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A structured approach for the compliance analysis of battery systems with regard to the new EU Battery Regulation

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ABSTRACT

The introduction of the European Green Deal has triggered various legislative projects that will require product manufacturers inside and outside the European Union (EU) to ensure compliance with the new regulatory framework. As this is a complex task we present a methodology that manufacturers can use to derive a strategic focus for future product development to fully comply with and prioritise regulatory requirements. Further, the method helps to assess the difficulty of achieving compliance. A case study is employed to examine the applicability of the methodology to the EU Battery Regulation. Consequently, the extent to which a currently available battery would comply with the 121 requirements was investigated. The method revealed a number of hot spots requiring immediate action. It therefore helps stakeholders to identify key issues that need to be addressed in future battery development and to classify them according to their importance.

1. Introduction

Manufacturing contributes about one fourth of all carbon emissions in the European Union (European Energy Agency, 2023). Accordingly, immense emission reductions are necessary in this sector to reach the desired decarbonisation by 2050 as stipulated by the EU Green Deal (European Union, 2023). This setting has two major consequences for the European industry: Firstly, various Green Deal-related legislative regulations and directives have been initiated that challenge companies to comply with a multitude of new provisions and legislative requirements. Secondly, the industry is required to focus on the development of a green technology infrastructure, an area in which in addition to large original equipment manufacturers (OEMs), many smaller, medium-sized companies and start-ups are operating. For these in particular, manoeuvring a constantly evolving legislative landscape poses a challenge (den Heuvel and Matyas, 2020). It is not always clear how exactly a new regulation will affect their businesses in concrete terms. For example the consequences that arise for product design, which is a subject area that exhibits a large number of conflicting objectives, are difficult to anticipate (Vysoudil et al., 2023).

Accordingly, a methodology that helps with structured, textual analysis of legislative texts is needed, that companies can use in order to derive focus areas to shape their response to changing legislative framework conditions. To address this issue, in this study we present a three-step-methodology, present developed a three-step-methodology that aims to provide a suitable focus in product development. The method is applied to the new EU Battery Regulation due to its many

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legislative innovations. In this context, we performed an analysis of a state-of-the-art battery system and evaluated its performance with regard to the new legislative requirements. Few studies have so far been published on the problem of deriving focus areas in product development, to structurally meet new legislative requirements. The studies identified to be relevant will be discussed in the following section.

2. State of research

In the framework of this publication, the scientific literature on the derivation and prioritisation of requirements from legislative texts was analysed. In addition, existing publications on the consequences of the introduction of the new EU Battery Regulation were considered to support the choice of case study. The most relevant studies identified in these contexts will be briefly presented below followed by a short list of conclusions regarding the current state of research.

Regarding the structured derivation of focus areas from legislative texts Makri et al. present and discuss a requirements management model helping OEM's technical design centres to translate and integrate legislative environmental requirements into their product. The authors focus on the communication and integration of environmental requirements through a company's supply chain. The aim of the study was among others to aid in the communication of legislative and environmental requirements with suppliers to ensure environmentally conscious design (Makri et al., 2004).

Ingolfo et al. propose a framework and modelling language for establishing regulatory compliance for a given set of software requirements. The language allows for an evaluation of the compliance with certain requirements that originate from legislative frameworks for software development (Ingolfo et al., 2014). The same application case was considered by Breaux et al. who published on the development of a semantic model that is able to analyse legislative texts in order to structurally derive of important provisions. These provisions can then be transformed into system requirements, that a software needs to satisfy (Breaux et al., 2006). Otto/Anton 2007 summarise various research efforts in handling legal texts for software system development, providing insights into specifying, monitoring, and testing software systems for compliance with legal requirements. The paper aims to aid requirements engineers and auditors with testing procedures for software systems (Otto and Anton, 2007). Pigosso et al. (2016) present a guideline for structured identification, analysis, and deployment of product requirements from environmental product-related legislation in form of a step-by-step approach. The study puts emphasis on the product development process in order to derive relevant requirements as early as possible in the product life cycle (Pigosso et al., 2016).

On the topic of textual analyses of the new Battery Regulation Barkhausen and et al. investigated the policy changes in the field of batteries within the last decades and the according underlying drivers. They found several external events that lead to an alignment of economic and environmental interest. Accordingly, respective lobby groups formed coalitions on certain topics which entailed a strong focus on circular economy in the new legislation (Barkhausen et al., 2023). Melin et al. investigated the implications of the regulation on a global scale. Although at this point hard to predict, consequences to be expected in science from the regulation's implementation are contributions to the desired growth of a steady and sustainable battery economy in Europe. This growth is expected to also affect battery industries on a global level that might lead to unintended consequences. According to the authors open questions concern among others the way in which data is exchanged across global value chains. They further demand International standards to ensure a level playing field for different actors (Melin et al., 2021).

Our analysis of the current state of research led to the following 4 conclusions:

1. In general, the process of deriving legislative requirements for formulating engineering guidelines lacks structure, and existing publications on the subject are partially outdated.
2. The lack of substantial publications addressing the difficulties of compliance, especially regarding future product characteristics, makes it challenging to derive focal areas for examination. A method is needed, that helps identify key legislative requirements and the corresponding effort required to fulfil them. The analysed studies collectively suggest that the difficulty of compliance can be influenced by the complexity of legal requirements and the ability to measure compliance.
3. Currently, the derivation of relevant legislative requirements and their implications is predominantly directed towards software development. The absence of a thorough examination of the new Battery Regulation and the consequences of its implementation renders this an ideal case study.
4. There exist only few analyses of the new EU Battery Regulation, none of which addresses the changing framework conditions regarding battery design and characteristics. This leads to a lack of knowledge regarding the extent to which battery design has to be adapted and where involved battery distributors should emphasise and prioritise their development efforts.

The following section describes the developed methodology that helps to cope with these research gaps and provides battery distributing companies with an orientation to derive a focus for their product development.

3. Methodology

In order to provide an initial information basis for companies on how to focus product development in the context of upcoming legislative requirements, we developed the approach shown in Fig. 1.

From an initial textual analysis of the legislation all relevant provisions are investigated and form the basis for a comprehensive list of requirements. The aforementioned requirements are organised into categories, to facilitate a more comprehensive understanding of the topics encompassed by the regulation. The derived requirements are then analysed with regard to cross-references in the legal text that reveal dependencies. These dependencies indicate that other requirements must be taken into account for the complete fulfilment of a specific requirement. Meaningful visualisations, such as chord diagrams can support the identification of these cross-references, by transparently displaying them.

In the second step, an exemplary product is evaluated for its degree of compliance with the analysed requirements. The data sources may be diverse and depend on the individual access options to information on the product and its development status. Ways of obtaining information include contacting suppliers, product disassembly investigations and consulting public sources. For each of the requirements, a binary evaluation is conducted, revealing that the requirement is either fulfilled or not fulfilled. This assessment, together with the previous categorisation of the requirements makes it possible to identify the categories in which the analysed product is deficient in relation to the new legislation. A radar chart can be used to illustrate the degree of fulfilment the product under consideration has in each category and thus to transparently reveal the overall result. It also allows for comparisons of different products.

Subsequently, in the final step 3, an analysis is carried out to determine the level of difficulty associated with the fulfilment of each requirement. Therefore a four key questions are raised regarding the compliance with future legal regulations: (I) When to fulfil? (II) What will be changed? (III) Who should be involved? and (IV) What other requirements are there? Accordingly, four evaluation criteria were identified that influence the difficulty of reaching fulfilment:

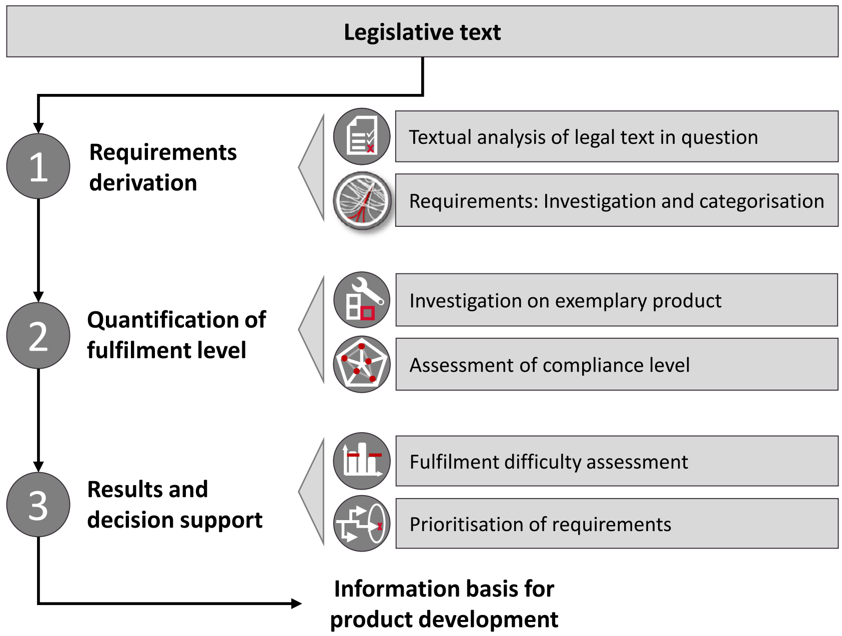

Fig. 1. Overview of the applied 3-step-approach and the intermediate steps and necessary inputs.

I Time sensitivity: The time frame, within which the provision has to be fulfilled
II Adjustment of product: To what extent the product's design will have to be adapted
III Third party involvement: If and to what extent a third party has to be involved
IV Information unavailability: Whether all necessary information is available to fulfil the requirement

The requirements are evaluated in a semi-quantitative manner, whereby a value between 1 and 5 (for criteria I and IV) or 1 and 4 (for criteria II and III) is assigned to each criterion. This rating scheme is applied to each criterion and each requirement in order to determine the extent to which the criterion influences the fulfilment of the requirement. The gradations between the scores of the criteria are chosen in such a way that a clear assignment to the scores is possible. The application of these criteria enables the derivation of focus areas regarding the procedure of compliance, which can be visualised by the application of heatmaps. An example of the scoring will be illustrated in Section 4. These illustrate the primary factors contributing to non-compliance. In combination with the gaps in fulfilment identified in step 2, it is possible to draw conclusions that facilitate the prioritisation of tasks during the compliance procedure.

Overall, for each identified gap in fulfilment, it is thus possible to derive information on the conditions that need to be established to ensure compliance, as indicated by the contribution of the four evaluation criteria.

4. Application to case study

In the course of our analysis we applied our three-step-methodology to the new EU Battery Regulation, which is introduced in the next sub section, in form of a case study. The procedure of requirements-derivation (step 1) is explained in Section 4.2. For step 2 of our procedure, we performed investigations on a specific battery accompanied by a disassembly analysis. For some requirements, it was necessary to make further assumptions e.g. regarding the batteries circumstances of origin in order for us to derive the extent to which they are fulfilled, as the performed analysis of the battery alone would not deliver all required information. Therefore, we chose the perspective of a European OEM that sources its batteries from a non-EU country and intends to recycle its batteries company-external in Europe. Figure S1 in the supplementary shows the according areas of influence assumed for the OEM. The outcomes of this case study on the basis of which the fulfilment-level of the derived design-related requirements is shown in the following. Further, this section provides the overview and evaluation of the respective fulfilment-difficulty, as described above. The following subsection provides a short overview of the Battery Regulation, its public reception and expected consequences from its implementation.

4.1. Legislative text: Introduction to the new EU battery regulation

The new EU Battery Regulation is a central component of the Green Deal because of the prominent position and important role of batteries in the desired shift towards greener industries (Halleux, 2023). The overall goal of the regulation is to ensure that batteries make a significant contribution to the ultimate objective of achieving a net-zero greenhouse gas economy by 2050, to be in line with the EU Commission's communication on the European Green Deal (Vettorazzi, 2021). As evidenced by the public reception from industry, academia and European Non-governmental Organisations, handling the new regulatory circumstances will potentially be quite challenging (Hoffmann et al., 2021; Melin et al., 2021; Hoffmann et al., 2022; Tedesco et al., 2021). It is therefore necessary to clarify to what extent traction battery systems can already cope with the requirements and where shortcomings can be identified.

4.2. Step 1: Requirements derivation

This section provides an overview of the identified requirements. In accordance with our case study battery, we limited our scope to the requirements relevant for traction batteries used in electric and hybrid vehicles because of their environmental and economic significance due to the expected increase in sales within the coming years (Figgener et al., 2022). Further, in our analysis, we included characteristics that go beyond the design of the batteries that are subject to the OEM's direct or indirect influence (see Figure S1 in the supplementary). This includes for example the information that has to be provided in accompanying documents such as the technical documentation. For each category between 2 and 57 relevant requirements have been identified,

Table 1
Extract from the list of requirements for the category carbon footprint, derived according to step 1 as shown in Fig. 1.

Number	Requirement	Source
The Battery has to be accompanied by a carbon footprint declaration, containing the following information:		
1.1	Carbon footprint declaration is available calculated for each battery model per manufacturing plant and differentiated per life cycle stage excluding use stage	Art.7 §1
1.2	Administrative information about manufacturer	Art.7 §1 a
1.3	Information about the battery model for which the declaration applies	Art.7 §1 b
1.4	Geographic location of the battery manufacturing facility	Art.7 §1 c
1.5	The carbon footprint of the battery is calculated as kg of carbon dioxide equivalent per one kWh of total energy provided by the battery over its expected service life	Art.7 §1 d
1.6	The carbon footprint of the battery differentiated per life cycle stage	Art.7 §1 e
⋮	⋮	⋮
1.14	The carbon footprint shall be calculated according to the international agreements and technical and scientific progress in the area of life cycle assessment	Annex II (2)

resulting in a total of 121 requirements. These are presented in Table 1 as well as in Tables S1 to S8 in the supplementary. The analysis, however, does not include the specific provisions that are relevant on company level such as due diligence requirements, as it focuses on product evaluation. Our analysis revealed that the relevant requirements for future vehicle battery design can be classified into eight categories, primarily based on the respective articles they originate from:

1 Carbon footprint (article 7)
2 Recycled content (article 8)
3 Performance and durability (article 9)
4 Labelling and marking of batteries (articles 13/38)
5 Information on the state of health and expected lifetime (article 14)
6 Repurposing and remanufacturing (article 59)
7 Information on prevention and management of waste batteries (article 60)
8 Battery passport (article 60)

The first category about carbon footprint requirements is presented as an example in the following subsection. For categories 2–8, the descriptive texts and necessary definitions but also the derived requirements are presented in the supplementary to this publication.

4.2.1. Carbon footprint (category 1)

Provisions regarding the carbon footprint are dealing with the consideration of greenhouse gas emissions that arise throughout the entire life cycle of a certain battery type from raw material extraction and production until the End of life (EoL) stage. Article 7 and Annex II define a basic framework on how this impact is to be determined and declared in the future. Figure S2 in the supplementary document shows the timeline according to which the central stipulations regarding the carbon footprints of vehicle batteries will be implemented. Table 1 shows an excerpt of the requirements from the category carbon footprint, as derived according to step 1 of the methodology.

Several of the derived requirements will be preceded by a delegated act in the framework of which the exact procedure for their fulfilment will be explained. These delegated acts will thus show how the batteries' carbon footprint will be determined, how the performance classes yet to be established are defined which allow for a comparison of each individual battery's footprint with those available on the market. Further, an upper limit of the carbon footprint will be defined that must not be exceeded. According to Annex II, the determination of the carbon footprint has to be consider the Product Environmental Footprint Category Rules (PEFCR). However, the Battery Regulation states, that the Commission's joint research centre will be responsible for further development of the battery-specific PEFCR to further specify how to calculate and declare the carbon footprint.

4.2.2. Interconnections between single requirements

A considerable number of articles prescribing design-related requirements have dependencies through cross-references to other requirements. Fig. 2 provides a visual representation of all explicit references of the articles from which the design requirements are derived and also when specific topics directly link two provisions. The figure only shows those requirements that are part of such inter-connections which implies that both topics cannot be treated independently of each other. On the one hand the figure helps to gain a comprehensive understanding of the regulation's impacts, facilitating the overview of all design relevant aspects touched by the regulation. On the other hand, the figure provides stakeholders responsible for a single category (such as carbon footprint) the dependencies to other categories and requirements that also need to be considered for compliance. It is thus possible to determine if all essential prerequisites have been thoroughly examined when attempting to address one specific requirement.

The strong links between the requirements regarding the battery passport and several other requirements are identifiable. This relationship is attributable to the fact that the requirements for the battery passport necessitate the integration of a substantial amount of information specified in other articles. Further, the information stored in the battery passport needs to be accessible through a QR code, that is defined in the category labelling (requirement 4.15, see Supplementary). An additional significant connection exists between the management of waste batteries-category (7) and the labelling requirements (4) as the requirements for waste batteries mandate the explanation of all labels affixed to the battery. Moreover, the carbon footprint declaration (1.12) imposes a requirement to incorporate information regarding recycled content (2), thereby establishing a substantial connection between these two categories.

4.3. Step 2: Quantification of fulfilment level

To identify the extent to which a traction battery would already meet the requirements derived in the previous subsection, we performed a detailed investigation of an exemplary battery to acquire information for step 2 of the developed methodology (see Table S9 and Figure S3 in supplementary). For this analysis initial information about the battery was acquired by analysing attached labels on each surface and by consulting publicly available information sources as well as data platforms provided by the manufacturer. During the teardown, properties such as used materials, their respective weights and information about the battery condition and joining techniques were documented.

In the following the results of the compliance analysis are presented. For each of the eight categories, the quantified requirements can be found in the supplementary of this work. Fig. 3 shows the respective level of fulfilment as a percentage.

For the analysed battery, no carbon footprint declaration was available. Accordingly, the majority of the upcoming 13 design related requirements regarding the carbon footprint and its declaration still

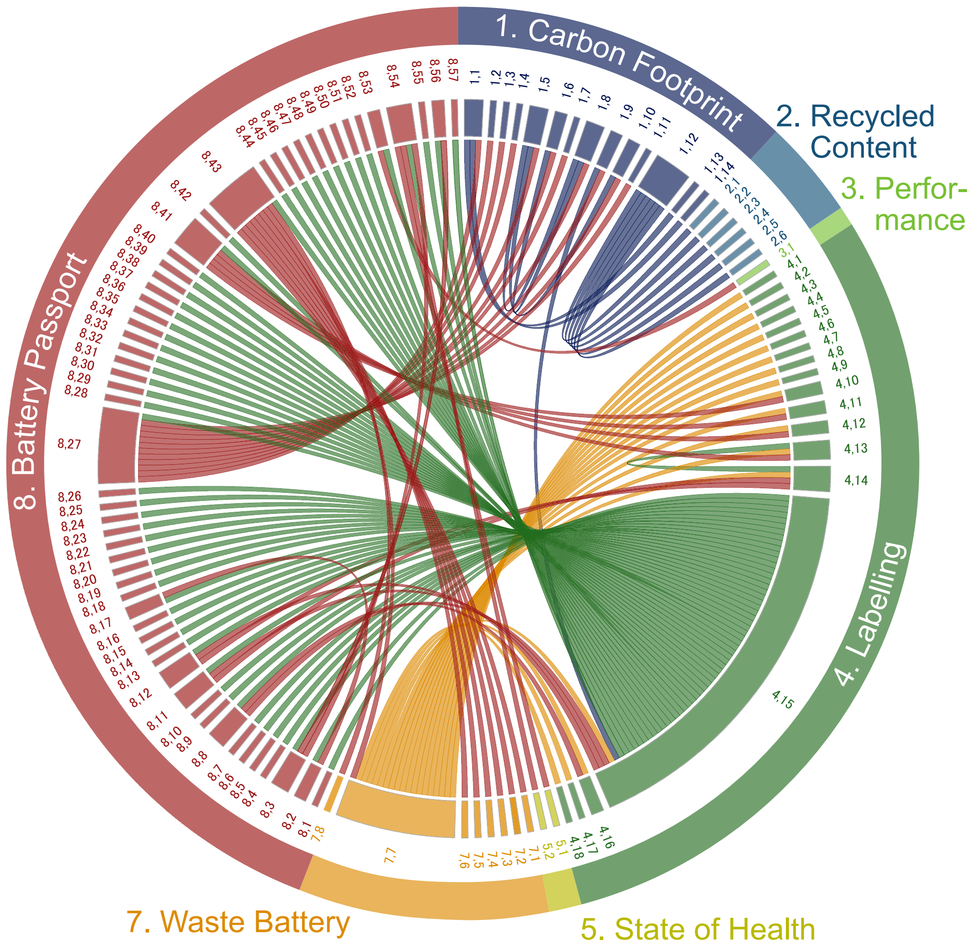

Fig. 2. Depiction of the interrelationships between identified design-relevant provisions and the articles they are based upon in the EU Battery Regulation.

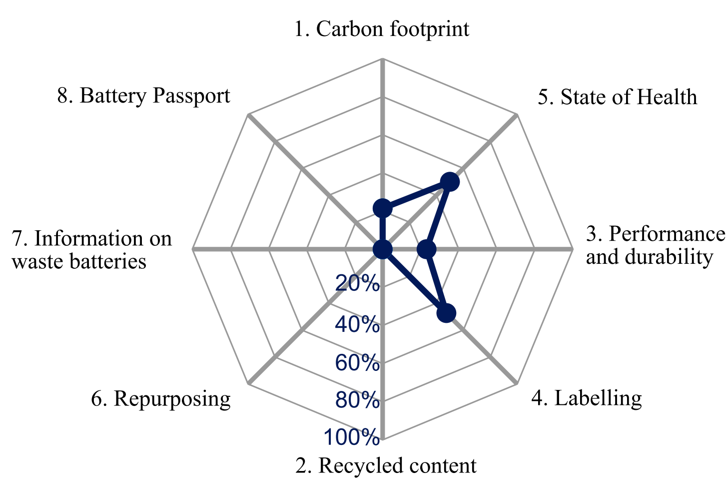

Fig. 3. Respective level of compliance with the requirements identified across the eight categories expressed as a percentage.

remains to be dealt with, which leads to an overall fulfilment rating of about one fourth. Still, this comparatively high level of compliance can be attributed to certain requirements that only require providing administrative information (like requirements 1.1–1.3).

Given the current status of the recycling industry, it is reasonable to assume that newly manufactured lithium-ion batteries does not yet contain recycled materials. (Boston Consulting Group, 2023). This corresponds with the evaluation result of 0 %, as all relevant requirements from article 8 require the integration of recycled content. Of the complete set of 12 requirements regarding the category of performance and durability, only the nominal capacity and power specifications are met by the battery system under investigation. The main reason for this is that most of the data is not available in the required form of general technical documentation.

Almost half of the information required to be disclosed for the category of labelling is already available, resulting in the according fulfilment quota. Information already provided in the form of labels includes battery-specific details such as its manufacturing date and place and general information that allows for the manufacturer's identification.

For the analysed battery, half of the requirements concerning the disclosure of information on state of health and expected lifetime is regarded as fulfilled as it was disclosed via the battery management system (BMS). According to the requirements for the category of repurposing and remanufacturing the battery holder must be enabled to present information about a battery that shall be subject to product recycling and respective treatment processes. For the present example, no information was available. Furthermore, when the battery was obtained, we were not provided with the necessary data that would enable us to determine its state of health, as required by article 59 §5. Consequently, the evaluation result is zero.

In total 57 provisions regarding the battery passport have been identified in the framework of this analysis, none of which are met in this example. This is not surprising as the entire system including the electronic exchange platform that the battery passport is intended to be linked to, does not yet exist. The exemplary battery also fulfils none of the 12 requirements regarding the category information on the prevention and management of waste batteries. For the compliance with this category, the information shall be made available to end users at the point of sale and through an online marketplace. Neither was the case for the battery obtained in the framework of this study.

4.4. Step 3: Results and decision support

In this step the identified evaluation criteria for the difficulty of the fulfilment are applied for each requirement. The criteria are: (I) the time sensitivity, (II) the extent to which an adjustment of the product is necessary, (III) whether a third party involvement is necessary for fulfilment and (IV) the information unavailability. Fig. 4 shows the procedure that was applied to derive quantifiable values from the textual analysis taking requirement 1.1 as an example. In order to determine the evaluation results in the four categories (I–IV), the broader context of the requirement in the legislative text is analysed. The assessment result options are selected in such a way that the relevant text passages can be clearly assigned to them. In the end, this procedure makes it possible to determine each categories relevance to reach the determined requirements' fulfilment.

Fig. 5 shows the results for each individual requirement in the form of heatmaps based on the rating scheme below. The numbering is defined according to Table 1 and the respective tables S1-8 in the supplementary.

Based on these results, conclusions can be drawn about the level of difficulty involved in meeting each individual requirement. In general it can be seen, that certain requirements that appear to be the hardest to fulfil like the quotas for *recycled content* for newly manufactured batteries also often leave the most time for their fulfilment. Accordingly, for all identified *recycled content*-related provisions (category 2), the time sensitivity was evaluated to be low, due to the fact that the first quotas are not required to be met until 2031. Fig. 5 also reveals that if the current situation does not allow the OEM to acquire necessary information, the requirement's fulfilment mostly depends on the contribution third party to fill the information gap. Article 7 of the regulation contains a number of *carbon footprint*-related provisions (category 1), that still require the European Commission to adopt delegated acts, that are intended to specify the criteria for their fulfilment. Accordingly, the third party involvement is rather high due to the necessary involvement of the commission, that will have to finalise the rules. The information unavailability is rather high and it is impossible to obtain the necessary data at present. A similar case applies to the *battery passport* requirements. As the entire system still has to be established and the criteria that specify the conditions to which data has to be provided remain unclear, the contribution of third parties was evaluated high. Overall, the fulfilment of some *battery passport* requirements seems be rather straightforward once the system is established, but the analysis also reveals a number of hotspots, that need to be considered with increased awareness. The analysis shows that the larger part of the *information on waste batteries* to be disclosed for category 7 would already be accessible to the OEM, except for the process details to be provided to guide a structured dismantling (requirement 7.10). As most other batteries, the one that was investigated for the case study was not designed to allow for disassembly, which means that to comply with this specific requirement, effort must be put into the development and documentation of the according process chain. This might require a high level of involvement of the company-external upstream actors along the supply chain, as is the case for other requirements of this category.

4.5. Discussion and limitations

The method developed in the framework of this paper to analyse products regarding compliance with new legislative provisions consists of 3 steps: requirements derivation, identification of fulfilment level and results and decision support. It is applied to an automotive lithium-ion battery and the corresponding new regulation in Europe. The result of the gap analysis performed in step 2 revealed for the investigated battery that many of the identified requirements are yet to be fulfilled. The investigation further revealed several cross-references within the Battery Regulation that in turn led to links between the derived requirements. Combining these two assessments leads to a more comprehensive picture of the necessary steps to ensure compliance with the new legislation. An illustrative example would be the set of battery passport related requirements. This category not only contains by far the most identified requirements (none of which can yet be fulfilled) but also meeting these requirements in many cases depends on requirements from other categories. Having transparency about these links enables the entities that are responsible for the requirement's fulfilment to identify which other entities within an organisation or the supply chain need to be contacted.

In the third step of the analysis, the difficulty of compliance was determined, which allows conclusions to be drawn on the reasons behind the under-fulfilment.

For the fulfilment of various provisions, the disclosure of information is necessary which would often already be feasible. This becomes obvious when considering that for many requirements the necessary information to disclose is presently already accessible to the OEM, also without requiring the involvement of any other stakeholders. It can be assumed that this information was not yet shared only due to the lack of incentives, and meeting these specific requirements will prospectively not present a challenge in the future.

In contrast, a high level of unavailable information is often strongly linked with the necessity to involve other stakeholders, the contribution of which is required in order to access the needed information. These stakeholders often are other companies along the OEMs' up- and downstream supply chains that either design the battery or are otherwise involved in its production or recycling. In other cases, a high level of third party involvement implies that a contribution of legislative authorities is a precondition, as still numerous regulations remain unspecified and will be elaborated on in upcoming delegated acts. For example in the category of carbon footprint, in the context of which many requirements shall be put into practice in the upcoming year, there is still a number of unresolved regulatory issues that need to be addressed. As a result, it is important for companies to urgently focus their efforts on developing related expertise and to collect data regarding their supply chain, in order to avoid to be unprepared once the new system is established. The same applies to the category regarding provisions for the battery passport. The implementation and utilisation of this new system will prospectively present a complex task, however, details are difficult to estimate as it still needs to be developed.

At present, there is a lack of knowledge regarding the use of recycled materials in battery cells, which in combination with the absence of a

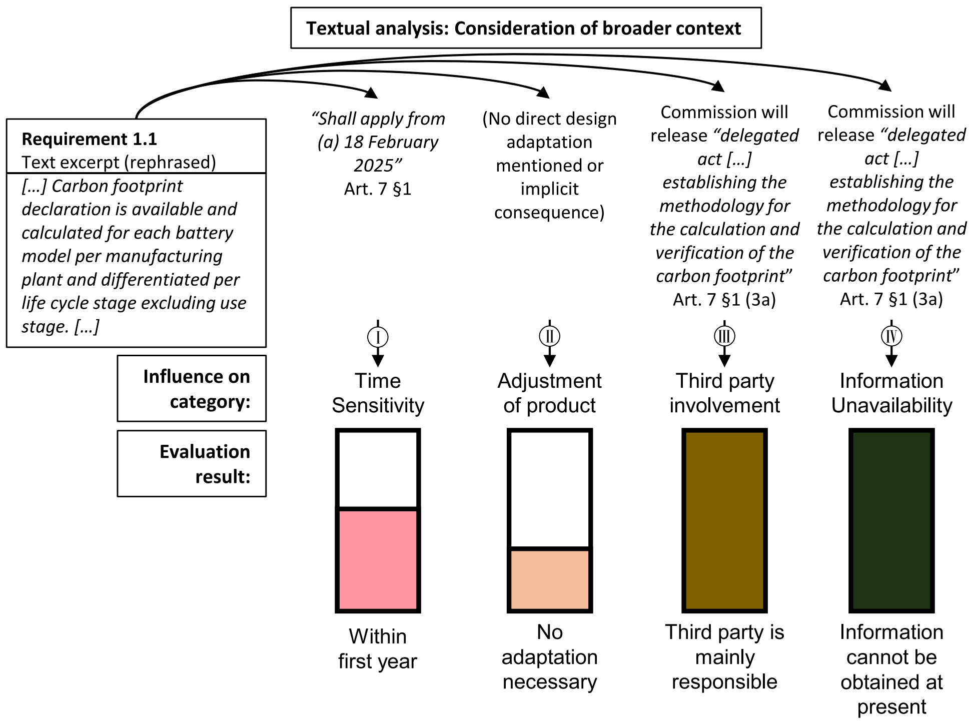

Fig. 4. Procedure for the derivation of quantifiable values the requirements based on the performed textual analysis taking requirement 1.1 as an example.

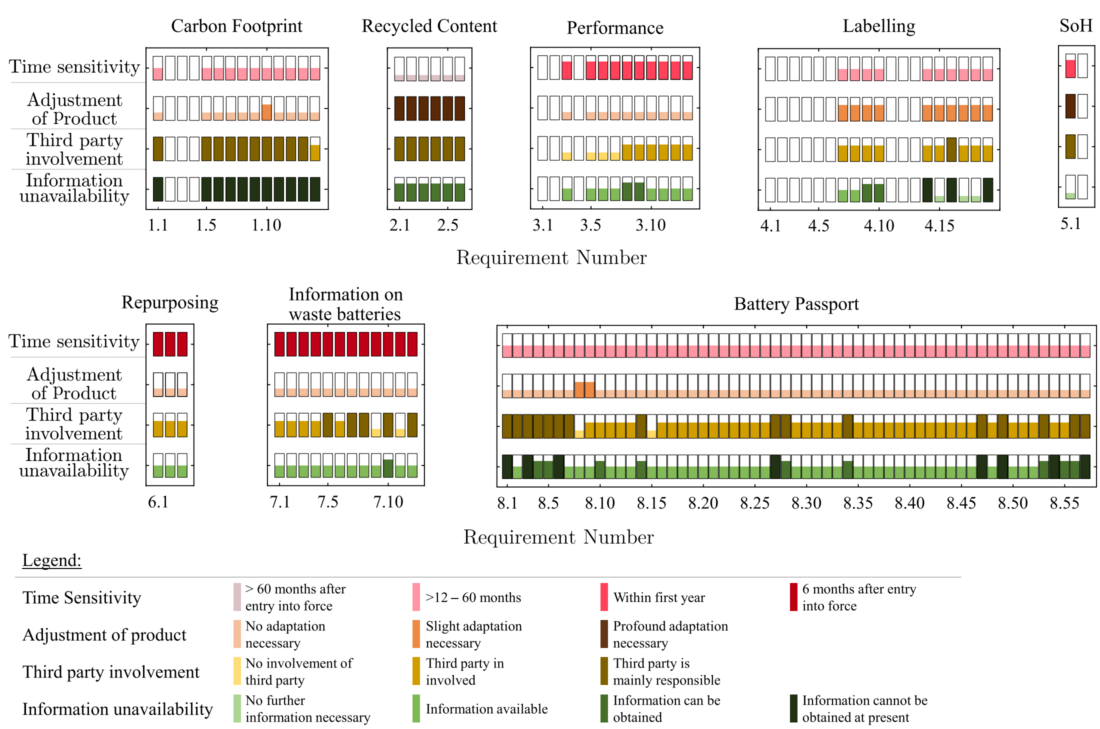

Fig. 5. Heatmaps for the identification of hot spots towards compliance with the future Battery Regulation in the categories. The numbering is according to the requirement number. The darker the colour and the more the bars are filled the more significance has the criterion in order to meet the respective requirement. An empty bar means, that the requirement is already fulfilled by the analysed battery.

market for such materials renders their inclusion in the manufacture of new battery cells challenging. These conditions lead to a high necessity to involve third parties and a moderate to high unavailability of necessary information. Companies should therefore focus on contributing to the establishment of a sufficiently developed recycling infrastructure to already claim access to future volumes of recycled materials. Otherwise, the shortage of available recycled materials can impede the production of the required volume of cells or force OEMs to import significant amounts of recycled material.

When applying the developed methodology, it is important to consider a few limitations and challenges. One such limitation is that the availability of information sources depends very much on the user.

To gain a comprehensive understanding of the battery, we conducted an analysis from the manufacturer's perspective. However, as a third party, we cannot access certain information, such as details regarding the specific supply chain. It cannot be excluded that the available information basis might impact the results. Further, the semi-quantitative evaluation of the specific requirements is conducted based on the expertise of the relevant professionals. While multiple independent experts may be consulted, some categories' results are rated subjectively to a certain extent. Therefore, it is important to emphasise the methodology employed to determine the relevant evaluation parameters to ensure the highest degree of objectivity. On the one hand, due to the intentional unambiguous categorisation of the criteria assessment levels, the extent to which this may influence the results is limited. On the other hand, this rather rough categorisation also means that the actual consequences resulting from an assessment result cannot be certain. To illustrate, the adaptation of a product that is necessary due to the mid-level evaluation in the category ''adjustment of product'' might be to attach an available label or QR Code to the product or could maybe also entail the replacement of certain components. Therefore, it is not necessarily clear from the analyses how complex the fulfilment of the requirement will be, but it only allows for an estimation. Thus, the methodology enables only the identification of key requirements but cannot fully demonstrate the extent of the necessary efforts to address shortcomings in these requirements. Furthermore, the methodology is highly contingent upon alterations to legislative texts, necessitating iterative adaptation in response to each amendment. This can result in significant expenditure in the event of a change, and the results are only valid for the current iteration of the legislation. Consequently, it is paramount to pay meticulous attention to the specific version of the legislation and technical documentation employed at any given time.

5. Conclusions

The aim of this analysis was to provide both OEMs and SMEs with a methodology to prioritise within their product development, in order to seamlessly comply with upcoming legislation, that is expected to have a major impact on their business environment. The case study presented revolves around the knowledge gained regarding the compliance of a state-of-the-art battery with the EU Battery Regulation. To this end, the battery system design and its inherent characteristics were examined, to identify the extent to which the exemplary battery system would already meet future requirements and where it would fall short. Furthermore, in order for OEMs to identify where to focus their future battery development, the difficulty of fulfilling each of the requirements that was not met so far was analysed . This assessment considered four key criteria, namely:

(I) the timeframe for the requirement to take effect,
(II) the need for design adjustments to the product,
(III) the need for collaboration with or preliminary work of other stakeholders and
(IV) the availability or absence of necessary information.

The analysis showed that for the eight identified categories deemed critical to future battery design, the average fulfilment rate was found to be less than one third for almost all of them. In many cases, only a lack of incentives was identified as the main reason for not sharing necessary information which would already be sufficient to meet certain requirements. The analysis identifies the requirements for which this is not the case and also provides the reader with possible reasons for an increased difficulty in achieving compliance. The application of the developed method shows its suitability for identifying focal points in product development. Evaluating the current product range with regard to upcoming requirements, combined with assessing the difficulty of requirements that still have to be met, is a crucial help in terms of prioritising in product development. The methodology developed could be applied to other legislative texts in the future, such as the Ecodesign for Sustainable Products Regulation for which the Battery Regulation is seen as a blueprint.

CRediT authorship contribution statement

Sönke Hansen: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Tom Rüther:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Mark Mennenga:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition. **Christoph Helbig:** Writing – review & editing, Validation, Supervision, Resources, Methodology. **Gregor Ohnemüller:** Writing – original draft, Investigation. **Filip Vysoudil:** Writing – original draft, Investigation. **Constantin Wolf:** Writing – original draft, Investigation. **Bernd Rosemann:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition. **Sandra Pavón:** Writing – review & editing, Supervision. **Alexander Michaelis:** Funding acquisition. **Thomas Vietor:** Writing – review & editing, Supervision, Funding acquisition. **Frank Döpper:** Writing – review & editing, Supervision, Funding acquisition. **Christoph Herrmann:** Writing – review & editing, Supervision, Funding acquisition. **Michael A. Danzer:** Writing – review & editing, Supervision, Funding acquisition.

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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Appendix A. Supplementary data

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References

Barkhausen, R., Fick, K., Durand, A., Rohde, C., 2023. Analysing policy change towards the circular economy at the example of EU battery legislation.
Boston Consulting Group, 2023. Striking gold with EV battery recycling.
Breaux, Vail, Anton, 2006. Towards regulatory compliance: Extracting rights and obligations to align requirements with regulations. In: 14th IEEE International Requirements Engineering Conference. RE'06, IEEE, pp. 49–58.
European Energy Agency, 2023. EEA greenhouse gases — data viewer.
European Union, 2023. 2050 Long-term strategy.
Figgener, J., Hecht, C., Haberschusz, D., Bors, J., Spreuer, K., Kairies, K., Stenzel, P., Sauer, D., 2022. The development of battery storage systems in Germany: A market review (status 2023).
Halleux, V., 2023. New EU regulatory framework for batteries: setting sustainability requirements.
den Heuvel, C.V., Matyas, P.K.M., 2020. Factors driving and hindering business model innovations for mobility sector start-ups. Res. Transp. Bus. Manag..
Hoffmann, M., Barczak, P., Tedesco, R., Keynes, A., 2021. Proposal for batteries regulation 2020/353 (COD), repealing directive 2006/66/EC and amending regulation (EU) no 2019/1020 - recharge statement to public consultation. p. 21.
Hoffmann, M., Barczak, P., Tedesco, R., Keynes, A., 2022. EU-batteries regulation: Four-position-paper. p. 6.

Ingolfo, S., Alberto, S., Mylopoulos, J., 2014. Nomos 3: Reasoning about regulatory compliance of requirements.

Makri, C., Rajkumar, R., Sackett, P., 2004. Translating environmental legislation into the engineering design domain.

Melin, H., Rajaeifar, M.A., Ku, A., Kendall, A., Harper, G., Heidrich, O., 2021. Global implications of the EU battery regulation. Science 373 (6553), 3.

Otto, P., Anton, A., 2007. Addressing legal requirements in requirements engineering.

Pigosso, D., Ferraz, M., Teixeira, C., Rozenfeld, H., 2016. The deployment of product-related environmental legislation into product requirements.

Tedesco, R., Barczak, P., Tedesco, R., Sommer, P., Keynes, A., 2021. Enhancing the sustainability of batteries: A joint NGOs' postition paper on the EU battery regulation proposal. p. 27.

Vettorazzi, S., 2021. Updating the EU regulatory framework for batteries. EPRS: European Parliamentary Research Service.

Vysoudil, F., Hansen, S., Mennenga, M., Fukuda, M., Ohnemüller, G., Rüther, T., Goers, D., Koller, J., Nikolowski, K., Rosemann, B., Wolter, M., Danzer, M., Döpper, F., Herrmann, C., Vietor, T., 2023. Procedure model to support the recycling-oriented design of lithium-ion batteries for electric vehicles. In: Fukushige, S., Kobayashi, H., Yamasue, E., Hara, K. (Eds.), EcoDesign for Sustainable Products, Services and Social Systems I. Springer Nature Singapore, Singapore, pp. 383–397.