INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.134

Systems thinking towards holistic, sustainability-oriented assessment and decision-making for lightweighting

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Abstract

Multiple industries have hailed lightweighting promise to reduce the mass of their product at equivalent or improved performance. Lightweighting as a strategy encompasses lightweight end-product desired attributes and through-life processing decisions. Assessment of lightweighting gathers information for decision-making towards the optimization of these strategies. An exploratory study, using systems thinking is conducted, to identify requirements of lightweighting and its assessment in terms of holistically defining its impact on the sustainability of its background system, the Earth.

Keywords: lightweighting, life cycle assessment (LCA), sustainability, decision making, systems thinking

1. Introduction

Lightweighting promise lies in the reduction of mass of a product at equivalent or improved performance (Lewis *et al.*, 2019). "*Lightweighting is becoming a major trend, reaching many industrial sectors*" including "*transportation [...], manufacturing, and clean energy technologies*" (Czerwinski, 2021). This trend is tangible, as publications on lightweighting have risen exponentially since the turn of the century. Within the automotive industry, lightweighting is key to meet environmental standards and improve performance with manufacturers "*expressing a high level of confidence in lightweighting*" and "*49% of companies surveyed sa[ying] that lightweighting is their main strategy*" (Isenstadt *et al.*, 2016). It has been echoed that "*aerospace has been on the lightweight path since its origin*" (Czerwinski, 2021), and that lightweighting is key for clean energy technologies e.g., wind turbines (Kupfer *et al.*, 2022). This lightweighting popularity has broadly been reported as attributable to achieving sustainability-aligned performance desires, across sectors with profound global impact. Despite the increased use of lightweighting over the past three decades, continued climate change exacerbations indicate that "*existing pattern[s] of development, production, and consumption [remain] unsustainable*" (Roy, 2021). Kupfer et al. (2022), recently, acknowledged that "*pressure to provide sustainable products is forcing the lightweight industry to rethink [...] to integrate sustainability criteria in all decisions*". There is opportunity to augment lightweighting towards sustainability, and explore where current shortcomings may lie.

Lightweighting is typically framed as a complex endeavour due to the multiple interrelated strategic decisions on a lightweight product and processing that it involves. Strategies consider goals, and decisions and activities to achieve these. Strategies should be evidence-based to support informed decisions (Woods, 2000). Data can be collated for decision-making through assessments. Thus, existing lightweighting strategies - decisions taken, processes selected, and end-products developed - may be assessed to inform future lightweighting. Assuming that decisions are informed, current assessment derived data may be a source of deficiency in supporting sustainability-oriented decisions to be effectively made. While availability and quality of input data for assessments has been identified as an issue in lightweighting assessment (Lewis *et al.*, 2019), a review of the assessment formats themselves in terms of their suitability to support sustainability-oriented strategic decisions is suggested.

Through-life (or life cycle) assessments are considered some of the most well-aligned, popular sustainability-oriented assessment formats to avoid displacing impacts. Assessing lightweighting has traditionally used the ISO 'Life Cycle Assessment' (LCA) format, with environmental focus (Zanchi *et al.*, 2021) and assimilation to sustainability therethrough. However, increasingly sustainability is interpreted as principally anthropogenically relevant (Lövbrand *et al.*, 2009), and important to species on Earth to ensure their habitat is protected in the form in which they know how to survive and live well. Thus, socio-constructed systems such as economies and societies add dimensionality of relevance to sustainability. Life Cycle Sustainability Assessments (LCSA), using "*environmental, social, and economic dimensions*", are now being investigated to address notions of interconnection within the Earth that affect sustainability (Zanchi *et al.*, 2021). Nonetheless, previously LCAs had been deemed representative enough to inform sustainability-oriented decision support; how can we now be sure that LCSAs are wholly apt to inform the sustainability performance of lightweighting with fidelity?

For effectivity of lightweighting as a sustainability-oriented (S-O) strategy, aligned to its reported goals, it should be considered systematically and wholly, considering its impact across space and time (i.e., across physical aspects of relevancy, and through-life with inclusion of lightweight design, lightweight manufacturing, the lightweight end-product, and end-of-life processing considerations, respectively). This is because sustainability has roots in systems thinking (Osorio *et al.*, 2009), and requires "*holism and system-wide approach[es] […] in order to deal with complexity*" (Sala *et al.*, 2013) of the almost unfathomable volume of simultaneous, interlinked activities on Earth affecting its behaviour. Lightweighting activities, of course, account for a limited proportion of these, but these can be argued as not insignificant to sustainability on Earth, as it is a dominant strategy in some of the world's largest industries. Ensuring that all lightweighting decisions can be effectively informed through assessments also rooted in systems thinking (ST) may address making lightweighting more sustainable. There is no evidence or mapping, however, that ST requirements underpin LCSA origins in the most popular format proposals by Kloepffer and Renner (2008) and Guinée et al. (2011).

In lightweighting, complexities arise in navigating trade-offs of sustainability-optimal design and process decisions, which become particularly evident in holistic, through-life consideration. As mass varies with density and volume, lightweighting couples the increased complexity of using advanced, less dense materials e.g., composites, (Fan and Njuguna, 2016) with volumetric optimisation techniques such as topology optimisation (TO) and latticing. Typically, products constituted of composites exhibit more intensive production and end-of-life processing, but support better sustainability performance in product use such as better fuel efficiency (Raugei *et al.*, 2014). Similarly, TO is often assimilated with 'design for additive manufacturing' (DfAM), where AM enables lighter, more energy efficient products in use (Beyer, 2014), at the expensive of computational intensity in design (Rasulzade *et al.*, 2023) or energy intensity in production, which are unfavourable for sustainability. The interconnectedness of required decision-making in lightweighting undoubtedly adds complexity that requires more sophisticated assessment formats to inform decision-making. Not only do lightweighting decisions trade-off a whole array of potential novel combinations of designs and processing, but it is inherently linked to new innovations and technology advancements through-life, that may be linked to multiple aspects of sustainability (Zanchi *et al.*, 2021). Systems view of lightweighting would intrinsically complement the sustainability-required systems view, and support decision-making against displacing unsustainable impacts of human driven activities, which originally led to the need for sustainability due to a lacking comprehensiveness of awareness and consideration.

Increasingly, lightweighting is being considered "*at the systems level to ensure proper balance with all other critical requirements*" (NRC, 2012). Herrmann et al. (2018) specified both the lightweighting "*product-and the background system*" as setting "*requirements for lightweight structures*". It may be considered that these requirements of lightweight structures and lightweighting are relevant to the criteria by which to assess lightweighting, also. In turn, collating information through assessment across specific criteria, can support targeted decision-making aligned to the requirements of lightweight structures. Assessment criteria are "*points of reference*" or "*abstractions"* that *"compress information, and represent* *the essential substance of what individuals or organizations aim to accomplish*" in decision-making, and for meeting requirements (Colyvas, 2012). Thus, to understand the requirements of lightweighting assessment formats, systems thinking in relation to lightweighting is important. As noted, both a system's understanding of lightweighting and its background system - of the Earth, within the context of lightweighting's overarching aims being derivative of the sustainability thereof - is required.

Systems thinking (ST) is an epistemological approach for "*the identification, modeling, and prediction of complex systems as entities rather than isolated phenomena*" (Mambrey *et al.*, 2020), in holistic manner. ST is considered "*a much-needed competence to deal better with an increasingly interlinked and complex world*" (Hieronymi, 2013), and is *"a prerequisite for sustainability*" (Voulvoulis *et al.*, 2022). Clearly, ST in relation to lightweighting and sustainability-oriented assessments thereof, can offer a comprehensive perspective of the requirements of lightweighting and of the assessment and decision-making criteria therefor. Despite their suggestions, Herrmann et al. (2018) did not portray both the lightweight product system (i.e., lightweighting) and the background system using systems thinking to evidence the criteria by which to assess lightweighting for holistic understanding. No current research has been found to do so. The potential of a ST approach to the problem of understanding format requirements for holistic, sustainability-oriented (S-O) lightweighting assessments and decision support remains untapped. This research proposes to address this opportunity and aims to answer the following research questions (RQs): RQ1. Does system's thinking indicate that lightweighting sustainability-oriented assessment formats should differ from existing formats? RQ2. By employing system's thinking, how should assessment formats for lightweighting differ from existing formats?

2. Methodology

The RQs query procedural knowledge associated with sustainability-oriented (S-O) assessments of lightweighting. RQ1 suggests theoretical evidence must be collated to verify systems thinking (ST) applicability for lightweighting assessment format and criteria requirement definition, for subsequent comparison to existing formats. RQ2 suggests distinguishing lightweighting assessment requirements and used lightweighting assessment formats explicitly, therefrom, making inferences on how procedural knowledge or 'instruments' for lightweighting assessment should be extended, founded on ST. This dictates the inductive portion of wider exploratory mixed-methods research for 'instrument development' or 'intervention'. Combining mainly qualitative data formats using a literature review and synthesis, this research informs theory building. For RQ1, theory is built by conducting: (1) a 'rapid review' (RR) of systems thinking suitability to the research problem, and in understanding lightweighting and the Earth as systems for their requirements identification; and (2) a 'meta-synthesis' (M-S) of lightweighting assessment research for overview of current lightweighting assessment format trends. Section 3 presents these. To answer RQ2, analysis and comparison of lightweighting assessment formats against requirements for lightweighting assessment formats, based on ST, was conducted. Section 4 discusses this juxtaposition to propose new theory on extensions to current formats. Snyder (2019) affirmed methodological suitability, corroborating that literature reviews "*create a firm foundation for advancing knowledge and facilitating theory development*". Specifically, RRs use streamlined review phases to address "*questions explicitly requested by decision makers*" (Garritty *et al.*, 2021) through integrative information synthesis, which RQ1 requires. Meta-syntheses are used for joint interpretation and integration of qualitative data to generate new theories and attain greater generalizability, and can produce "*stronger results because the source of evidence comes from many different scholars*" (Leary and Walker, 2018). Increased breadth of the M-S is proportionate to the desire to evidence how encompassing current S-O assessment and decision-making formats of lightweighting are.

While there exist varying ways of reporting review searches, STARLITE has been identified as a fitting approach to convey essential elements (Booth, 2006). Table 1 gives a STARLITE summary of the RR and M-S. The JBI 'Quality Assessment and Review Instrument' (QARI) can be used for quality assessment, "*methodological rigour*" and to add "*validity of qualitative research*" (Newton *et al.*, 2012). The tool ensures congruity across the research methodology, philosophy, research objectives, data collection and data analysis, and ethical considerations (where appropriate). Summary of QARI outputs supports the 'congruity' and quality of this research, and the quality of evidence sources used. Philosophically, pragmatism is compatible to RRs, and M-S derived knowledge (Hannes and

https://doi.org/10.1017/pds.2024.134 Published online by Cambridge University Press

Lockwood, 2011). For pragmatism, reality is consequent of experiences, and truth of knowledge depends on enabling successful action. Pragmatism states value is situationally-and-subjectively-consequent, such that values can align with achieving "*shared goals to which society aspires*" (Costanza, 2004) (e.g., sustainability). As such, pragmatist view dictates that the information synthesised by the research reviews can be considered true and real if there is proof that it has functionality and benefit (i.e., only peer-reviewed, evidence-based papers are considered to confirm RQ1 and characterise RQ2 response). Pragmatist view affirms that the synthesized novel knowledge generated in this research can be valuable and true, where it is tested and validated, as further planned.

Table 1. STARLITE summary of Rapid Review and Meta-synthesis methodologies

STARLITE summaries for **RR and M-S**			
Sampling Strategies	**For RR**: Purposive i.e., One representative database (ScienceDirect as largest scientific database) For M-S: Comprehensive i.e., Multiple scientific databases via search engines (Engineering Village, ProQuest, and ScienceDirect)	**Inclusions and Exclusions**	**+ Inclusion**: **For RR**: Qualitative descriptions of systems/ systems thinking/ systems engineering; qualitative descriptions of modelling systems; qualitative descriptions of lightweighting representations; qualitative or mixed-methods descriptions of the Earth system representations **For M-S**: Qualitative or mixed-methods studies and reviews of any form of sustainability-oriented/ through-life/ life cycle assessment(s), with or without decision-making support, of lightweighting/ lightweight products/ lightweighting-related processes. Dimensionality of sustainability-oriented assessments of products/ processes considered generally, also, for comparison. **- Exclusion**: **For all (i.e., RR and M-S):** Where exclusively process or service systems are discussed, non-scientific/ non-engineering articles
Types of Studies	**For RR and M-S**: Any kind of qualitative or mixed-methods study approach where theoretical, conceptual, or empirical information is presented		
Approaches	**For RR**: Systematic with Boolean operators & Citation Snowballing For M-S: Systematic with Boolean operators	**Terms Used**	Full terms for RR and M-S noted in associated research Generally, terms combined using Boolean operators AND or OR (ocassionally NOT used to limit search per general inclusions/ exclusions) RR **Terms (or synonyms of)**: 'systems', 'systems thinking', 'systems engineering', 'systems modelling' **Some M-S Terms (combinations and/ or synonyms of):** ('lightweighting', 'lightweight products', 'lightweight structures', 'lightweight manufacturing', 'lightweight engineering', ('lightweight' AND 'product system*')...), ('life cycle assessment', 'sustainability assessment', 'LCSA', 'through-life assessment', 'product assessment'...), ((environmental, social, societal, economic*, politic*, legal, legislative...)'assessments' or 'analysis'), 'decisions', 'decision support', (('multi-criteria'/ 'multi-attribute'/'multi-objective')'decision-making')
Range of years	**For RR and M-S**: No restrictions; to the beginning of each candidate database up to 2023		
Limits	**For all (RR and M-S):** - Language limits: English and German; & - Only peer-reviewed articles as evidence	**Electronic Sources**	**For all (i.e., RR and M-S):** ScienceDirect database, and/or Scientific and Engineering databases accessible through ProQuest (including, but not limited to, Ebook central, SciTech Premium Collection) and/or Engineering Village (Compendex and Inspec)

3. Literature review and synthesis

To interpret information and advance knowledge, the reviews below summarise systems thinking, and systems-dictated requirements for sustainability-oriented lightweighting assessment and decision-making, along with the current research on these assessment types for comparison, respectively.

3.1. Rapid Review (RR)

3.1.1. Applicability of Systems Thinking to the research problem

Systems thinking (ST) was identified as an effective, "*needed*" way to deal with complexity (Hieronymi, 2013). Studies report ST as a holistic approach to look at wholes (Voulvoulis *et al.*, 2022), with benefit in doing so to "*analyz[e] a system's constituent components, how they are interconnected to form a structure, and how systems work over time, including within the context of larger systems*" (Robinson, 2021). Thus, using ST to situate lightweighting as the 'system of interest' (SoI) within the system context and environment of the Earth, provides potential to understand the complexities of their interconnection and behavioural influences on each other, holistically – particularly with respect to sustainable Earth behaviours. Voulvoulis et al. (2022) added: "*understanding the many factors that cause the system to function the way it does [...] is a prerequisite for sustainability transformation*". Moreover, the RR evidenced ST relevancy to the research by assimilation of search output vocabulary, linking ST benefit to 'knowledge management', 'decision making', 'problem solving', 'sustainable development', and 'risk management', as notable cross-cutting themes.

The RR highlighted that systems must be defined by: their goals (with respect to stakeholder needs of the system); their elements (parts); their structure; and their, therefore, resultant behaviour (Robinson, 2021; Watson *et al.*, 2020). An often-differentiated system type was 'Systems of systems' (SoS) that have independently managed systems with their own goals, combining to achieve a goal beyond the sum of the capabilities of each (Nielsen *et al.*, 2015). Considering the temporal and spatial scales, across systems was, also, identified as imperative in terms of understanding behaviours, dynamics, and functional trade-offs (Herrmann *et al.*, 2018).

Systems Engineering brings systems into being, actioning ST, and would be employed to fully understand lightweighting and the Earth as systems (or SoS). A 'focus' of SE was determined as understanding "*sensitivities, and behaviors of the system, stakeholder needs, and its operational environment*", using "*system information represented and maintained in models*" (Watson *et al.*, 2020). Research highlights the significance of the fidelity in the way SE establishes and can model systems representatively to real-world occurrences and impacts. Where systems modelling is deficient,

https://doi.org/10.1017/pds.2024.134 Published online by Cambridge University Press

emergence can occur where a level of indistinguishability exists in the traceability of how elements interact in systems, or systems in SoSs. The effects of emergence are experienced at systems boundaries in SoS or between elements in systems, such that this can dictate systems' behaviours (Nielsen *et al.*, 2015). In the context of lightweighting and the Earth System (ES) - which could be considered as connected systems or in a SoS -, a high level of unpredictability is undesirable as this translates in the Earth to unexpected patterns of behaviour such as climate change (Burch *et al.*, 2019), which sustainability efforts look to mitigate. Therefore, in establishing lightweighting and the Earth as systems (i.e., by elements, attributes of those elements, and behavioural descriptions of those elements), important factors for systems modelling are considered; the representativeness and completeness of which influences our understanding and ability to mitigate lightweighting and ES behaviours through decision-making or interventions. The noted system characterisations are considered sufficient to highlight interactions (and sustainability impacts) that should be measurable by lightweighting S-O assessments, and upon which subsequent lightweighting decision-making can be based.

3.1.2. Sustainability-oriented assessment and decision-making requirements based on lightweighting and Earth systems interpretations

Lightweighting and its environment of the Earth are systems of interest for this research. Systems framing these spatially and temporally, per the foundations established in section 3.1.1, elucidates sustainability-oriented requirements of lightweighting and criteria by which to assess this. The RR supported the following observations of lightweighting as a product system. Multiple sources make lightweight product systems synonymous only to end-product structures e.g., Czerwinski (2021). Such assimilations are not accurate to standard (ISO) definitions of the term with end-product and processes inclusion. Thus, the coverage of lightweight product systems and lightweighting strategy should be synonymous, meaning for system's framing these terminologies can be used interchangeably. Herrmann et al. (2018) appropriately asserted "*lightweight structures as part of product systems*", this being the limited research that could be determined attributing the appropriate system scope to lightweighting. There is, thus, currently a lack of sources to determine appropriate systems framing for lightweighting, however evidenced proposals are made subsequently. The research of Herrmann et al. situated lightweight structures within four physical process stages (raw materials extraction, manufacturing, usage, and end-of-life) as a 'product system'. While these could be considered as appropriate lightweight product system 'elements', further research suggests that representing only a physical life-phase breakdown offers insufficient granularity to assess lightweighting robustly, and that stages/ phases and activities relating to the product's cognitive existence (e.g., in Design) should also be accounted for (Kupfer *et al.*, 2022). Mapping of prevalent phases and activities of lightweighting could give an indication of the most functional delineations by which to represent 'elements' of lightweighting, alongside the end-product. These elements would contribute to establishing an effective structure of assessment and decision-making format for lightweighting. As the granularity of 'elements' of a lightweighting system links to the extent to which interactions of these elements (within and external to lightweighting) may be studied, this research considers value in abstracting these to activity level; as 'activity' refers to "*some goal-directed physical or cognitive action*" (Hay, 2015), rather than groupings of actions with potentially slightly variant goals, such as in a phase or stage.

Research links behaviours of systems and elements to their interactions at system boundaries, considering what each system gives or takes, affecting each system's behaviour (Semmlow, 2012). Thus, lightweighting system inputs and outputs should be defined for system's framing: which many studies already do, as material, resource, and/or energy inputs from the Earth system (ES) to invoke ES behaviour change; or emissions and wastes (Akhshik *et al.*, 2017) from lightweighting elements to the ES, again invoking ES behaviour change. A system's goals inform its behaviour, also. Multiple goals for lightweighting were identified, including: "*to reduce material consumption and energy consumption over the whole life cycle of the product and improve resource efficiency*" (Roy, 2021); for "*weight savings and possible cost savings*" or to reduce harmful emissions (Fan and Njuguna, 2016). Evidently, these lightweighting goals reflect interaction effects with its background ES, where less frequent interaction, input or output, is desirable and aligns more optimal lightweighting to being an "*effective enabler for sustainability*" (Herrmann *et al.*, 2018). As ST shows that lightweighting goals focus on

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sustainability, this aligns to producing sustainability-oriented (S-O) assessment and strategic decision-making format requirements. From motivations for lightweighting given, environmental and economic factors tend to be those discussed as S-O goals of lightweighting (also evidenced herein in section 3.2). However, no studies have offered concrete evidence as to whether these motivations align with sustainability ambitions of lightweighting holistically. This may derive from limited ST related to both lightweighting and its background Earth system with understanding of elements and dimensions that characterise the behaviours of both. While Herrmann et al. (2018) did reference a system's view of a lightweight product system within a background system in the Earth, their work exemplified impact criteria of focus, rather than offering derivations and reasonings as to why these factors are of significance when assessing lightweighting related to sustainability. This study defines the ST structure for the Earth system, needed also, for resultant deductions to be made on which factors across the studied systems should be considered for sustainability-oriented decision-making thereupon.

As previously evidenced, within this research's context, the Earth as a system is understood by humanity's interpretation of its goals, its sub-systems or elements, and the behaviour of the system and its sub-structures. Humans have linked their goal for the Earth (which lightweighting as a connected system can affect) to fulfilling their needs, the Earth doing so relatively well in its current form, inciting a sustained need to do so, and sustainability remaining a persistent, common goal across all stakeholders (Kupfer *et al.*, 2022), despite perceptively there being multiple, dynamic goals. Through ST, Earth System (ES) structural elements of relevance on its stable, sustainability-oriented behaviour to fulfil human needs may be identified, which are conducive to exposing S-O assessment parameter category requirements of lightweighting performance or impact across interactions therewith. Multiple systems abstractions, to varying levels of granularity, linked Earth sustainability-related behaviour beyond the combined effect of interactions across sub-systems. Nevertheless, multiple abstractions were identified that have proven functional to further ES knowledge of the link and effects between anthropogenic (e.g., lightweighting) and natural elements within the Earth, the work of Schellnhuber (1999) being predominantly referenced. At the "*highest level of abstraction*", they consider the ES as a combination of the "*ecosphere*" (i.e., the 'natural Earth-System') and the "*anthroposphere*" (i.e., an anthropogenically constructed subsystem). These were found to be further decomposable, the ecosphere to "*its subsystems […] the atmosphere, biosphere, and cryosphere*" (Lövbrand *et al.*, 2009); and the anthroposphere to containing social and material sub-systems (such as the technosphere) (Přikryl *et al.*, 2016). Kuhn and Heckelei (2010) proposed these anthropogenically-derived spheres could, also, contain socio-economic, political, and technological elements. Further research, also, indicated PESTLE analysis dimensions as conducive to understanding the environment of an entity of study. McMahon added that "*PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) analysis*" was a systems approach for "*sense-making*" of "*complex, indeterminant, wicked problems*" (McMahon, 2022) within the ES. The above abstractions identify spatial elements (or dimensions) of significance to the ES, across which temporal behaviours (through-life), and ES interactions, of lightweighting could be exhibited. While not proven that this level of dimensionality is more conducive to understanding ES behaviour (for sustainability) more robustly, systems element level of fragmentation (by dimensions considered) can correlate to the (un)predictability and, thus, informativeness and relative accuracy of an assessment. In understanding lightweighting sustainability impact on the ES, SE modelling with the more comprehensive PESTLE dimensions supports reducing behavioural unpredictability levels and supports better managing the complexity of the interacting sub-systems towards reducing unplanned emergence for less perceived volatile functioning of the ES's climate. Thus, a dimensional extension to assessment formats of lightweighting may be beneficial for increased predictability of ES behaviour and 'sustainability' outcomes associated therewith.

Using ST, the RR also determined further useful extensions to lightweighting assessment formats, linked to the complexity of the ES, which manifests itself in the difficulty to model interrelations and dynamisms sufficiently, introducing sources of uncertainty (Burch *et al.*, 2019). The highly dynamic interaction of ES elements, results in instantaneous ES states, meaning that existing assessment data used in subsequent predictive decision-making has a level of inherent uncertainty. Antucheviciene et al. (2017) emphasised that "*managing uncertainty [was] a prerequisite to effective problem-solving and decision-making in complex systems*". Lightweighting assessment information should, therefore, be coupled with uncertainty quantification, for stakeholders to make informed lightweighting decisions. However, in decision-making, stakeholders can find difficulty in translating how these uncertainties can affect outputs, "*constrain[ing] the effectiveness of decision-making and requir[ing] the adoption of approaches that either help to reduce, or to cope with, uncertainty*" (Sniazhko and Muralidharan, 2019). Effective ways to cope with uncertainties have been found to be 'risk-based' or 'risk-informed' (Dezfuli *et al.*, 2010) approaches, where risk relates uncertainties to known ranges of possible outcomes with probabilities of occurrence of each. As such, lightweighting strategic decisions based on lightweighting assessment would be a "*compromise*" between the preferential lightweighting option and "*optimising the level of risk*" (Milburn and Billings, 1976). From a ST perspective, it, therefore, appears appropriate that current lightweighting assessments should not only be extended in terms of dimensionality, but also in format to account for risk in decision-making. The subsequent section summarises the findings of the M-S review on current lightweighting sustainability-oriented assessment and decision-making formats to contrast to the above derived and evidenced assessment format requirements and extension proposals.

3.2. Meta-synthesis

This section summarises findings of the meta-synthesis (M-S) of lightweighting assessment format trends, to date, as basis for the above-stated comparison. A main focus of the meta-synthesis was to understand the existing lightweighting assessment formats in terms of their dimensionality or aspects that could be considered relevant to sustainability. Figures 1a and 1b summarise the outputs from a dimensional exploration of lightweighting sustainability-oriented (S-O) assessments (across three key lightweighting industries). As has been discussed in section 3.1.2, these dimensions are representative of system elements that may be significant to ES behaviour and sustainability. The figure includes search outputs where any portion of lightweighting had been undertaken, such that this may give an inflated view of holistic assessments of lightweighting conducted to date.

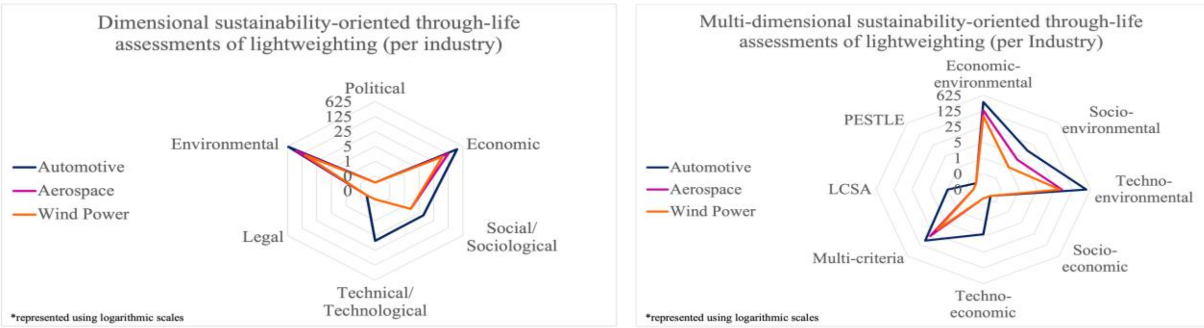

Figure 1. a) Dimensional and / b) Multi-dimensional lightweighting S-O assessments

The M-S found limited, and only partially relevant, literature on multi-dimensional S-O assessments, per Figure 1. Research by Rodriguez et al. (2020) reviewed "*life cycle tools fostering holistic sustainability assessment*" for bio-composites, determining that the LCSA format was currently the most comprehensive identified. Their research attributed three quarters of related research to "*evaluation of one single dimension (environmental, technical, social, and economic), where the LCA methodology represents 60% of those*". Zanchi et al. (2021) was the most dimensionally comprehensive identifiable research on lightweighting, using LCSA. Their research focussed on "*integrating life cycle sustainability assessment results using fuzzy-TOPSIS in automotive lightweighting*". Fuzziness deals with imprecise numbers to give a range to solutions, as potential alternative to the explicit risk-informed approach proposed earlier in this paper. However, their research does not advocate the same level of dimensionality discussed by this research. Further, the M-S of qualitative papers on the lightweighting assessment and decision-making link confirmed that approximately 40% explicitly noted decision-making intentions related to lightweighting assessment. Implicitly, lightweighting assessments and decision-making may be linked by many more studies, which could be confirmed beyond M-S information. Decision-making capability related to lightweighting assessments is evidently important. The M-S affirmed that there exist limited multi-dimensional lightweighting assessment formats that include integrated decision-making support (<4%), and none that do so in a risk-informed way.

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4. Discussion

RQ1 proposed exploration of systems thinking (ST) in relation to setting lightweighting sustainability-oriented assessment format requirements. Section 3.1 data infers that ST does dictate that current lightweighting assessment frameworks should be extended to support stakeholders in achieving more holistic sustainability-oriented insights for lightweighting strategic decisions. Section 3.1.2 explored Earth system (ES) abstractions to understand assessable 'elements' of the Earth, upon which lightweighting impacts. PESTLE dimensions were determined of potential significance to the functioning and 'sustainability' of lightweighting's background system of the Earth: 'sustainability' of the ES being a goal commonly linked to lightweighting, as well, by previous research. ST principles proposed that a broader understanding in assessment may reduce unpredictability (associated with real lightweighting impacts) to reduce unexpected, emergent behaviours which manifest through the ES climate. The M-S of current lightweighting assessments confirmed that currently no research has used PESTLE dimensions in a sustainability-oriented through-life assessment of lightweighting. Benefit of extending lightweighting assessment formats to incorporate PESTLE dimensions, understandably yet remains to be validated - which further associated research proposes to do. However, this study has presented a theoretical basis therefor. Further, based on ST, section 3 outlined that lightweighting assessment outputs should implement a utile interpretation of uncertainties for robustness of often coupled decision-making, such as by quantified risk-informing. No research could be determined combining lightweighting S-O through-life, PESTLE dimension assessment with risk-informing outputs for decision-making support. This extension proposal resolves RQ2. Once these proposals are formally validated, this new procedural knowledge could be formally applied, for lightweighting to be better supported with sustainability in mind, such that it may further increase industry appeal of the strategy.

Despite the newly proposed S-O assessment format being derived based on ST for lightweighting within the Earth, the derived format could be transferable to general product assessment and decision-making strategies where these share common systems definition characteristics, such as a goal for S-O products, also, with the same element breakdown. The level of commonality would dictate the level of additional validation required for this transferability.

5. Conclusion

This study has evidenced the opportunities for systems thinking (ST) to extend procedural knowledge on lightweighting assessment. In response to RQ1, it has been demonstrated that yes, ST does infer that sustainability-oriented requirements for lightweighting assessment differ from existing lightweighting assessment formats. RQ2 outputs highlight that ST around lightweighting sustainability-oriented assessments dictates that these should consider a broader range of sustainability-representative dimensions and in a more robust manner. Therefore, a PESTLE dimension, risk-informed through-life assessment format for lightweighting has been proposed for holistic assessment and on which to base lightweighting sustainability-oriented decisions. To validate these propositions, further work will be conducted, aligned with assuring the quality of the proposed new procedural knowledge.

Acknowledgements

This research work and publication was funded by the University of Strathclyde.

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