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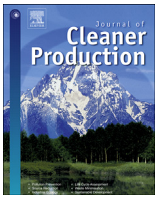

A comprehensive framework for automotive sustainability assessment

Dominik Jasiński [a], [*], James Meredith [b], Kerry Kirwan [a]

[a] *Warwick Manufacturing Group, University of Warwick, Coventry, CV4 7AL, UK*
[b] *Department of Mechanical Engineering, University of Sheffield, S1 3JD, UK*

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ABSTRACT

Business efficiency, stakeholder pressure and the need for legislative compliance compel the automotive sector to design and manufacture fuel-efficient, low-impact, environmentally responsible and sustainable vehicles. Managing and responding to these multiple and sometimes conflicting interests requires the measurement of economic, environmental and societal performance. Although a number of automotive sustainability measures are mentioned within the literature, there is no single and unique approach for the complete and integrated sustainability assessment of vehicles. This study has developed a comprehensive automotive sustainability assessment framework by selecting a set of sustainability assessment criteria from the literature and refining these through an interview study with 24 automotive experts from academia, car manufacturers, consultancies and non-governmental organisations. Based on this approach, 26 midpoint and 9 end-point environmental, resource, social and economic impact categories have been identified for the construction of a framework for automotive sustainability assessment. The proposed framework can be used as a decision-supporting tool at the early stages of the vehicle development process. It allows source and sustainability issues to be identified throughout the entire vehicle life cycle and provides the means to sharpen analysis and discussion around these issues. The framework can also serve as a design structure for a wide range of sustainability assessment methods and tools (e.g. multi-criteria decision adding or sustainability accounting methods). It serves as guidance on what needs to be measured in an integrated sustainability assessment of vehicles and leaves the choice of what to include in the decision-making process to the discretion of individual companies.

1. Introduction

The expansion of car-based transport over the last half-century has brought a wide range of ecological and social impacts, such as noise, congestion, accidents, air and water pollution, climate change and resource depletion (see Graedel and Allenby, 1998; Mayyas et al., 2012). In order to manage and respond to these multiple impacts, the automotive sector requires effective and credible measurement tools for sustainability assessment (Arena et al., 2013; Mayyas et al., 2013; Jasinski et al., 2015).

There are many different methods and tools for measuring sustainability performance (see Ness et al., 2007), each of which provides potentially useful, although different, insight for decision makers (Ramos and Caeiro, 2010). Despite this diverse range of tools and methods, sustainability assessment criteria and indicators almost always play a fundamental role in any sustainability evaluation (Ramos, 2009; Singh et al., 2012; Cinelli et al., 2014). Sustainability criteria are considered to be condition attributes employed to assess the relative sustainability of a set of alternatives through measurable indicators (Foxon et al., 2002; Cinelli et al., 2016). Defined and applied properly, they are a powerful element of more informed and optimum choices and contribute to a more structured and consistent decision-making process (Pastille, 2002; Mascarenhas et al., 2010).

Automotive sustainability assessment criteria can be found in the literature; however, there has been no clear consensus amongst automotive experts and other stakeholders on which criteria are critical and which framework should be used as a standard. The major limitations of existing frameworks stem from the area they cover. For example, Olugu et al. (2011) developed a key environmental performance measures for the automobile supply chain only. Other methods, such as Volvo's Environmental Priority Strategies (EPS) system (Steen, 1999), as well as automotive life cycle assessment (LCA) frameworks (Arena et al., 2013; Del Duce et al., 2013; Rivera and Reyes-Carrillo, 2016), extend the scope of the

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[*] Corresponding author.
E-mail address: d.jasinski@warwick.ac.uk (D. Jasiński).

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assessment to the entire life cycle of the vehicle, but they are still limited to environmental assessment only and ignore the social and economic spheres. Ford, with its Product Sustainability Index (PSI), made a first attempt to reflect the triple bottom line vision of sustainability; however, this model still suffers from a lack of complete coverage of sustainability metrics. Ford included only five environmental, two social and one economic criteria in its PSI (see Schmidt and Taylor, 2006).

Considering all these limitations, it is evident that a holistic framework covering a comprehensive set of sustainability criteria for automotive sustainability assessment is needed, and this paper is intended to fill this research gap.

2. Research methods

The development of a framework for automotive sustainability assessment involved two major steps. Initially, a set of sustainability assessment criteria was selected from the literature to create a conceptual draft of the framework. These criteria were then critically evaluated by a multidisciplinary panel of automotive experts. The selection of a diverse group of experts was critical to ensure the credibility, transparency and robustness of the process (Buchholz et al., 2009; Ramos and Caeiro, 2010; Carrera and Mack, 2010). Qualitative interview study was selected as a research method because it provides a level of depth and complexity not available to other research instruments (Silverman, 2011). Open-ended and flexible questions are more likely to receive a considered response than closed questions and therefore provide better access to individuals' perceptions, views, values, opinions, understandings and experiences (Gillham, 2000; Gray, 2004; Silverman, 2011). Fig. 1 summarises the research approach.

2.1. A conceptual framework for automotive sustainability assessment

In order to identify and select assessment criteria for the framework, relevant literature on automotive sustainability assessment was reviewed, including existing frameworks and models, company reports, original theoretical and practical research papers and recommendations from relevant institutions (e.g. The European Commission). The following set of published guidelines was adopted to aid the criteria selection and refinement process (Akadiri and Olomolaiye, 2012; Akadiri et al., 2013):

- **Comprehensiveness:** the chosen criteria should demonstrate progress towards all dimensions of sustainability.
- **Applicability:** the chosen criteria should be applicable across a range of alternative options in order to ensure comparability.
- **Transparency:** the criteria selection process should be transparent to all stakeholders.
- **Practicality:** the chosen criteria should be practical in the sense of the tools, time and resources available for analysis and assessment.

Elkington's (1999) triple bottom line model distinguishes three major categories of sustainability: economic, environmental and social. The automotive industry is one of the most resource-intensive industrial systems in the world (Mildenberger and Khare, 2000); therefore, for practical reasons, the environmental category has been split into resource and other environmental impacts. The criteria selected for the automotive sustainability assessment framework and an explanation of each criterion are presented in Table 1.

Existing automotive sustainability assessment tools and studies have proven that life cycle thinking is deeply ingrained in the automotive industry (Steen, 1999; Schmidt and Taylor, 2006; Hawkins et al., 2013). Hence, the metrics selected for the framework represent the sustainability performance of a car during its entire life cycle, beginning with the extraction of minerals to produce raw materials and components, moving to manufacture and assembly, usage and its eventual end-of-life disposal.

2.2. Interview study

A semi-structured interview was developed with the aim of obtaining the following input from experts about each area of a

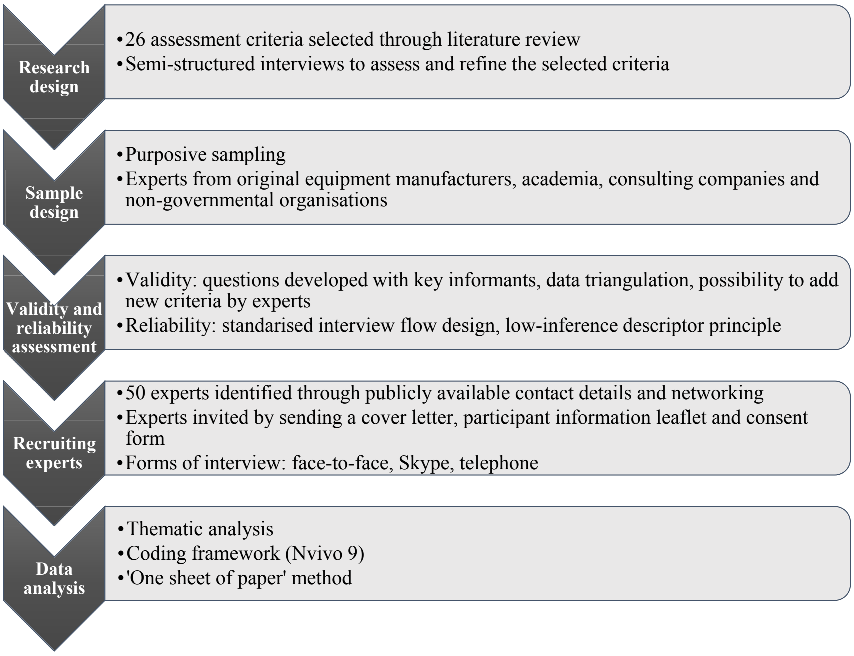

Fig. 1. A summary of research methods used for this study.

Table 1
Assessment criteria selected for the framework based on the literature review.

Category	Assessment criteria		References
Economic impact	Money to contractors	All expenditures paid to contractors/suppliers (material and service costs)	(Cuenca et al., 1999); (Maclean and Lave, 2003); (Schmidt and Taylor, 2006); (Goedecke et al., 2007); (Mayyas et al., 2013)
	Production cost	Manufacturing cost, warranty charges, research and development, depreciation/amortisation of tooling and facilities	(Cuenca et al., 1999); (Maclean and Lave, 2003); (Schmidt and Taylor, 2006); (Goedecke et al., 2007); (Mayyas et al., 2013)
	Acquisition cost	Distribution, advertising and dealer support cost, gross margin per car	(Cuenca et al., 1999); (Maclean and Lave, 2003); (Goedecke et al., 2007); (Ciroth et al., 2008)
	Operating and maintenance cost	Fuel, insurance, taxes, cost of washing, financial service, parts and servicing cost	(Cuenca et al., 1999); (Maclean and Lave, 2003); (Schmidt and Taylor, 2006); (Goedecke et al., 2007); (Ciroth et al., 2008); (Mayyas et al., 2013)
	End-of-life cost	Disposal cost/residual value	(Schmidt and Taylor, 2006); (Goedecke et al., 2007); (Mayyas et al., 2013)
Environmental impact	Global-warming potential	Greenhouse gas emissions contributing to global warming	(Graedel and Allenby, 1998); (Schmidt and Taylor, 2006); (2013/179/EU); (Arena et al., 2013); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Stratospheric ozone depletion	Thinning of the stratospheric ozone layer due to anthropogenic emissions such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs)	(Graedel and Allenby, 1998); (2013/179/EU); (Del Duce et al., 2013)
	Photochemical ozone creation potential	Volatile organic compounds (VOCs), and nitrogen oxides which react in the presence of sun and cause ground-level ozone concentration	(Graedel and Allenby, 1998); (Schmidt and Taylor, 2006); (2013/179/EU); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Acidification potential (terrestrial and aquatic)	Increase in the quantity of acid rain-producing substances such as sulphur dioxide, nitrogen oxides, ammonia, hydrogen chloride, hydrogen fluoride and hydrogen sulphide	(Graedel and Allenby, 1998); (2013/179/EU); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Eutrophication potential (terrestrial and aquatic)	All potential impacts of excessively high levels of macronutrients such as nitrogen compounds (fertilisers), phosphorous compounds and organic matter	(Graedel and Allenby, 1998); (2013/179/EU); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Eco- and human toxicity	Emission of toxic substances to air, water and soil over accepted limits	(Graedel and Allenby, 1998); (2013/179/EU); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Particulate matter formation	Hazardous solid and liquid particles in air (both organic and inorganic) such as pollen, dust, smoke and liquid droplets	(2013/179/EU); (Hawkins et al., 2013)
Resource impact	Energy consumption	Resource depletion due to energy consumption	(Graedel and Allenby, 1998); (Steen, 1999); (Nunes and Bennett, 2010); (2013/179/EU); (Arena et al., 2013); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Water consumption	Water depletion due to fresh water and industrial water consumption	(Graedel and Allenby, 1998); (Nunes and Bennett, 2010); (2013/179/EU); (Arena et al., 2013)
	Renewable and recyclable materials	Renewable and recyclable materials used	(Graedel and Allenby, 1998); (Steen, 1999); (Schmidt and Taylor, 2006); (Nunes and Bennett, 2010); (2013/179/EU); (Arena et al., 2013); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Other non-renewable and non-recyclable materials	Resource and minerals depletion due to non-renewable and non-recyclable materials consumption	(Graedel and Allenby, 1998); (Steen, 1999); (Nunes and Bennett, 2010); (2013/179/EU); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Land use	Loss of land as a resource in the sense of it being temporarily unavailable	(Nunes and Bennett, 2010); (Arena et al., 2013) (Del Duce et al., 2013)
	Resource consumed during customer use	Resource and minerals depletion due to fuel, oil, filters, lubrication, tyres, batteries used	(Graedel and Allenby, 1998); (Arena et al., 2013)
Social impact	Vehicle users and pedestrian safety	The level of safety of vehicles (i.e. Euro NCAP rating)	(Schmidt and Taylor, 2006); (Arena et al., 2013)
	Drive-by noise	The social impact of sound, sound pressure level from engine, exhaust and rolling noise	(Schmidt and Taylor, 2006); (Goines and Hagler, 2007); (Arena et al., 2013); (Del Duce et al., 2013)
	Vibration	The whole-body vibration impact on the driver's health, such as musculoskeletal and lumbar spine disorders	(Wikström et al., 1994); (Wilder and Pope, 1996); (Makhsous et al., 2005); (Griffin, 2007); (Mayyas et al., 2013)
	Vehicle interior air quality	VOCs emitted from materials and finishes used to make vehicle interior	(Brown and Cheng, 2000); (Schmidt and Taylor, 2006); (Geiss et al., 2009); (Arena et al., 2013)
	Human health effects from external air quality	Human health effects as a result of particulates, ozone, polycyclic aromatic hydrocarbons, heavy metals emission	(Steen, 1999); (Friedrich and Bickel, 2001); (Kampa and Castanas, 2008);
	Mobility capability	Number of seats and luggage, possibility to travel by the elderly, handicapped and disabled	(Schmidt and Taylor, 2006); (Nunes and Bennett, 2010)
	Employment	Product-based employment	(Schmidt, 2007); (Nunes and Bennett, 2010)
	Occupational health and safety	Occupational health and safety performance (injury and illness rate)	(Benoît et al., 2010); (Traverso et al., 2013); (Aluminium Stewardship Initiative, 2014)
	Labour rights	Freedom of association, child labour, forced labour, discrimination, remuneration, working hours	(Benoît et al., 2010); (Traverso et al., 2013); (Aluminium Stewardship Initiative, 2014)
	Human rights	Women rights, indigenous people rights, resettlements, conflict minerals, corruption, cultural and sacred heritage, access to resource, local communities development	(Benoît et al., 2010); (Epstein and Yuthas, 2011); (Traverso et al., 2013); (Aluminium Stewardship Initiative, 2014)

vehicle's sustainability performance:

- Evaluation of criteria selected from the literature according to each expert's main area of expertise;
- Identification of any assessment criteria not listed in the framework that they considered to be important.

Participants were able to discuss and add any comments about other areas of sustainability not related to their main area of expertise.

2.2.1. Sample design

Qualitative research does not aim to draw statistical inference or produce a statistically representative sample and therefore purposive sampling (also called judgement sampling) was used to select quality informants for this study (Wilmot, 2005; Tongco, 2007). There was no clear set of quality criteria for the selection of experts found in the literature. The selection process may be based on attitudes, demographic characteristics, experience, list of qualifications or, indeed, on any other kind of standard (Ritchie et al., 2003; Tongco, 2007); hence, the following criteria were used to select experts for this study:

- decision influencers in original equipment manufacturers (OEMs) (e.g. directors, heads of department, senior managers, leaders, technical specialists) with a minimum of three years' professional experience in the area of sustainable automotive systems;
- academics publishing extensively on the topic of green and sustainable automotive systems;
- consultants and advisory bodies with a proven track record of working with automotive organisations in the area of sustainability; and,
- leaders of influential governmental and non-governmental organisations with expertise in the area of sustainable mobility.

Tongco (2007) asserted that there is no cap on how many informants should be considered in purposive sampling, but five is the minimum number for the data to be reliable. According to Guest et al. (2006) and Gray (2004), a sample size of between six and twelve interviews is often sufficient to achieve data saturation for every theme. As there is no consensus as to the number of interviews required to achieve the desired research objective, the sample size representing different perspectives continually increases until such time as no new viewpoints emerge from the data (Ritchie et al., 2003; Gray, 2004). Interviewing a wide range of specialist experts from different organisations and with different perspectives ensured the data's high quality and strengthened the generalisability of this study. All interviews were conducted between April and July 2015. Interviews ranged in duration from 19 to 42 min excluding introduction but including discussion of other topics.

2.2.2. Analysing the data – thematic analysis

Thematic analysis, alongside content analysis, is the principal technique used by researchers to analyse qualitative data and is a process of encoding qualitative information (Boyatzis, 1998; Marshall and Rossman, 1999; Braun and Clarke, 2006). The process of conducting thematic analysis in this paper is summarised in supplementary materials. All interview questions and answers went through a process of word-for-word transcription. Once all interviews had been transcribed, they were read several times to obtain a broader understanding of the data and to generate initial ideas regarding all of the themes and categories. Boyatzis (1998) and Braun and Clarke (2013) outlined three major methods of developing themes, categories and codes based on existing theory, the data collected and prior research. A combination of the first two methods was used to develop the coding framework and all interview data were coded against 6 themes and 30 categories with the assistance of NVivo 9 (QSR International) (the coding framework is provided in Table S2 in supplementary materials). A ‘one sheet of paper’ (OSOP) analysis, a method developed by the University of Oxford for interpreting qualitative data, was performed in order to better understand the data and to potentially reduce the number of themes and categories (see Ziebland and Mcpherson, 2006 for more details about the OSOP method).

3. Results of the analysis

Of the 50 experts invited to participate in this study, 24 were interviewed, representing different sectors and roles within their respective organisations (see appendix 1 for respondents' characteristics). Personal information about respondents was anonymised and each interviewee received a unique ID. All respondents were distributed from developed countries, including the USA, UK, Germany, Sweden and Italy. Results of the interview analysis commence with general comments about the framework and then go into more detailed analysis of each individual section of the framework.

3.1. General comments about the assessment criteria

The general impression about the automotive sustainability assessment framework was positive and interviewees saw value in conducting this type of assessment. Most automotive companies are presently conducting at least an LCA, and by incorporating other areas of sustainability are able to make richer decisions, as emphasised by one respondent:

> *I think it is interesting to see this holistic view on car development. Incorporating the several pillars of sustainability idea at the engineering level in my view is a worthwhile and very fruitful concept. (O6.02.07.2015)*

All respondents appreciated the comprehensive approach towards developing the framework; however, two interviewees suggested expanding the system by looking at what is beyond vehicle development:

> *… in our organisation, we take a system view of sustainability, which means thinking beyond individual companies, beyond individual products which is a classical previous way of doing things. Cars do not operate by themselves, they operate in the entire system and everything is interrelated.* (N1.08.06.2015)

This system approach is critical because looking at something by itself is to ignore a long history of unintended consequences. Biofuels are a pertinent example, where people did not think about what would happen if fuel crops were grown in addition to crops grown for food. This was not considered because the focus was on just one industry. However, achieving this level of understanding is not easy and a few participants expressed concern that these criteria are already too complex to be used at the engineering level:

> *This framework is good because it goes into a huge amount of depth, the danger is that it is also very complex. So it is going to make it quite difficult for an engineering company to make simple decisions because it produces quite broad ethical challenges to which there is not a clear answer. (A7.18.06.2015)*

The interviewee further explained that what had really accelerated change in the automotive industry since 1995 was the introduction of regulation concerning CO_2 emissions and fuel consumption in different markets and that this had put in place a few very clear and straightforward metrics for the automotive sector to work on. The risk of having more metrics is that they might be difficult to balance and may overload engineers. Another respondent recommended that the number of LCA stages should also be limited to those most significant for OEMs, including car production, the customer-use phase and end-of-life disposal of the car.

Three interviewees indicated the lack of clearly visible links between different sustainability dimensions in addition to assessment criteria missing from the framework. These links arise from the interdependence between the environment, society and economy and each of these spheres creating positive and negative impacts on each other represents the nested-dependencies model of sustainability (see Nunes and Bennett, 2010). These links can be expressed in the form of midpoint and end-point impact categories:

> *When you describe environmental impact it is a choice of both midpoint and end-point measures and there are three steps that need to be covered or selected when you measure your system boundaries of impact assessment: what emission and resource impacts you are focusing on, what type of impact pathway you want to include and, at the end, what are the end points. (A8.25.06.2015)*

Interviewees expressed their concerns that having a mixture of midpoint and end-point categories increases the risk of double counting and it is therefore critical to separate impacts to eliminate any potential overlap between criteria. The next part of this section provides more detailed analysis by discussing each individual section of the framework.

3.2. *Environmental criteria*

The environmental and resource criteria are more agreed upon and developed than, for example, the social criteria, due to the existence of legislation and standards (such as the ISO 14040 series). One issue highlighted by respondents is the fact that the selected environmental criteria are not equal and that significantly more emphasis is placed on climate change potential than on any of the other criteria. For example:

> *Ecotoxicity is so far still subject to scientific discussion and I am always a little bit reluctant to use ecotoxicity as a criterion with the same weight as climate change or acidification. Of course it still should be considered but to a lesser extent than, for example, climate change potential because the scientific background is not as developed as for other impact categories. (C1.18.05.2015)*

The major issue with toxicity is that existing measurement tools (such as LCA) are not capable of providing a reliable toxicity impact assessment. Instead, the automotive sector uses the globally agreed automotive list of declarable substances, which regulates the use of restricted substances in automotive components. Two interviewees suggested that ozone depletion ceased to be a problem for the automotive sector when chlorofluorocarbons (CFCs) were replaced by hydrocarbons (HFC-134a in particular) as a cooling agent in vehicle air conditioners. Hydrocarbons have been recognised by the US Environmental Protection Agency as having no ozone-depletion potential. Hence, the impact of new vehicles on ozone depletion is low, limited mainly to the release of certain chlorine- or bromine-heavy substances through their tailpipe emissions.

Six experts suggested that air quality assessment criteria (such as acidification, photochemical ozone creation and particulate matter) could be condensed into a single criterion as most of these issues are regulated and the automotive industry does not get a choice as to how it balances these interests:

> *For automotive, the important bit is the emission standard and this is highly regulated anyway. We fully support efforts to ensure that test procedures more closely match the real-world conditions that customers experience under normal driving conditions. (O4.22.05.2015)*

Thresholds for air quality issues are given and it is highly unlikely that automotive companies will go beyond these thresholds because to do so would mean reductions in profit. The costs of environmental compliance (e.g. capital investment in clean technologies and emission control products) are already high and any move beyond compliance would increase these costs yet further, with no guarantee of a positive financial return. Hence, if looking at the use phase only, there is no real difference between looking at vehicle A or vehicle B. The difference might occur if upstream impacts (e.g. from power plant) were to be considered.

A more detailed assessment of the potential impact of vehicles on biodiversity was another area of sustainability discussed by the experts. Biodiversity is usually considered as an indirect impact of different emissions such as acidification, eutrophication and ecotoxicity. However, two respondents emphasised that automotive organisations do not impact biodiversity solely by emitting toxic substances, but also via their presence in any given area. It can be associated with car production as well as types of car use, for example, greenlaning (off-roading) and soil erosion caused by driving off-road vehicles in the countryside. Biodiversity can also be affected by the automotive supply chain:

> *If you have hybrid or electric vehicles, both of them use batteries. There is no way that you can mine today some of the metals that are going into the battery, like gold or silicon, perhaps, without affecting biodiversity, for example, by cutting down forests or affecting the quality of land. (A3.24.04.2015)*

Four experts suggested that the impact on biodiversity is important for OEMs, typically when biofuels are involved. For any other situations, biodiversity impact is simply too complex for OEMs to measure. The level of depth in biodiversity performance assessment depends upon the amount of time and resource available for undertaking the analysis.

The final issue discussed in the environmental section was waste, as there was confusion among a few respondents as to how waste is covered within the framework. It was thus explained that the framework does not directly measure waste but rather looks at the impacts from waste, such as global warming, toxicity and eutrophication.

3.3. *Resource impact*

Although there was full agreement about the importance of water consumption and land use, not all of the interviewees agreed with the concept of resource depletion. One interviewee suggested that resource scarcity has never had a big impact on the automotive industry, and that:

> … *our growth is not limited by a restricted input but our growth is limited by the output such as the capacity of the planet to cope with the carbon dioxide and other emissions. This is the limiting factor for growth, not the resources.* (O4.22.05.2015)

Based on this view, internal combustion engines will not be replaced by alternatives (e.g. electric vehicles) due to the planet running out of fuel, they will instead be replaced because of their carbon dioxide emissions and impact on air quality. However, another interviewee asserted that there is a limited amount of raw material and that this is particularly burdensome for the industry in the case of scarce resources such as gold, platinum or helium. If these resources are extracted and embedded into a component and this component is then disposed of in such a way that the resource is no longer usable and available for future generations, then there is an associated resource impact.

Five experts expressed their concerns that having energy consumption and resource consumed during customer use might lead to double counting. Energy consumption includes fuel because, as suggested by one interviewee:

> … *if we are looking in a holistic way to make sure that the automotive and fuel industry are delivering on the policy objectives, you do need to consider these two together.* (A7.18.06.2015)

In fact, a separate impact category for resource consumed during customer use is not needed as long as resources other than fuel are also incorporated into the vehicle life cycle, including the lubrication, tyres and batteries used. Resources and minerals are also used in vehicle production and these have been broken down into renewable and recyclable and non-renewable and non-recyclable materials. The renewable and recyclable materials metric caused confusion amongst the experts as it was not clear what it actually measured. It was explained that everything is recyclable and it is only a question of whether there is a need for the recycled products and if recycling makes sense from an environmental and economic viewpoint. One interviewee's recommendation for dealing with renewable and recycled materials is not to measure them at all because recyclability is a legal requirement. Another recommendation was to combine renewable, recycled and reused materials with all other materials and resources used and derive their combined net impact, because the greater the amount of materials recycled or reused in the vehicle life cycle, the lower the resource and material impact of the vehicle.

3.4. Economic criteria

Interviewees confirmed that life cycle costing (LCC) is an appropriate method for measuring the economic performance of vehicles because it takes into account the different stakeholders affected by the economic impact of a car. For example, money to contractors addresses suppliers, production and acquisition costs address OEMs and the costs of operating and maintenance capture the user perspective. However, respondents were not clear about the economic consequences of disposing of a car and which stakeholders are affected. Based on the End-of-life Vehicle Directive (2000/53/EG), OEMs are legally responsible for the environmental impact of disposing of end-of-life vehicles, usually performed with the assistance of approved treatment facilities. In an ideal world, OEMs should extract value from disposed-of vehicles, which should in turn be net of their production cost. However, one interviewee suggested that a vehicle's end-of-life disposal is neither a value nor a cost for car manufacturers at the present time:

> *It all depends on the value of a vehicle when it is scrapped. We do not share in any profit from recovery but if vehicle take-back begins to cost the recovery industry, which it hasn't so far, this cost will be passed on to the OEMs. (O2.05.05.2015)*

Another interviewee suggested that OEMs can extract value from disposed vehicles by reusing materials:

> *As the original producer, we are required to make sure that the vehicle can be dismantled and depolluted but, in effect, the vast majority of materials are downcycled. So they are going to be reused but at lower grade and less intelligent use. A reasonable way that you could structure this is by actually reusing a material for the same purpose or even upcycling and then using it for a greater purpose. It is all possible and you then retain the value inherent in the material. (O1.05.05.2015)*

A few participants emphasised the increasing trend towards new business models, for example, the sale of a mobility provision as opposed to a vehicle, which would result in the reuse of a greater proportion of materials and alter the way economics around vehicles work. Vehicle ownership would thus shift from a customer to a company, which would subsequently be encouraged to consider more retrofit options as a means of extending the useful life of its asset and extracting more value at the end of its life, as opposed to recycling it. Some examples of new business models are already being seen. Renault, for example, leases their batteries for electric vehicles and this reduces the vehicle purchase price. BMW leases certain models of their i-series vehicles.

There was a debate among the interviewees on whether the macro-scale economic impacts of vehicles should also be considered. Cars contribute to the economy of society in a number of ways, for example, by impacting national trade figures, taxes, gross value added and dividends. The interviewee representing the Corporate Social Responsibility department suggested that although individual cars or car ranges contribute to these macro-scale economic indicators, they are more relevant at the corporate level than at the product level.

3.5. Social criteria

The social impact of a car is the area least understood and agreed upon out of the remaining areas of sustainability. In contrast to the environmental and economic dimensions, no widely accepted standards and assessment criteria exist. Two interviewees emphasised accidents and congestion as the biggest external costs associated with vehicles. Accidents are covered in the framework under the vehicle users and pedestrian safety impact category; however, two interviewees suggested a particular focus on active safety:

> *I would be more inclined to focus on active safety and the contribution of active safety going forward. There is a pretty consistent level of passive safety delivered by vehicles and there is not a huge spread between them. I think what will start to differentiate new products will be active safety and accident avoidance. (O5.26.05.2015)*

Another respondent confirmed that manufacturers will make choices about the extent to which they build their cars for the safety of pedestrians, cyclists and other road users. An increase in active safety systems aimed entirely at collision avoidance (such as new telematics-connected vehicles or autonomous vehicles) is something upon which the global New Car Assessment Programme is currently focused. Congestion was not included in the original set of criteria because it was understood as an impact of the transportation system as a whole and therefore difficult to allocate to a specific vehicle. Measuring the impact of a specific vehicle on congestion is complex but three interviewees suggested technology as a potential solution, in a similar way to its application to the accident and safety aspect.

> *There are some things that OEMs can do to influence congestion. For instance, if you have got very intelligent vehicle management systems that understand the route the vehicle is going to take and they can automatically do scheduling, then you take decisions out of the users' hands and the correct decision is more likely to be made. (A7.18.06.2015)*

Companies such as Siemens and IBM are working on these devices and Honda is working on technology that will allow a car to interact with the external environment and the infrastructure managing the urban mobility system.

None of the interviewees questioned drive-by noise as an important impact of cars. Drive-by noise is regulated (72 Db average peak value) but these noise limits vary depending on the country and vehicle class. Also, drive-by noise legislation concerns mainly exterior noise and not interior noise:

> *The regulation covers mainly the exterior noise and primarily as a manufacturer you are interested in the interior noise. In Europe, I do not believe there are interior noise regulations at all. You can have a really loud car and it will be perfectly fine. People might not buy it but it will be legal. (O7.22.07.2015)*

The interior noise targets are specified by customers and they are usually lower than the exterior limits. Two interviewees recommended renaming this impact category simply as noise as there are other types of noise impact from vehicles (not solely drive-by noise). Vibration is a less obvious social impact category than noise which could be included in the framework. Although car manufacturers measure vibration (mainly inside the car), the target limits laid out in legislation are much higher than the OEMs' targets, therefore passenger cars should not suffer vibration capable of causing injury:

> *There are some government limitations on vibration and human contact and these levels are very high. If you want to sell a car, it needs to be far below that and it is based on our competitors, what anyone else is doing […] Off-highway vehicles, possibly, and heavy commercial vehicles might have vibration issues there, but I would expect that all OEMs and any new vehicles now are capable of well below these levels. (O7.22.07.2015)*

All interviewees confirmed that employment is an important impact in absolute terms, although several experts suggested that access to jobs is one issue but that the quality of those jobs is a separate issue:

> *I think, with employment, for instance, I tend to classify it into two types: the quantity of jobs and the quality of jobs. So it is one thing to create a lot of quantity and another thing is that you create high-quality jobs. I think you need to consider a little bit of both. (A3.24.04.2015)*

Wages, labour rights and health and safety conditions were suggested as potential measures of employment quality. Three interviewees confirmed that measuring the quality of employment and human rights throughout the whole vehicle life cycle is extremely important for OEMs; however, they also mentioned that it is very complex to measure considering the size of the supply chain.

The remaining social criteria were accepted by study participants with only minor recommendations for improvements.

4. Discussion

The interviewees' comments were analysed and taken into consideration to build the framework for automotive sustainability assessment, which represents the vehicle life cycle sustainability performance and consists of 26 midpoint and 9 end-point impact categories (see Fig. 2). Links between criteria are also highlighted to indicate the interdependence between sustainability dimensions. For example, the air quality impact causes a social impact in terms of human health, and there is then an economic impact of increased government expenditure on health. All sustainability areas are covered in the framework; however, the level of depth and comprehensiveness of the criteria generated discussion among the experts. There were proposals to expand the system by looking beyond an individual vehicle life cycle as well as simplifying it so as not to overload engineers with too many criteria. Obtaining this wider system approach is difficult considering the complexity and scale of global automotive manufacturing but is also important if the aim is to obtain a holistic view of a car's sustainability performance. In order to simplify the framework, knowledge about the importance of each criterion would have to be obtained from study participants, which was outside the scope of this study.

A few interviewees questioned the practicality of measuring upstream impacts due to the lack of reliable measurement tools and because they are outside of OEMs' control. Indeed, there are many obstacles to measuring the upstream impacts of the automotive sector, the most important being the size and complexity of the supply chain. However, existing automotive sustainability assessment tools (see Steen, 1999; Schmidt and Taylor, 2006; Arena et al., 2013) all emphasise the importance of life cycle thinking in measuring the sustainability of cars. Also, excluding upstream impacts from the assessment may negatively impact a company through a potentially tarnished reputation and lead to a fall in sales. If a company is part of the industry responsible for deforestation in Brazil, for instance, then that company is part of the deforestation story in the mind of the public. Modern media, social networking and information and communication technologies are widely accessible, and any environmental or social indiscretion cannot be hidden or excused (Shah, 2015). BMW recognised that responsible corporate governance requires examination of the environmental and social impact generated throughout the entire life cycle of the product (see Traverso et al., 2013).

The level of complexity involved and the imperfection of existing measurement tools, especially in terms of social assessment, is an obstacle; however, methods do exist or are under development for measuring the criteria proposed in this framework (at least at the midpoint level). For example, the practicality of the LCC method has been proven through its application to different products (see Ciroth et al., 2008), including automobiles (Schmidt and Taylor, 2006; Goedecke et al., 2007). A widely accepted and applied method for monitoring the cradle-to-grave environmental performance of a vehicle is LCA (Khan et al., 2004; Del Duce et al., 2013; Hawkins et al., 2013). LCA is capable of measuring all of the environmental and resource criteria proposed in the framework, although the method's reliability varies from one criterion to another. For example, impact assessment methods for human toxicity (such as the USEtox model) are less certain than, for instance, scientifically robust climate change impact assessment models. The European Commission (see EC-JRC,

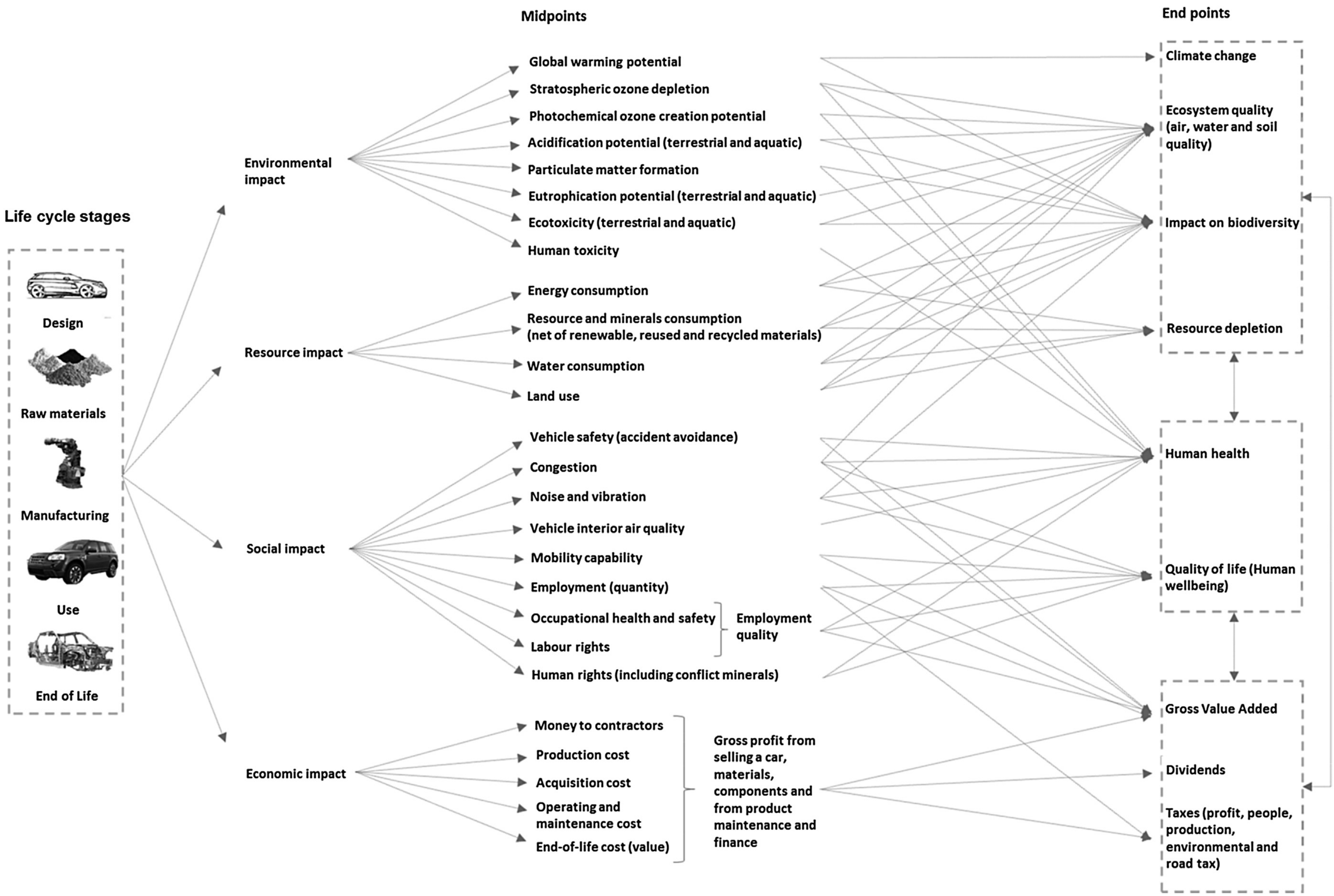

Fig. 2. The automotive sustainability assessment framework developed based on the literature and interview study.

2011, 2013/179/EU) and Hauschild et al. (2013) assessed the quality of all existing characterisation models for environmental impact assessment and provided recommendations (both at the midpoint and end-point levels) about the best models for each environmental and resource criterion. With the growth in the number of characterisation models, these recommendations can help guide the LCA practitioner in choosing the best available and most scientifically valid method for the assessment of environmental and resource impacts.

Social criteria such as vehicle noise, safety, interior air quality, congestion and mobility are largely customer-use impacts and are already monitored by OEMs' different business units. For instance, the Noise, Vibration and Harshness department measures noise and vibration performance, the Safety Attribute department measures vehicle safety performance, the Environment Attribute department monitors vehicle interior air quality, while engineers working on autonomous driving and traffic communication systems assess the potential impact of technology on traffic congestion. Other social impacts, such as human and labour rights and occupational health and safety, require much more complex systems of measurement because they may occur at each stage of the vehicle life cycle and especially in the supply chain (Traverso et al., 2013). The Aluminium Stewardship Initiative (2014), in partnership with major car manufacturers such as Audi, BMW and Jaguar Land Rover, released a performance standard consisting of assessment criteria relevant for monitoring the social impacts of the aluminium value chain. This standard is largely in line with the UNEP-SETAC guidelines for the social LCA of products (see Benoît et al., 2010). Of course, measuring these criteria is still complex because of the scale of the automotive supply chain; however, GreenDelta has recently released an innovative and comprehensive database (see Ciroth and Eisfeldt, 2016) which can lay the foundations for social LCA. This database contains global data for approximately 15,000 industry sectors and commodities and covers a broad set of quantitative and qualitative social indicators. The concept remains in its infancy and is therefore limited if one wishes to conduct an accurate social LCA. However, it is a significant step forward, which should at least allow for the analysis of hot spots along the entire supply chain. The results obtained from this database may not be perfect but it is still better to be approximately right than precisely wrong (Rubenstein, 1992). It can help to indicate the source and magnitude of issues along the entire supply chain and provide the means to sharpen analysis and discussion around those issues.

5. Conclusions

This study has developed a comprehensive automotive sustainability assessment framework by selecting a set of assessment criteria from the literature and refining these through an interview study with experts from the automotive sector. The developed framework consists of 26 midpoint impact categories and 9 potential end-point effects of the selected criteria, including: climate change, ecosystem quality, impact on biodiversity, resource depletion, human health, quality of life and macroeconomic indicators such as gross value added, dividends and taxes. It was necessary to group criteria into midpoint and end-point effects in order to avoid double counting and to reveal the links between criteria. This framework provides a broad and holistic view of the sustainability performance of automobiles. It presents economic, environmental and social impacts for cars that enhance engineers' ability to make decisions during the product development phase that consider sustainability. This represents a compromise between the wider system approach and the minimum that the car manufacturers should consider at the early stages of designing and developing a vehicle.

Although this framework was qualitatively assessed by an expert panel, it still requires empirical testing with input data from OEMs. Qualitative research can be very effective in examining different meanings, views and perspectives, which is important for such a complex issue as sustainability; however, it is also known as being subjective, open to interpretation and limited to assuming there is one universal truth to be discovered. Researcher bias is unavoidable in qualitative research, therefore empirical testing is critical in order to strengthen the validity and reliability of this framework. This will be the subject of future work.

Another limitation of this study is that all interviewees represent a developed world context. This is due to the fact that the world's largest car manufacturers are located in developed countries and therefore experts from these countries were easier to identify and access. However, if participants from the developing world were asked to answer the same questions, their priorities may be different. Therefore, for the purpose of future research, the pool of interviewees could be expanded by also including experts from developing countries. This developed world bias does not pose a great problem so long as the framework is intended for use only within a developed world context.

This paper reports on the beginning of a journey that seeks to develop models for a more holistic and comprehensive sustainability assessment of automobiles. It aids both practitioners and academics with an expert-driven framework which is an essential prerequisite for the delivery of an integrated automotive sustainability assessment method. This framework has the potential to serve as a design structure for a wide range of sustainability assessment methods and tools (e.g. multi-criteria decision adding or sustainability accounting methods). It provides guidance on what needs to be measured in an integrated sustainability assessment of vehicles and leaves the choice of what to include in the decision-making process to the discretion of individual companies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.07.027.

Appendix 1. Anonymised list of experts that participated in this study.

Participant identifier	Interview date	Sector	Role in organisation	Years of experience
A1	15/04/2015	Academia	Director of Automotive Research Centre	20+
A2	15/04/2015	Academia	Co-Director of Automotive Research Centre	20+
A3		Academia	Lecturer – Consultant	5

(*continued*)

Participant identifier	Interview date	Sector	Role in organisation	Years of experience
	24/04/2015			
A4	06/05/2015	Academia	Associate Professor	20
A5	07/05/2015	Academia	Programme Manager	5
A6	15/05/2015	Academia	Research Fellow	18
A7	18/06/2015	Academia	Professor – Vehicle Powertrain	20+
A8	25/06/2015	Academia	Adjunct Professor – Environmental System Analysis	20+
C1	18/05/2015	Consultancy	Vice President Mobility	20+
C2	29/06/2015	Consultancy	Managing Consultant	16
C3	10/07/2015	Consultancy	Principal Consultant	15
C4	15/07/2015	Consultancy	Director	20+
N1	08/06/2015	NGOs	Principal Adviser – Sustainable Mobility	20
N2	10/07/2015	NGOs	Managing Director	20+
N3	17/07/2015	NGOs	Head of Sustainable Business	3
N4	20/07/2015	NGOs	Programme Manager	20+
O1	05/05/2015	OEMs	Sustainability Engineer	14
O2	05/05/2015	OEMs	Sustainability Engineer	11
O3	05/05/2015	OEMs	Sustainability Engineer	3
O4	22/05/2015	OEMs	Director Sustainability	20+
O5	26/05/2015	OEMs	Safety Attribute Senior Manager	20+
O6	02/07/2015	OEMs	Group Environmental Strategist	15
O7	04/07/2015	OEMs	Head of Corporate Responsibility	10
O8	22/07/2015	OEMs	Principal Engineer NVH	14

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