierarchy for batteries is also applied to vehicles, but it is not the predominant one. Regarding the price ratio, the most recommended approach for batteries is also the most recommended for vehicles. For the period of the price average, the battery industry again favours an approach that is only applied to a limited extent for vehicles.

The high level of inconsistencies highlights the importance of (i) identifying key consistency checks that should be performed in LCA studies to ensure consistency throughout a supply chain or at system level and (ii) further harmonisation between key players.

### 3.3 Implications of inconsistencies

#### 3.3.1 Quantitative analysis

To further discuss the implications of inconsistencies in the guidelines, we address them in two case studies: (a) one for a primary co-production and (b) one for a co-production of secondary materials from a recycling process.

For primary co-production, a simplified cobalt-copper co-production based on Dai et al. (2018) was modelled with different ways to handle the multifunctionality. The process begins with the mining of cobalt-copper ores, which are then further hydrometallurgically processed to separate the copper-cobalt solution into two distinct solutions: one containing copper and the other containing cobalt. The copper solution is further processed by electrowinning to recover copper. The cobalt solution is further processed to recover different cobalt products (Dai et al. 2018). Here, we focused on producing battery-grade cobalt sulphate and excluded further cobalt products from the system boundary.

To analyse the co-production of secondary materials, an EV LIB recycling process is modelled, which recovers a range of materials (Husmann et al. 2023). The process starts with a mechanical treatment where the first materials and components are recovered. A pyrometallurgical melting process follows the mechanical treatment. The slag from the melting process is further mechanically and hydrometallurgically processed to recover the lithium carbonate contained in the slag. Additionally, the alloys created in the melting process are further hydrometallurgical processed to recover, among other materials, nickel sulphate, cobalt sulphate and copper (Husmann et al. 2023).

We applied the relevant material- and industry-specific guidelines for both case studies. We excluded guidelines from our analysis that are either not applicable or where the modelling decisions would depend significantly on the LCA practitioner, as the allocation rules are not further specified. We analysed how the co-production would be treated based on the hierarchy and modelling details provided in each guideline, and what climate change impacts per material this would lead to. Additionally, we performed a full sensitivity analysis of all potential modelling options contained in the hierarchies (see Figures S3-1 and S3-2). For the analysis in this section, we consistently applied the allocation on the unit process level, sometimes referred to as partial subdivision and allocation (Husmann et al. 2024; Lai et al. 2021). While this last aspect is not directly addressed in the guidelines, it can significantly influence the results (Husmann et al. 2023).

Similar work for the EoL allocation has been done in a previous publication (Du et al. 2022). The authors analysed seven different methods to handle the EoL allocation, including those relevant to the guideline analysis: (i) cut-off, (ii) avoided burden and (iii) CFF.<sup>1</sup> For NMC and LFP batteries, the life cycle climate change impacts allocated to the battery

<sup>1</sup> As the publication by Du et al. is from 2022, it does not apply the CFF with the newest default values from the PEFCR and the Delegated Act. It also does not give insights into potentially different versions of the CFB-EV, the PEFCR and the Delegated Act.

vary by around 50%. Which allocation approach leads to the highest results depends on whether the recycling credits with avoided burden offset the recycling impacts. If they do, avoided burden typically leads to the lowest and cut-off to the highest results. If not, it is the other way around. As the CFF is a hybrid approach between the two, the life cycle impacts are also in between cut-off and avoided burden (Du et al. 2022).

#### a) Case study primary raw material production

We applied 13 guidelines relevant to copper and cobalt to the co-production process (see Fig. 8). The co-production can be modelled in six different ways: (i) system expansion, (ii) mass-based allocation, (iii + iv) economic allocation with a 5- or 10-year price average and (v + vi) a combination of mass-based and economic allocation with a 5- or 10-year price average. While subdivision was present in the hierarchies of several guidelines, it was not feasible based on the available data. In general, most guidelines recommend economic allocation in this situation; however, varying price averages are the baseline for the modelling (see Fig. 8).

System expansion (recommended in two guidelines) takes a completely different perspective than allocation. It does not give impacts per kilogram of materials but for a specific amount of ore mined and processed or the combined amounts of materials recovered. Therefore, the results cannot be compared with those from allocation.

Looking at the results from the different allocation approaches, the variations of climate change impacts per kilogram of copper are relatively small with max. 11%. For cobalt, the variation is up almost to a factor of five. The reasons for the difference in variations are as follows: Depending on the allocation approach, 87% to 97% of the 154.4 kg CO<sub>2</sub>-eq. are allocated to the overall recovered amount of copper. As in total 38.16 kg of copper are recovered, this leads to a relatively small variation of impacts per kg of copper. The impacts assigned to the total amount of cobalt recovered vary between 3 and 13%. As only 1.02 kg of cobalt are recovered in the process, this leads to a variation of almost 500% of the impacts per kg of cobalt.

#### b) Case study co-production of secondary materials

We applied ten guidelines relevant to lithium, copper, nickel and cobalt, as well as all battery and vehicle guidelines to the described recycling process. Four general modelling approaches were identified: (i) system expansion/substitution, (ii) mass-based allocation and (iii + iv) economic allocation with different price averages. Most guidelines would lead to economic allocation for this process (see Fig. 9). This is because the recycling process also recovers iron at a low price compared to the other

recovered materials. Therefore, the price ratio is above 10, and almost all guidelines would apply economic allocation. Again, different price averages can be observed.

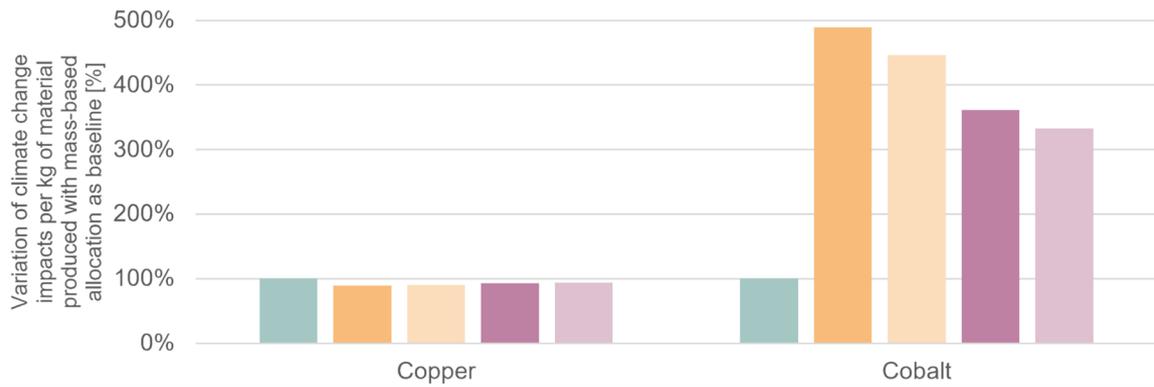
As described for the primary co-production, system expansion takes a process-focused perspective and is, therefore, not comparable with the allocation results, which take a material-focused perspective. For recycling, this perspective also enables the comparison of the impacts of recycling with the benefits from credits for avoided primary products (Husmann et al. 2023). With the different allocation approaches, the impacts per kilogram of nickel and lithium vary by less than 10%. Several process steps are only performed to recover lithium carbonate. Therefore, these are always fully allocated to lithium carbonate. How the allocation in the rest of the process steps is performed has a minor influence on the impacts per kilogram of lithium carbonate. Copper and cobalt, on the other hand, experience more considerable variations of more than a factor of two and almost a factor of two, respectively. The mass share recovered for copper and cobalt varies significantly from the value share.

### 3.3.2 Qualitative analysis

After the quantitative analysis of the implications of inconsistencies, further aspects will be analysed qualitatively. This includes how different the hierarchies are in the application in practice, how relevant the price developments of materials are and which methodological combinations will lead to an over- or underestimation of the impacts on the system level.

#### a) Hierarchies and their application in practice

Various publications and guidelines discuss the limited applicability of system expansion or substitution to multifunctional situations with several metals (e.g. Cobalt Institute 2023; Lai et al. 2021; Santero and Hendry 2016). The case studies also underline that system expansion or substitution is rarely applicable in practice, and most of the presented hierarchies would lead to solving multifunctionality between metals with allocation, most likely with economic allocation as the case studies showed. However, the details on how to apply allocation are less consistent. The different value ratios indicating when to apply mass-based or economic allocation can significantly influence the results. Different price averages also lead to different allocation results, as the case studies show. The guidelines do not explicitly state whether to apply allocation on the process chain or the unit process level, which will also significantly influence the results (Husmann et al. 2023). So, while a lot of the hierarchies lead to allocation, further consistency is needed regarding several aspects:



Guidelines	System expansion	Mass-based allocation	Economic allocation		Mass-based allocation for mining and economic allocation for ore processing		Hierarchy applied
			With 5-year price average	With 10-year price average	With 5-year price average	With 10-year price average	
LCA metals and mining <sup>1</sup>	x			x	x	x	C
LCA cobalt				x			A
PEFCR		x					B
CFB-EV			x				B
GHG rulebook				x			A
Delegated Act		x					B
TranSensus LCA			x				A
LCA VDA		x					B
Catena-X			x				A
LCA Chemicals			x				A
LCA Steel	x						E
PCR 2024:06 <sup>2</sup>					x	x	B
PCR 2019:14 <sup>2</sup>					x	x	B

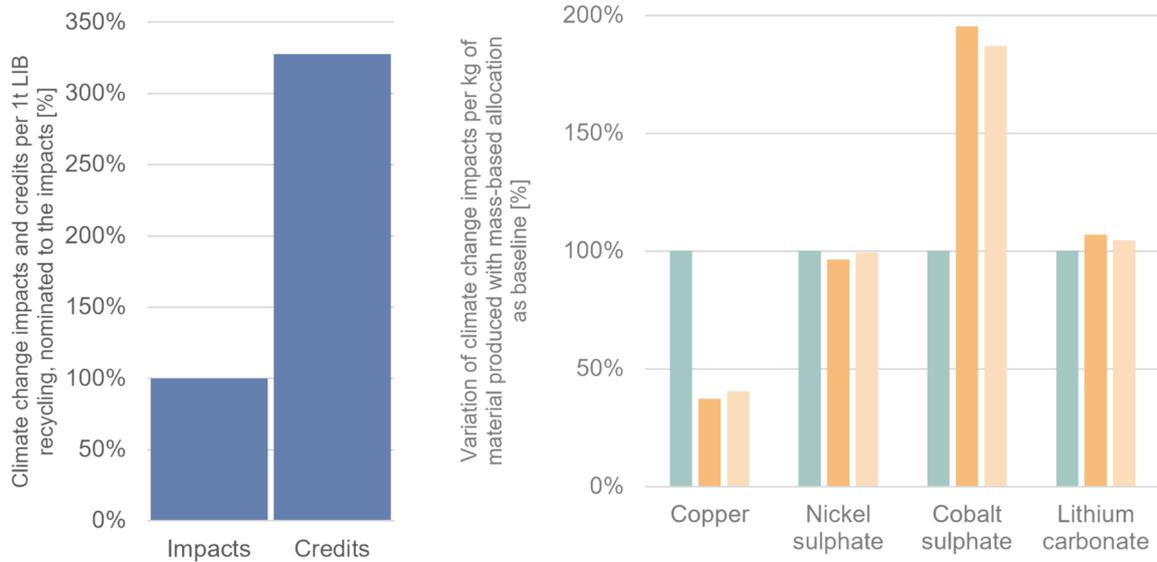
<sup>1</sup> LCA metals and mining provides different guidance throughout the paper. Their general recommendation is system expansion if the data is available. Without data, this co-production process would lead to economic allocation. However, throughout the discussion, they also introduce the recommendation to model upstream processes like mining with mass-based allocation and downstream processes for further processing with economic allocation.

<sup>2</sup> Based on the PCRs, it is unclear which period should be used for the price average. Five and ten years were modelled to show variation.

**Fig. 8** Overview of modelling implications from different guidelines relevant to copper and cobalt applied to a copper-cobalt co-production process and the resulting variance in the impacts of climate change

- i) Reasons provided why or why not system expansion/ substitution is applicable
- ii) Application level of allocation
- iii) Price ratio
- iv) Price average

Overall, while the results for metals might be somewhat similar, these guidelines also partly apply to other products



Guidelines	System expansion	Mass-based allocation	Economic allocation		Hierarchy applied
			With 5-year price average	With 10-year price average	
LCA metals and mining <sup>1</sup>	x			x	C
LCA cobalt				x	A
LCA Lithium products				x	A
PEFCR				x	B
CFB-EV			x		B
GHG rulebook				x	A
Delegated Act				x	B
TranSensus LCA			x		A
Catena-X			x		A
LCA VDA		x			B

<sup>1</sup> LCA metals and mining recommend system expansion if the data is available. If no data is available, their recommendation for this process would be economic allocation. LCA metals and mining does not explicitly include recycling processes. The reasoning of their approach was transferred to recycling.

**Fig. 9** Overview of modelling implications from different guidelines relevant to lithium, nickel, copper and cobalt applied to a lithium-ion battery recycling process and the resulting variance in the impacts of

climate change. The results are focused on the materials analysed in this publication. However, more materials are recovered in the recycling process and considered in the modelling

or components (e.g. other parts and components of a vehicle) for which system expansion might be practicable. Then, the hierarchies might lead to very different results depending on whether they include system expansion.

b) Price developments of key material over time

Guidelines recommend using 5- or 10-year global average prices to determine the price ratio. We therefore analysed the price development for lithium, nickel, cobalt and

copper and determined their average prices from 2019 to 2023 and 2014 to 2023<sup>2</sup> (DERA 2025; US Geological Survey 2024; World Bank 2024a, b). For all analysed materials, the price average over 5 years is higher than over 10 years (see Figure S3-3). The difference is between 17 and 32%.

<sup>2</sup> For cobalt, prices were only available from 2016 to 2023. As a proxy, we used the 8-year average as the 10-year average. The substances might be used in various different forms. For reasons of simplicity and accessibility, we used commodity prices.

Relevant to the allocation is the price average itself, whether it influences the choice between mass-based and economic allocation and whether it changes the allocation factors. Regarding the former, for the analysed materials, all price ratios except the one of cobalt and copper are below four and would, therefore, lead to mass-based allocation. The price ratio of cobalt and copper with the 5-year average is above five, with the 10-year average below five but above four. For a more long-term analysis, we also calculated the rolling price ratios based on 5- and 10-year averages from 1961 to 2020 based on US data (U.S. Geological Survey 2023a, b, 2024a, b). This more long-term analysis highlights several things: (i) the 10-year average typically follows the trends of the 5-year average with a short delay, (ii) the 10-year average is more stable than the 5-year average, and (iii) for some material combinations, the price ratios experience significant variations over time, leading to different allocation decisions based on the ratio thresholds of four, five and ten (see Figure S3-4). As the price averages of 5 and 10 years vary to different extents between the analysed materials, the chosen price averages also influence the allocation factors if economic allocation is applied, which was also shown in the case study. While the price averages influence the overall results (variation mostly below 10% in the case studies) and need further standardisation, the price ratio seems more significant (variation of up to a factor five in the case studies).

- c) Which methodological combinations might lead to over- and underestimating impacts?

For the EoL allocation, the most significant discrepancies of impacts on the system level stem from consecutive life cycles where either cut-off or avoided burden are, respectively, applied. If the first life cycle applies cut-off, it excludes the recycling from the system boundary, and the second life cycle would have to take the recycling impacts with the secondary materials. However, if avoided burden is applied in the second life cycle, they do not consider upstream recycling and assume to get the secondary materials burden-free. None of the life cycles would have accounted for the recycling impacts. If the situation is reversed and in the first life cycle avoided burden is applied, it takes the impacts and the credits of recycling. The consecutive life cycle should, therefore, take the secondary materials burden-free. But when in that life cycle cut-off is applied, it also takes the recycling impacts. Therefore, the impacts would be double-counted. Based on the case study by Du et al., 15–35% of the life cycle impacts of one product could be not accounted for at all or double-counted with different EoL allocation in consecutive life cycles (Du et al. 2022).

Regarding allocation for co-production systems, different allocation approaches become an issue when co-products have (i) different value and mass shares of the produced

materials and (ii) different prices, but the price ratio is treated differently depending on the guideline. Which combinations lead to an over- or underestimation of the impacts and to which extent depends on the exact combinations of guidelines. In general, any deviation in applying allocation in the different product guidelines (e.g. price ratios, price average) leads to wrongly estimated impacts on the system level. Assuming a co-production where one material has a large value but is recovered in small quantities, and the other has a low value but is recovered in large quantities. If the industry taking the large-value material applies mass-based allocation and the industry taking the large-quantities material applies economic allocation, then the total impacts would be underestimated. For an overestimation, it would be the other way around: the industry which takes the large-value material applies economic allocation and the industry that takes the large-quantities material applies mass-based allocation. In the case studies in this publication, the impacts on the process level could be underestimated by up to 10% and overestimated by up to 15% when different industries taking the materials apply different multifunctionality hierarchies.

## 4 Discussion and recommendations

### 4.1 Background of guideline recommendations

Most analysed guidelines state instructions without providing insights on how and why these are given, neither for the multifunctionality hierarchies nor the EoL allocation. More transparency on how the instructions were developed is needed for standardisation efforts because it provides insight into different reasoning and practices in the industries, which is necessary to identify key differences and common ground.

The analysed guidelines do not justify why they deviate from the ISO hierarchy by omitting or combining certain steps in their hierarchy. Of the three most applied hierarchies, one follows the ISO hierarchy (hierarchy A), one omits system expansion (hierarchy B) and one subdivision (hierarchy C). Omitting subdivision seems to be a practice of the metals industry, while system expansion is omitted in various industries and is the favoured approach of the batteries industry. Most guidelines state that price averages are necessary to smooth out price volatility. However, it is not further explained why 5- or 10-year averages ensure this, for example, with analyses of typical metal cycles. For a price ratio larger than four, as a rule, to apply economic allocation instead of mass-based allocation, most guidelines refer to Santero and Hendry as the source. However, these do not state this price ratio directly but only state the following in their guidance: “Allocation by mass is generally preferred when the economic value per unit of output between

co-products is similar. [...] As guidance, EN 15804 defines ‘small’ as less than 25% difference in value” (Santero & Hendry 2016, p. 1547). From this, the guidelines derived their recommendation for a price ratio larger than four. Other guidelines include a price ratio larger than five or ten without justifying this threshold.

Regarding the EoL allocation, some guidelines include cut-off, justifying their choice with it being the most transparent approach (e.g. Global Battery Alliance 2023). The metal guidelines, which favour avoided burden, argue that it indirectly includes material quality, which is highly relevant for metal recycling (Norgate 2013; Santero and Hendry 2016). The guidelines do not further explain or justify the CFF development and the corresponding default values.

In general, as there is not one correct way to solve multifunctionality (Guinée et al. 2004), guidelines should acknowledge this aspect clearly and ensure that the recommended approach is commonly agreed on within and across industries and materials, for example, in an expert-based consensus process. The influence of choices made in the guideline definition (such as the price averages) should be made clear in the guidelines.

## 4.2 Consistency checks

Methodological consistency is highly relevant from different perspectives. The environmental impacts from the same product from different companies can only be compared if the methodological approach is consistent. Otherwise, it is difficult to determine whether different environmental impacts are caused by technological aspects or by a different modelling approach. Furthermore, consistency is relevant to correctly determine the environmental impacts of industries, sectors and societies, which is needed in light of sustainable development goals and absolute sustainability. Lastly, with mandatory requirements to report the environmental footprint of products, such as in the EU Batteries Regulation, the impacts on the whole supply chain must be reported (European Parliament and European Council 2023). The OEM needs to ensure that they are calculated using the mandatory approach. Hence, when data along the supply chain is shared on the impact assessment level, all suppliers must follow the same approach. Otherwise, this would lead to regulatory non-compliance of the carbon footprint reported by the OEM and would also undermine efforts to establish product carbon footprint labelling.

With the overarching goal to have reliable and robust carbon footprint calculation and declaration for sustainable development and regulatory compliance, three necessary consistency checks LCA practitioners should perform can be identified. These are: determining whether (i) the LCA of a supplier is balanced, (ii) the product LCA is consistent with downstream applications and industries, and (iii)

the EoL treatment between different product life cycles is consistent (see Fig. 10).

First, it shall be verified whether the LCA of the supplier of components/materials is balanced, meaning the sum of the process environmental impacts is equal to the sum of the environmental impacts reported with sold products. If not, the supplier probably applied different approaches to solve the multifunctionality problem depending on the industry buying the product or component. Different approaches can include different hierarchies applied, different interpretations of system expansion, and different price ratios or price averages applied in the allocation. This leads to an under- or overestimation of the total impacts and can, for example, hinder green procurement. Furthermore, the LCA practitioner must check whether their way of handling multifunctionality is consistent with potential downstream applications and industries (e.g. batteries or tyres for Evs). The challenge might be to get insights into the downstream LCA approach if the downstream industry is not reporting the environmental impacts and, therefore, does not demand a special approach from their suppliers. Special attention shall also be given to modelling EoL recycling processes and secondary materials with prior and consecutive product life cycles. If any of these aspects have inconsistencies, they should be reported in the LCA study to enhance transparency and indirect comparability. If possible, an estimation of whether the discrepancies lead to an over- or underestimation of the total impacts should also be made.

To achieve full consistency, the following aspects would need to be harmonised across all guidelines: (i) the EoL allocation approach including details such as the cut-off point or the CFF default parameters and (ii) the multifunctionality hierarchy including interpretations of system expansion and specific guidance on when and how to apply each step of the hierarchy (e.g. conditions for system expansion, price ratios, price averages, level of allocation). These are also the aspects necessary to verify methodological consistency when comparing the environmental impacts of products. However, retrieving this information from published LCA reports can be challenging.

## 4.3 Drivers of developments towards consistency and standardisation

The development towards consistency and standardisation can be driven bottom-up by metal associations or top-down by different industries or policies or as a combination of these. The guideline analysis shows that different metal associations have already become involved in developing guidelines. Previous work on the role of mining industry networks and the diffusion of innovations shows that metal associations are powerful in bridging gaps between producing countries and national organisations to spread information and

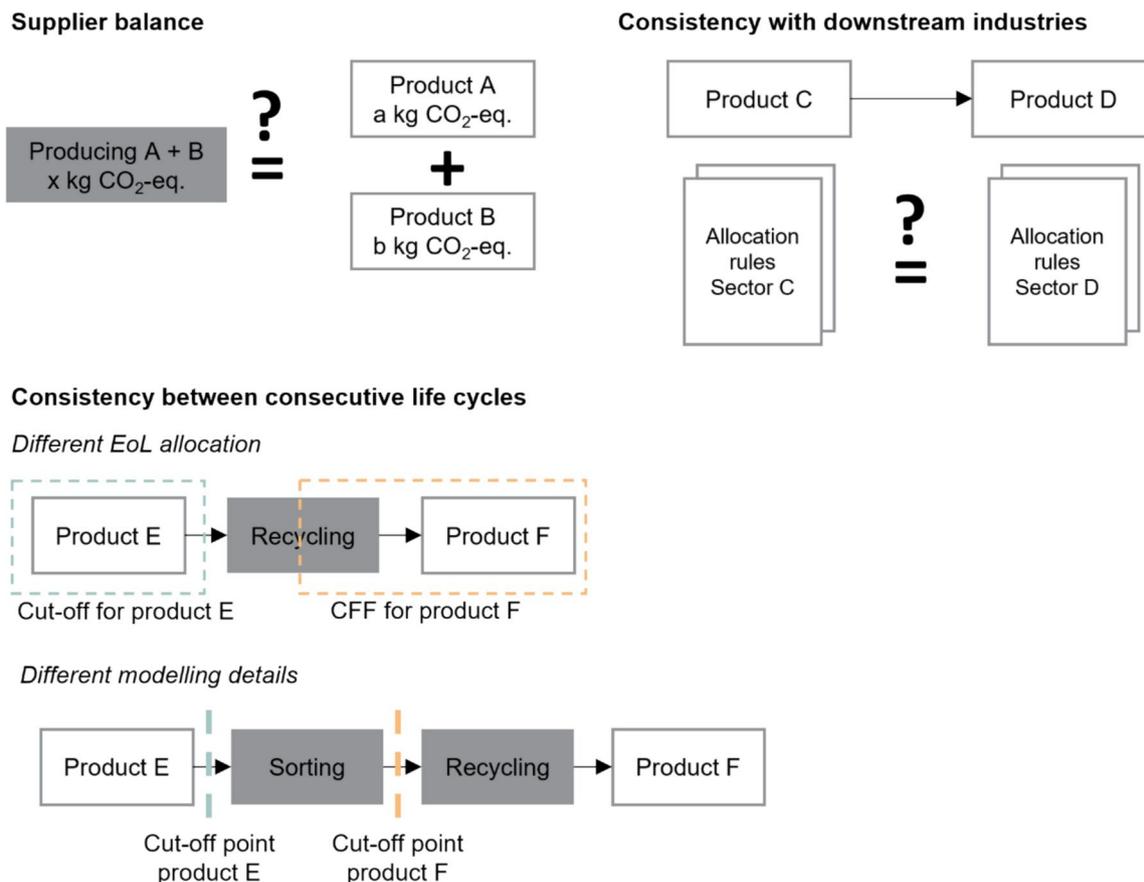


Fig. 10 Consistency checks to be performed by the LCA practitioners

innovation (Mendonca et al. 2024). While the authors did not specifically analyse LCA standards, their results might still be indicative of the role metal associations could play in developing consistent LCA standards. Metal associations could use their influence to bring together companies across countries to align on the LCA practice. With overarching associations such as the International Council on Mining and Metals, this could even happen across commodities. It should be in the great interest of companies in the metal and mining sector to drive the standardisation bottom-up to ensure they only have to perform one LCA for their products and not different LCAs depending on the downstream industry.

To determine how standardisation could be driven top-down by applications and industries, we analysed the interest and influence of the different industries. We, therefore, adapted the approach to analyse stakeholders in sustainable development, as described in Ashby (2016) to fit the context of industries and a potential standardisation process. An industry is assumed to have no interest when it has no LCA guidance at all, low interest if it has guidance or best practices, medium interest when it has existing guidelines and high interest if it has additional regulatory pressure. Three

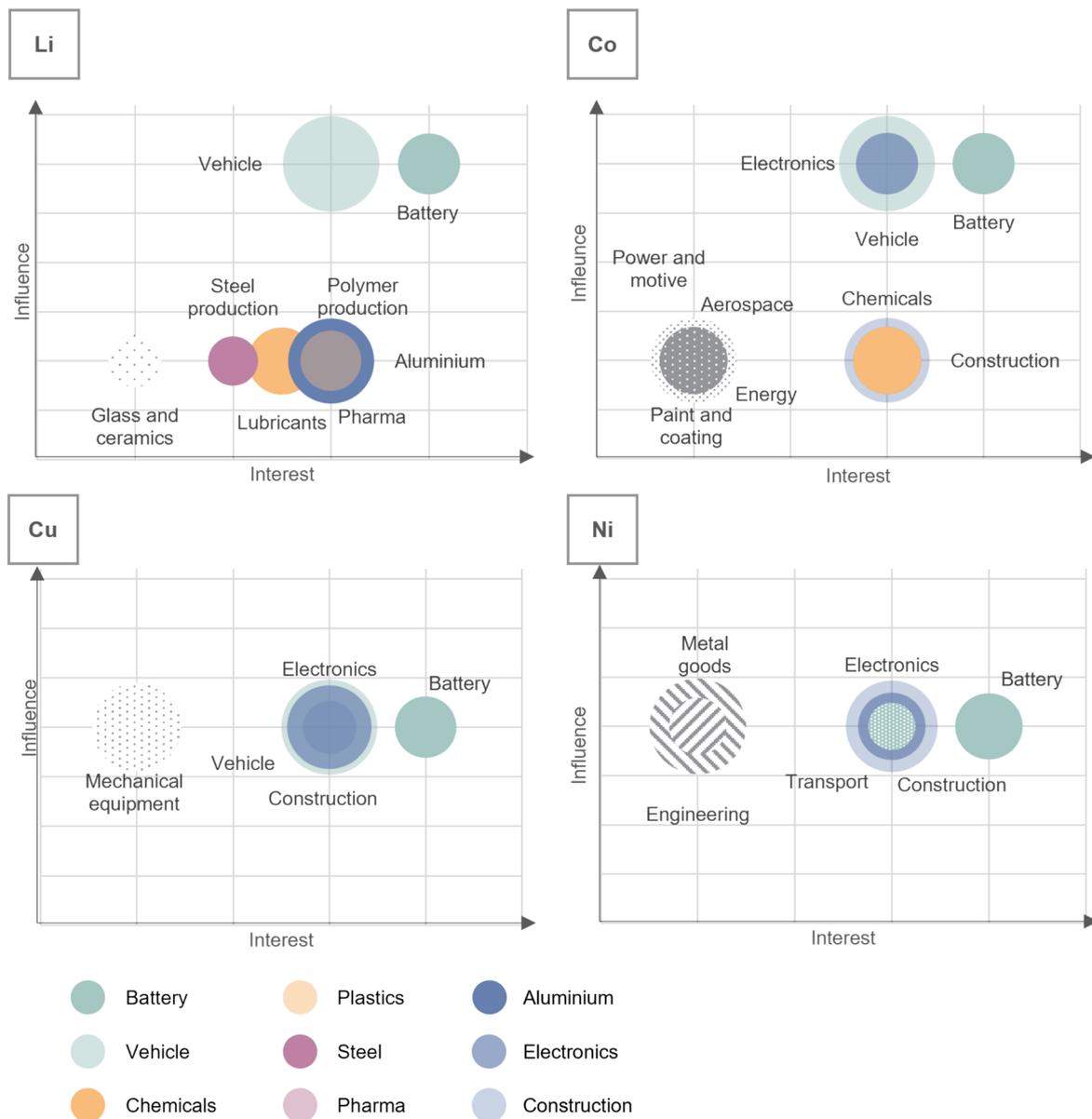
levels of influence were defined: (i) low influence for applications with a minor market share, (ii) medium influence for one of several similar relevant applications in terms of market share and (iii) high influence for applications which dominate the demand. As an additional dimension, we considered the value added of the NACE sectors behind the applications (see also Fig. 1). Several applications in the same NACE sector are all indicated with the same value added.

Based on the position in the matrix, likely roles for the industries in a standardisation process can be identified. Industries with high interest and influence (upper right corner) will likely be actively involved in the standardisation. Industries with high interest and low influence (lower right corner) are likely interested in being part of the standardisation but are less influential in the process. However, here, it should be differentiated whether it is also, in general, a small sector or if it is a large sector that only has a small influence on a specific material. Industries in this part of the matrix, especially when they belong to large sectors, should be involved in the standardisation process. Industries with high influence but low interest (upper left corner) should be kept informed, and it should be ensured that they support the

process because of their potential high influence. And lastly, industries with small interest and small influence (lower left corner) are irrelevant to the standardisation work. However, if an industry which belongs to a large sector is placed in this area, it is recommended to involve it as an industry with higher influence.

Based on this analysis, different starting points for potential standardisation and paths forward could be identified. The battery and vehicle industries are the two key industries for a standardisation process for lithium and cobalt (see Fig. 11). Several other high-interest industries should be further involved in the standardisation process for both

materials. The initial situation is different for copper and nickel, as no industry clearly has more influence than the others. There are also large industries for both materials that currently have low interest. One potential way forward could be to start the harmonisation between the most interested industries and focus on disseminating the work to the remaining industries. In general, the analysis of all materials shows that the vehicle and the battery industry are highly interested. This is also reflected in the number of guidelines created by different stakeholders and ongoing harmonisation initiatives (e.g. TranSensus LCA). However, this also underlines that there is currently no standard approach in the



**Fig. 11** Analysis of influence and interest of different industries in a potential standardisation process. The bubble size corresponds to the value-added of the linked NACE sectors. Industries without guidelines are displayed with grey-patterned bubbles

battery and vehicle industry. For industries to get involved in inter-industry standardisation, there needs to be a methodological consensus within the industry—this is true for batteries, vehicles and all industries. The ease of finding an industry consensus might also depend on the number of companies active in an industry. The more companies are involved, the more difficult it might become to reach a consensus. The analysis also shows that several industries are relevant for (almost) all materials, which evokes the question of whether a standardisation process should not rather be driven bottom-up by the metal associations and then extended with industry- or sector-specific rules.

Besides the potential top-down-driven standardisation by industries, policy regulations can significantly influence top-down standardisation processes. With the EU Batteries Regulation, it is clear that there will soon be a mandatory LCA guideline for batteries put on the EU market (European Parliament and European Council 2023). The upcoming regulation also drives the development of several guidelines in the battery and vehicle industries, as well as ongoing harmonisation efforts. This reflects the high interest of academia and industry in shaping the LCA guidelines for the future. In any case, the battery industry in the EU will have to follow the mandatory guidelines. The position of these mandatory guidelines will be further strengthened by the LCA guidelines, which shall be developed as part of the CRM act, as this will target even more materials, industries and sectors (European Parliament & Council of the European Union 2024). As these are also developed by or on behalf of the European Commission, they are likely to be aligned with each other. Consequently, consistency can only be achieved if other global industries acknowledge and consider this in their LCA practice and guidelines. The likelihood of adopting EU guidelines outside of the EU is hard to predict and likely dependence on the international relevance of the industries. While it is necessary for consistency, other industries or regions might favour different approaches for handling multifunctionality. The example of batteries already shows that industry stakeholders favour deviating approaches to what is currently developed in the EU Batteries Regulation. There are currently no mechanisms in place to ensure consistency between regulations and guidelines from different regions, industries, or stakeholders.

## 5 Conclusion and outlook

This work analysed relevant industry- and material-specific guidelines for four key battery materials (lithium, nickel, cobalt, copper) concerning their consistency in handling EoL allocation and multifunctionality throughout the life cycle. The analysis reveals inconsistencies within and between industries, as well as along supply chains. The

different guidance can, in practice, lead to variations in environmental impacts by a factor of up to 5 for 1 kg of material, depending on the specific case. In general, not all inconsistencies are equally relevant. The same EoL approach and multifunctionality hierarchy are most relevant, followed by further details in the modelling, such as the price ratios or periods for the price average. It is unclear how and why many aspects of the guidelines were developed in this manner, making the differences between the guidelines appear arbitrary to some extent.

The potential pathways to greater consistency are unclear. Standardisation could be driven bottom-up by metal associations or top-down by different industries. However, there is a special situation regarding regulatory pressure for LCA guidelines on the EU market for batteries, and this will also be the case in the future for raw materials more generally. For consistency, other industries would have to adopt these EU guidelines, and it is difficult to foresee whether that will happen internationally.

As long as inconsistencies remain, transparency, on which inconsistencies exist and what influence they might have, is crucial. Therefore, we identified key consistency checks, which include determining whether (i) the LCA of a supplier is balanced, (ii) the product LCA is consistent with downstream industries, and (iii) the EoL treatment between different product life cycles is consistent.

Future work could mainly focus on two aspects: (i) this work only considered inconsistencies linked to multifunctionality treatment. However, there are several more topics which might need consensus building to reach standardisation, such as the electricity modelling or the life cycle impact assessment methods (Beylot et al. 2024); (ii) the dynamics between the actors on the market could be further analysed to identify and support further pathways towards consistent guidelines.

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**Data availability** Data will be made available on reasonable request.

## Declarations

**Competing interests** The authors declare no competing interests.

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