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Life cycle energy optimisation: A proposed methodology for integrating environmental considerations early in the vehicle engineering design process

Ciarán J. O'Reilly [a, b, *], Peter Göransson [a, b], Atsushi Funazaki [c], Tetsuya Suzuki [c], Stefan Edlund [b, d], Cecilia Gunnarsson [b, d], Jan-Olov Lundow [b, e], Pontus Cerin [b, g], Christopher J. Cameron [a, f], Per Wennhage [a, b], José Potting [b, h, i]

[a] KTH Royal Institute of Technology, Aeronautical and Vehicle Engineering Department, Teknikringen 8, SE-100 44, Stockholm, Sweden
[b] The Centre for ECO^2 Vehicle Design at KTH, Teknikringen 8, SE-100 44, Stockholm, Sweden
[c] Japan Automobile Research Institute, 2530 Karima, Tsukuba, Ibaraki, 305-0822, Japan
[d] Volvo Group Trucks Technology, Gropegårdsgatan, SE-405 08, Göteborg, Sweden
[e] Bombardier Transportation, Östra Ringvägen 2, SE-721 73, Västerås, Sweden
[f] Swerea SICOMP, Bröderna Ugglas gata 208B, SE-581 88, Linköping, Sweden
[g] Swedish Energy Agency, Kungsgatan 43, SE-631 04, Eskilstuna, Sweden
[h] KTH Royal Institute of Technology, Environmental Strategies Research Division, Drottning Kristinas väg 30, SE-100 44, Stockholm, Sweden
[i] PBL Netherlands Environmental Assessment Agency, Antonie van Leeuwenhoeklaan 9, 3721, MA Bilthoven, Netherlands

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A B S T R A C T

To enable the consideration of life cycle environmental impacts in the early stages of vehicle design, a methodology using the proxy of life cycle energy is proposed in this paper. The trade-offs in energy between vehicle production, operational performance and end-of-life are formulated as a mathematical problem, and simultaneously balanced with other transport-related functionalities, and may be optimised. The methodology is illustrated through an example design study, which is deliberately kept simple in order to emphasise the conceptual idea. The obtained optimisation results demonstrate that there is a unique driving-scenario-specific design solution, which meets functional requirements with a minimum life cycle energy cost. The results also suggest that a use-phase focussed design may result in a solution, which is sub-optimal from a life cycle point-of-view.

1. Introduction

A major challenge in vehicle design today is to simultaneously meet the transport needs of society while minimising energy use and its associated environmental impacts. Efforts to reduce the environmental impacts of transport vehicles have been increasing over the past few decades. However, this challenge cannot be met by further extrapolating existing vehicle technologies alone. New step-changing solutions are needed. Finding new solutions, however, requires balancing a large number of economic, environmental and technical parameters. These parameters interact with each other in often quite complex and conflicting ways. The aim of this current work is to propose a new conceptual approach in which these trade-off considerations can be balanced so as to enable the emergence of new vehicle designs that have significantly lower environmental impacts.

1.1. Targeting vehicle architecture to reduce environmental impacts

Much of the effort to improve the environmental performance of vehicles has focussed on reducing the significant energy consumption during the use phase of the vehicle's life cycle (Nemry et al., 2008; Hawkins et al., 2013; Castro et al., 2003; Schweimer

* Corresponding author. KTH Royal Institute of Technology, Aeronautical and Vehicle Engineering Department, Teknikringen 8, SE-100 44, Stockholm, Sweden.
E-mail addresses: ciaran@kth.se (C.J. O'Reilly), pege@kth.se (P. Göransson), afuna@jari.or.jp (A. Funazaki), stetsuya@jari.or.jp (T. Suzuki), Stefan.H.Edlund@volvo.com (S. Edlund), Cecilia.Gunnarsson@volvo.com (C. Gunnarsson), jan-olov.lundow@se.transport.bombardier.com (J.-O. Lundow), pontus.cerin@energimyndigheten.se (P. Cerin), christopher.cameron@swerea.se (C.J. Cameron), wennhage@kth.se (P. Wennhage), Jose.Potting@pbl.nl (J. Potting).

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and Levin, 2000). In the case of cars, for example, the use phase contributes in the order of 80–90% of the life cycle energy demand, with production contributing 5–10% and end-of-life less than 5% (Nemry et al., 2008; McAuley, 2003; MacLean and Lave, 1998; Mayyas et al., 2012a). Mostly a combination of three basic strategies have been followed (Samaras and Meisterling, 2008) that are illustrated with the help of Fig. 1 (a) improving transport efficiency (i.e. reducing vehicle movement, $W_{Transport}$), (b) improving engine efficiency (i.e. increasing $E_{Transmission}/E_{Fuel}$), or by (c) switching to energy sources that have less environmental impacts (e.g. bio-based fuels or clean electricity, E_{Fuel}) (European Environment Agency, 2007; Sweeting and Winfield, 2012). These strategies, however, target only part of the total energy-use picture for a vehicle system over its life cycle (González Palencia et al., 2012). The overall energy profile of a vehicle is determined not only by the efficiency of the energy supply and conversion through the fuel, motor, transmission and operation, but also by the efficiency of the vehicle architecture over its complete life cycle.

Potentially large gains are achievable from rethinking the vehicle architecture (i.e. the designed structure of the vehicle and its complex emergent attributes) with a life cycle perspective. During the use phase, significant energy is required to overcome the dynamic losses (from aerodynamic drag, acceleration inertia, rolling resistance) of the vehicle itself, $E_{Loss,V}$. These account for approximately 50–80% of the fuel consumption depending on the vehicle and drive-cycle considered (Nemry et al., 2008; Koffler and Rohde-Brandenburger, 2010). The corresponding energy demands are intrinsic to the vehicle system's architecture, as a function of its material, structure and form, and have knock-on implications for the upstream energy supply. The vehicle architecture, as such, also offers an important starting point for reducing energy consumption and so environmental impacts (Knittel, 2011). However, changes to the vehicle architecture for use-phase gains must be balanced against their effect on production and end-of-life impacts.

1.2. The challenge of integrating environmental considerations

A redesign or rethink of the vehicle architecture offers a greater

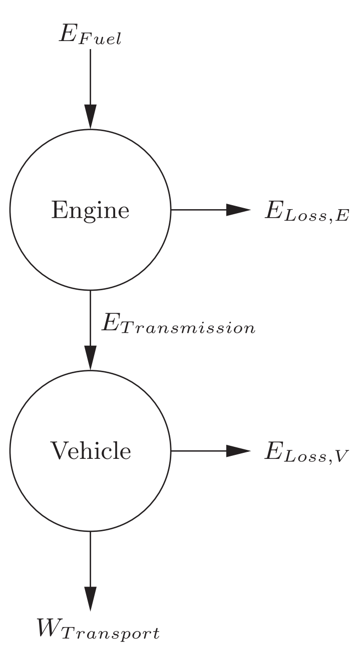

Fig. 1. Vehicle use-phase energy flow.

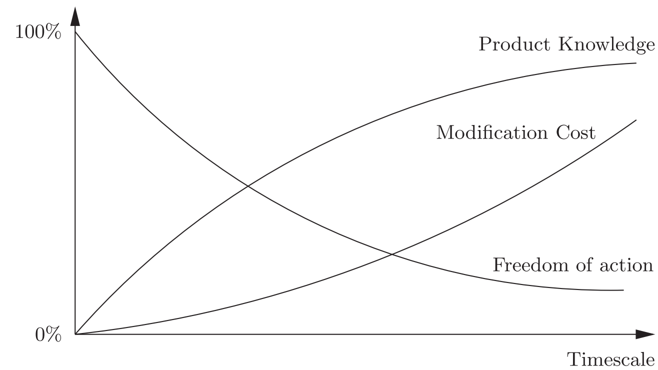

Fig. 2. The design paradox.

potential to reduce its environmental impacts than a repair or refinement of the existing architecture (as described by the Charter's 'four-step model' (Charter and Chick, 1997; Thompson and Sherwin, 2001)). However, modifying the existing architecture or designing radically new architectures to better incorporate these considerations presents a considerable challenge. Vehicle designers are faced with a design paradox (Lindahl and Sundin, 2013), as illustrated in Fig. 2, in which the freedom to design improved vehicle solutions early in the design process is accompanied by an inability to assess what these solutions will yield, while knowledge of the shortcomings in a vehicle design late in the design process is accompanied by an inability to make significant improvements. For established products such as vehicles, this paradox is mirrored in the conservative and late-stage nature of the conventional design process (Hodkinson and Fenton, 2000a; Minai et al., 2006). As the next generation of vehicles starts from the previous generation,[1] environmentally motivated changes to vehicle sub-systems may be characterised as repair or refine strategies of the existing architecture (Charter and Chick, 1997).

Modern vehicle architecture has being evolving gradually for more than 100 years through a traditional industrialised design process that is fundamentally top-down in nature (Minai et al., 2006). This means that the many functional requirements of the vehicle are decomposed into many levels of sub-functions, until a level is reached where the sub-functional task may be realised using available solutions, such as engines, chassis, etc. At this level, sub-functions are assumed to be independent of each other, and are designed separately. A concept solution is developed, refined and optimised for the sub-function in question. The sub-functional solutions or sub-solutions are then assembled to perform higher-level functional requirements.

At present, environmental considerations influence the design of technical sub-functional solutions through constraints (such as the prohibition of toxic materials (European Parliament and Council of the European Union, 2000)) or via a proxy (as in light-weight design (Hodkinson and Fenton, 2000b; Ermolaeva et al., 2004)). Furthermore, the environmental impacts of alternative solutions are assessed through life cycle assessment (International Organization for Standardisation, 14040 and International Organization for Standardisation, 14044) and this can be used as part of a down-selection process (Poulikidou et al., 2015). However, such eco-design methods have not been directly integrated into numerical optimisations, which often take place over thousands of

[1] There are cases such as the Chevrolet Volt, Nissan Leaf, BMW i3, Toyota Prius, Volkswagen XL1 that have a higher degree of originality but these are the exceptions that prove the rule.

iterations. Assessments are limited to a smaller set of candidate solutions that emerge from the optimisation. They therefore do not drive the optimisation in the sense that functions such as weight, drag coefficient, etc. are used to do so within optimum design approaches (Poulikidou et al., 2015; Arora, 2012). This means that eco-design approaches could be considered as re-active rather than pro-active. The challenge inherent here, as stated in Ref (Poulikidou et al., 2015), is that "materials offering the highest weight saving potential offer limited life cycle environmental benefit due to energy demanding manufacturing".

The conventional design approach also has a number of attributes which impede the development of improved environmental solutions. Firstly, optimising on a sub-functional level within a top-down design approach (optimisation for one sub-function at time) means that the solution is not optimal on a higher assembled system level (Cameron et al., 2009).

Additionally, it means that an assessment of the benefit of a new sub-solution within the overall system may be adversely biased as the other sub-systems may be preconditioned for the old sub-solution (Hodkinson and Fenton, 2000a). For example, substituting an electric motor into a conventional architecture and comparing the result with a conventional internal combustion (IC) engine vehicle is an unfair comparison as the conventional architecture has evolved over time for the IC engine. Changing the motor will enable changes in other sub-systems such as the removal of structures to damp IC engine vibrations, noise, and so on, and these complex interdependent effects should be taken into account.

Furthermore, the conventional design approach means that an improvement provided by one sub-solution can create a problem within another sub-solution as interdependencies between sub-functions are neglected. For example, the use of lightweight materials to meet structural requirements is known to adversely effect acoustic performance (Cameron et al., 2014), cross-wind stability (Favre and Efraimsson, 2011), etc. Such cross-functional conflicts emerge when sub-solutions are assembled in the latter stages of development, and a fix must be found. These can undermine the original benefits, and because they take place without a model for the functional interdependencies, they rely on existent knowledge or heuristics to solve the problem (Arora, 2012), which are not conducive to finding new solutions.

Overall the traditional top-down design approach is conservative and the existent vehicle architecture may well be locked-in (Kroll et al., 2001), which is problematic when it comes to addressing relatively new environmental considerations. New approaches are needed to better integrate environmental considerations so that they can drive the design, to balance environmental considerations with the many conflicting cross-functional requirements, and to optimise on a higher system level. These would open the way for more significant changes to the vehicle system's architecture.

To effect significant environmental improvement, it is imperative to influence early-stage design (Schöggl et al., 2014), where the possibilities for innovation have not already been severely constrained. Inherent in the exploration of the multitude of early-stage possibilities is the need to handle large sets of design variables, and to balance the outcomes of changing them on different time and component scales of the vehicle system. The development of radically improved solutions therefore cannot be achieved without the integration and optimisation on a higher system level of engineering and environmental analyses techniques, with a life cycle perspective and an appropriate level of fidelity.

1.3. Scope of this paper

The overall objectives of this work are therefore to integrate a life cycle environmental proxy within a multidisciplinary design optimisation framework, and to use it to directly balance environmental considerations with conflicting transport related functions so as to drive the early-stage design process towards environmentally optimal vehicle solutions. This integrative methodology could potentially break from the conventional design paradigm. It could be an enabler to integrate components, integrate functionality, simplify design, reduce financial and environmental costs, while maintaining existing performance.

In this paper the proposed methodology is presented and demonstrated through a simple illustrative example. This example is intended to show the details of the methodology at present, and its potential to find new solutions that not only meet specified functional requirements but also have lower environmental impacts. Certain aspects of the presented methodology (e.g. the end-of-life model) are at present not developed to a sufficient level for the methodology to be immediately used in an industrial design process – this is beyond the scope of this paper. Here, the focus is on a proof-of-concept demonstration.

This paper is structured as follows. The new methodological approach is presented in Section 2. The potential of this methodology is illustrated through a worked example in Section 3. The benefits and challenges of the proposed methodology are discussed further in Section 4. The conclusions of this work are presented in Section 5.

2. A life cycle energy optimisation methodology

In this section, the main building blocks of the proposed methodology are presented and discussed.

2.1. A new methodological framework

A design methodology is proposed here in which environmental considerations are formally integrated directly into a design methodology. This is done by building a mathematical model that uses life cycle energy as proxy for environmental considerations in a multidisciplinary design optimisation framework. The methodology is illustrated in Fig. 3. Furthermore, this environmental proxy is used as the objective function to be optimised, as is detailed in subsequent sections. It is therefore life cycle energy which is the overarching design consideration that joins the different disciplines together. The more traditional transport functions (such as load-carrying, vibrational, etc.) act as constraints on the design. The mathematical optimisation problem is numerically solved using computational resources, thus enabling much larger problems to be explored. The methodology searches for a solution which requires the minimum life cycle energy to meet the transport function constraints.

2.2. Core rationale

The core rationale of the methodology is that the environmental optimum of a simultaneous design problem is superior to the design found by optimising each discipline and life cycle phase sequentially. This is because the life cycle multidisciplinary design can exploit the interactions between different disciplines and life cycle phases. Life cycle energy trade-offs are therefore made directly within the design methodology, and different materials, shapes and topologies are chosen for the design based on minimising the life cycle energy.

2.3. Life cycle energy

A central component in the design methodology presented here

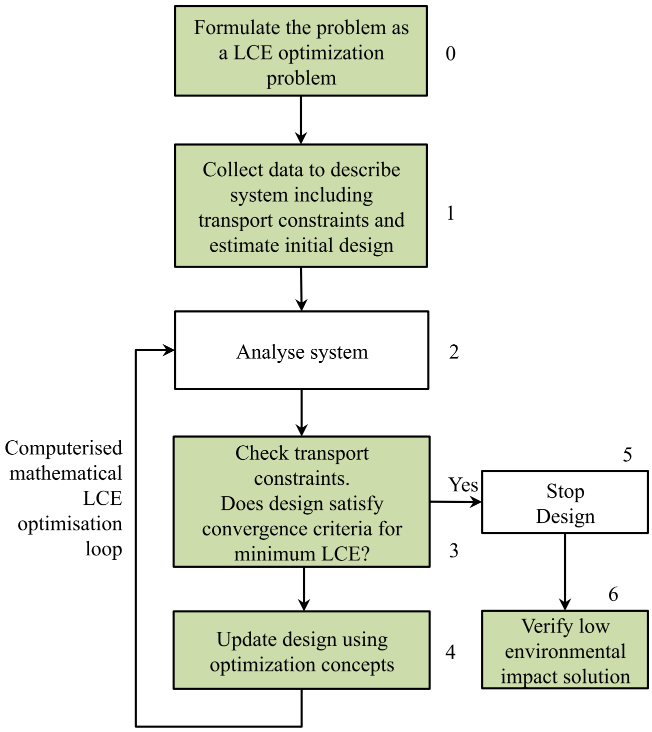

Fig. 3. Life cycle energy optimisation design methodology.

is the use of life cycle energy as a way of integrating environmental considerations into a vehicle design method. Life cycle energy (or total cumulative energy demand (Huijbregts et al., 2005)) is the total energy requirement of a product over its entire life cycle. This includes the cradle-to-gate production, the use-phase energy, and the end-of-life or waste-processing energy.

The choice of life cycle energy as a single-indicator environmental proxy for vehicle design methodology is justifiable. It has been demonstrated that life cycle energy may be used as a proxy for the life cycle environmental impacts of systems, in which energy plays a dominant role, such as vehicles (Fitch and Smith Cooper, 2004; Mayyas et al., 2012b). It is also compatible with more traditional transportation functions, for example, the energy required to produce the materials in a vehicle can be directly compared with the energy required for that vehicle's acceleration. It does not require additional conversion models, unlike other potential environmental indicators.

Life cycle energy also implies a broader view of the vehicle system than just the use-phase artefact itself. It not only creates connections between different sub-system levels within a vehicle system that contribute to the overall energy requirements, it also connects to the systems beyond the individual vehicle. For example, the production energy for an individual vehicle may be effected by economies of scale in the production and supply chain. Therefore, designing with a view to life cycle energy is in principle wide enough to potentially achieve more global benefits.

The life cycle energy required by a vehicle system may be modelled as a function of its design variables as

$$E_L(X) = E_P(X) + E_U(X) + E_E(X) \quad (1)$$

where E_L is the life cycle energy, E_P is the production energy, E_U is the use-phase energy, E_E is the end-of-life energy, and X is the set of design variables. To be useful in a design methodology, the contribution of each life cycle phase must be modelled further. Note that changing a design variable in X (such as the choice of material) will affect all phases of the life cycle. Exactly how will depend on the way the separate phases are modelled.

2.4. Designing a multifunctional multiscalar system

In addition to life cycle energy requirements, the vehicle system also has a number of other functions to fulfil, and may be described as a multifunctional system. The vehicle's primary or root function is usually defined as to carry and move a payload (driver/passenger/cargo) from one location to another, i.e. to transport. Although many more functions of the vehicle system could be included (such as to provide prestige to the owner) only transport and life cycle energy are considered here for the sake of clarity.

The vehicle's primary function is achieved through a large set of nested sub-systems, each with their own functions, such that the vehicle system may be described as multiscalar as it is comprised of many levels of sub-systems. For example, an engine for energy conversion, a chassis for structural support, etc.

These functions are also dependent on the same design variables as those in the life cycle energy function. For example, changing the material selection in the chassis sub-system will impact its load-carrying function and its vibration-damping function, whilst simultaneously impacting the life cycle energy of the overall system.

Rather than breaking the design up into a number of independent sub-problems with independent functional requirements as in conventional top-down design, a multidisciplinary design approach is adopted here (Cameron et al., 2009, 2014). This means that different methods are used to examine the functions simultaneously. For example, a modal analysis method may be used to examine vibrational performance and a structural mechanics method used to examine the load-carrying performance. Although this does not reduce the complexity of the overall problem, connecting the methods into a simultaneous methodology means that trade-offs between functions can be exploited to find design choices that are optimal for the functions considered.

2.5. Life cycle energy optimisation

In the present multifunctional design methodology, life cycle energy is not only integrated but is also selected as the design function to be optimised in a multidisciplinary design optimisation (Arora, 2012). The other transport related functions are taken to be constraints on this optimisation. The mathematical design optimisation problem may be expressed as

$$\min(E_L(X)) \quad (2)$$

subject to constraints of the form:

$$T^{(I)}(X) \le 0 \quad (3a)$$

$$T^{(E)}(X) = 0 \quad (3b)$$

$$X_{min} \le X \le X_{max} \quad (3c)$$

Eq. (3a) is the set of transport related functional inequality constraints. For example an inequality constraint could be that the design must carry at least a 100 kg load.

Eq. (3b) is the set of transport related functional equality constraints. These quite often arise as physical laws, which must be solved as sub-problems in order to assess an inequality constraint. For example, an inequality constraint could be that the internal noise level is less than 50 dB, which might need to be assessed by solving the acoustic wave equation (an equality relation) before assessing the original inequality constraint. Note that to solve the acoustic wave equation sub-problem would probably require the use of a computational acoustics solver as part of the multidisciplinary approach.

Eq. (3c) is the set of design variable constraints. The variables are constrained by the minimum and maximum values as indicated by the indices. These could be, for example, a material type, a thickness or a shape.

Recalling that the objective of this methodology is to change the design variables so as to find a design solution, which has the minimum life cycle energy use and simultaneously meets all the transport related constraints, an illustrative implementation example will be discussed in the following.

3. An illustrative example: designing a car roof panel

In this section, an example of a design is presented in order to further illustrate the application of the methodology. As the focus in this paper is on presenting the potential of methodological framework itself, the complexity of the design object, its functionalities, and the optimisation thereof, are deliberately kept simple. Furthermore, the production energy is modelled simply as an energy per kilogram of material relationship, while the end-of-life energy is not included. Although, these simplification undermine the real-world applicability of the result, the intended illustrative nature of the example is retained.

The life cycle energy optimisation (LCEO) methodology is therefore demonstrated through a case study in which a sandwich panel is designed, which is assumed to be part of a vehicle. As the case includes sub-functionalities which interact with each other and must be balanced, the principles involved in the proposed methodology may be demonstrated at this level of vehicle subsystem. Note that the general methodological framework, presented in Section 2, could be applied across different system levels and on different applications. The important point is that it raises the optimality compared to conventional single-function design by balancing cross-functional conflicts, and that the optimisation is driven by a life cycle environmental proxy.

3.1. Description of the case

The selected sandwich panel design case is based on a similar case explored previously as part of the multifunctional design of a car roof panel (Cameron et al., 2009, 2014; Cameron, 2011). In those instances the functions considered were limited to structural and acoustic performance. In a conventional design, the roof of a car is firstly required to perform a load-carrying function. A concept is proposed, usually an outer metal sheet supported by cross-breams, which might then be optimised for mass. This results in a structure that is an optimised sub-functional solution. However, the roof's other functions are designed separately and this usually leads to additional sub-functional solutions that are assembled together. So the roof's vibrational and acoustic functions lead to additional structures being added to the load carrying structure. As reducing the mass of a structure impacts negatively on its vibrational and acoustic properties, these functions are in conflict with each other. In the aforementioned multifunctional designs, these functions were designed simultaneously, with the design optimised for weight. This led to a design that met the structural and acoustic requirements for the roof, and was lighter and thinner than a conventional roof. Significantly, this roof was also constructed and tested on a car, and retained these benefits despite the simplified nature of the early design study. Here this sandwich panel is examined in order to demonstrate the LCEO methodology.

The sandwich panel consisted of two fibre-reinforced laminate face sheets, labelled 1 and 2, and a foam core, labelled c, as illustrated in Fig. 4, and is simply supported along its edges. The material composition and thickness of these layers is left to the optimiser to choose, and an unsymmetrical configuration may result. The full dimensions of the panel are 1.5 m by 1.7 m, but in the simulations performed a ¼ model with symmetry conditions applied in the planar directions is used.

To design this panel, a set of design variables are firstly selected. Then a set of constraints and life-phase models are defined in order to close the optimisation problem. The details of these choices for this case study are given in subsequent sections. From the large set of feasible solutions that meet the constraints, the solution with the lowest life cycle energy is arrived at by mathematical minimisation. A gradient-based method called the globally convergent method of moving asymptotes (GCMMA) (Svanberg, 2002) was used for this.

3.2. Design variables

To determine the thicknesses and material mixtures required to fulfil the functional constraints for the panel, a number of parameters are chosen as design variables. While implementing thickness variables is trivial, using material properties as variables requires a method of parameterisation to some meaningful physical quantity. The concept of hybridisation is employed to give a continuous representation of the properties of a mixture of materials (Ashby and Bréchet, 2003). $P_{i,j}$, where $i = 1,2,c$ are the face sheets and core, is the j-th material's engineering property, such as the Young's modulus, density or Poisson's ratio. These are proportionally determined depending on the volume fraction, $V_{i,j}$, selected.

A list of these design variables used is shown in Table 1. For the fibre-reinforced laminates, it should be noted that 40% of the laminate is epoxy resin and they are all symmetric layups consisting of 0,±45 and 90° fibre stacks. A number of materials are considered for possible use in this sandwich panel. These are listed in Table 2 along with their engineering properties (Cameron et al., 2009). Carbon-fibre (CF) and glass-fibre (GF) laminates are considered for the facing sheets with polyethylene (PET) foam, polyurethane (PUR) foam and polyvinylchloride (PVC) foam considered for the core. The list could be extended as required for other components.

The set of design variables is therefore given by the vector

$$X = \{V_{1,CF}V_{1,GF}V_{2,CF}V_{2,GF}\cdots \\ V_{c,PET}V_{c,PUR}V_{c,PVC}\cdots \\ t_1 t_2 t_c\} \tag{4}$$

3.3. Design constraints

Two linear elastic loading responses and two vibrational frequency responses are used to incorporate the functional

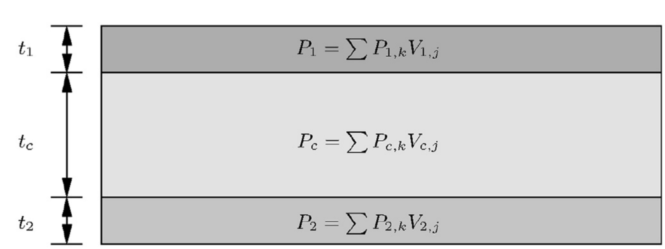

Fig. 4. The sandwich panel to be optimised with top and bottom facing sheets and a core.

Table 1
List of design variables. The i subscript here denotes the top ($i = 1$) and bottom ($i = 2$) face sheet.

Face Sheets	$V_{i,CF}$	Volume fraction of carbon fibre reinforced laminate (assuming 40% epoxy in the laminate)
	$V_{i,GF}$	Volume fraction of glass fibre reinforced laminate (assuming 40% epoxy in the laminate)
	t_i	Thickness of the face sheet
Core	$V_{c,PET}$	Volume fraction of Polyethylene foam
	$V_{c,PUR}$	Volume fraction of Polyurethane foam
	$V_{c,PVC}$	Volume fraction of Polivinylchloride foam
	t_c	Thickness of the face core

Table 2
Materials considered and their engineering properties.

Material	Young's modulus [MPa]	Density [kg/m^3]	Poisson's ratio [−]
Carbon fibre	150,000	1850	–
Carbon fibre lam.	57,379	1500	0.3
Glass fibre	40,000	1940	–
Glass fibre lam.	18,794	2520	0.3
Epoxy	3200	1150	0.3
PET	100	110	0.3
PUR	0.07	22	0.3
PVC	130	100	0.3

performance of the panel. Although more functions and constraints may need to be considered in a realistic design, the constraints considered here are sufficient to illustrate the methodology as such. Fig. 5 visualises these using the 1⁄4 symmetric model used here. The first load response is to a static pressure applied to a square area of approximately 100 mm in the centre of the panel. The second load response is to a static pressure distributed over the entire top surface of the panel. These represent loading cases for the roof in the event of the car rolling over. Maximum displacement constraints are set for both these loading cases. Also, two minimum frequency constraints are set for first and second natural frequencies of the panel with the chosen boundary conditions. These are important when it comes to avoiding flutter in the roof under driving conditions and have a bearing on the sound transmission properties of the panel. These four inequality constraints may be given by

$$\frac{d_k(X)}{d_{k,max}} - 1 \le 0, \quad k = 1,2 \tag{5a}$$

$$1 - \frac{f_k(X)}{f_{k,min}} < 0, \quad k = 1,2 \tag{5b}$$

where d is the displacement of the panel and f is the frequency of the normal mode. The k subscript indicates the constraint case for that type. Verification that these constraints are met is achieved by computing the linear elastic response and the normal modes via the integration of a finite element solver (COMSOL Multiphysics) into the LCEO methodology, i.e. further equality constraints are also solved. Note that engineering solver is integrated into the environmental optimisation framework (LCEO) here, rather than adding an environmental assessment tool as a back-end add-on to engineering solver (see (Poulikidou et al., 2015) for example). This difference is subtle but is of critical importance in terms of how the design is driven. The maximum and minimum displacements and frequencies selected for these constraints are $d_{1,max} = 2.5 \times 10^{-6}$ m, $d_{2,max} = 2.5 \times 10^{-6}$ m, $f_{1,min} = 50$ Hz and $f_{2,min} = 215$ Hz.

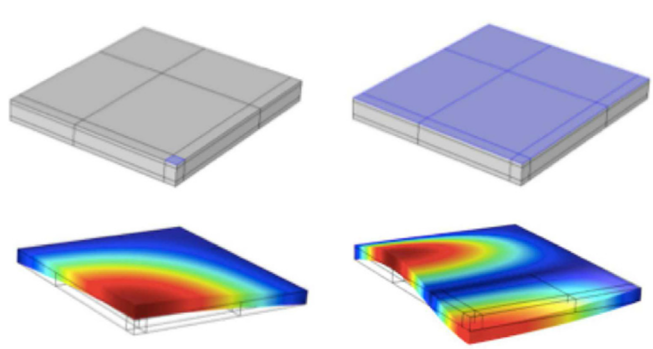

Fig. 5. Four functional constraints used – localised unit loading (top-left), global unit loading (top-right), normal modes analysis 1st mode (bottom-left) and 2nd mode (bottom-right).

Additionally, the following design variable constraints were set

$$0 \le \sum V_{1,j} \le 1, \quad j = CF, GF \tag{6a}$$

$$0 \le \sum V_{2,j} \le 1, \quad j = CF, GF \tag{6b}$$

$$0 \le \sum V_{c,j} \le 1, \quad j = PET, PUR, PVC \tag{6c}$$

$$t_{min} \le \sum t_i \le t_{max}, \quad i = 1,2,c \tag{6d}$$

Eqs. (6a)–(6c) ensure that the volume proportions do not exceed 100%. The maximum and minimum thicknesses of the total panel were selected as $t_{max} = 7 \times 10^{-2}$ m and $t_{min} = 5 \times 10^{-4}$ m.

3.4. Life cycle phase models

Although the framework presented in Section 2 includes the end-of-life phase, it is not included in this case study. The intention is to add this at a later point (Cheung et al., 2015). The focus in this example is thus limited to the production and use phases.

The production energy E_P (contribution to primary energy demand) may be modelled as

$$E_P(X) = \sum E_{P,j} m_j(X) \tag{7}$$

where E_{Pj} is the energy for each of the constituent materials, m_j is the actual contributed mass of each constituent materials given by $m_j(X)=2.55 V_{i,j} t_i \rho_j$ and ρ is the material density. The production energy inventory data used in this work are shown in Table 3. These data come from the following sources – carbon fibre (Suzuki and Takahashi, 2005; I values of carbon fibe, 2009), glass fibre (Research report on invent, 1999; Song et al., 2009), epoxy (Boustead, 2005a), PET (Liebich and Giegrich, 2010), PUR (Boustead, 2005b), PVC (Ostermayer and Giegrich, 2006). These data refer to total primary energy demand. In this proof of concept example, these data are sufficient to illustrate the potential of the methodology.

The use-phase energy for transportation E_U may be modelled as

$$E_U(X) = NW_T(X) \tag{8}$$

where W_T is the energy or mechanical work required to move the vehicle according to a prescribed drive-cycle and N is the number of such cycles during the entire use phase of a vehicle. The energy consumed during the use phase of the vehicle's life cycle is very much dependent on the makeup of the vehicle and how it is driven. To standardise the usage parameters, the energy required for a prescribed drive cycle is modelled (Koffler and Rohde-Brandenburger, 2010) as

$$W_T(X) = W_R(X) + W_A(X) + W_D(X) \tag{9}$$

where

$$W_R(X) = [1-r]gc_R C_R m(X) \tag{10a}$$

$$W_A(X) = C_A m(X) \tag{10b}$$

$$W_D(X) = 0.5\rho_a c_D C_D A(X) \tag{10c}$$

with W_R, W_A and W_D being the energy required to overcome rolling resistance, inertial resistance to acceleration, and aerodynamic drag respectively. r is the fraction (in %) of kinetic energy regained during deceleration, m is the total mass (i.e. $m(X) = \sum 2.55V_{i,j}t_i\rho_j$), c_R is the rolling resistance coefficient, ρ_a is the air density and c_D is the coefficient of drag. A is the frontal area of the vehicle and modelled as $A(X) = (h + t_1 + t_2 + t_c)B$. This is a synthetic model for the purpose of the present example, and it assumes that the front area is given by product of the frontal height $h = 1$ m plus the total panel thickness and the frontal width $B = 1$ m.

The remaining terms in these equations are dependent only on the chosen drive cycle, not on the vehicle, and are given in terms of the sum of discrete work increments Δs over the drive cycle with $C_R = \sum \Delta s_i$, $C_D = \sum v_i^2 \Delta s_i$ and $C_A = \sum a_i \Delta s_i$, where v_i and a_i are the incremental velocity and acceleration. To provide these, the New European Drive Cycle (NEDC), shown in Fig. 6, is employed. The drive cycle constants used are therefore $C_R = 11{,}013$ m, $C_D = 3{,}989{,}639$ m^3/s^2 and $C_A = 1{,}227$ m^2/s^2 and this drive cycle was repeated for a set of selected total life cycle driving distances. These were 60,000 km, 180,000 km and 360,000 km.

In the use-phase energy model, the following parameter values were chosen – the fraction of kinetic energy regained during deceleration $r = 15\,\%$, the rolling resistance coefficient $c_R = 0.01$, the air density $\rho_a = 1.2$ kg/m^3 and the coefficient of drag $c_D = 0.3$.

Table 3
Cradle-to-gate inventory data for materials considered. The Japan Automobile Research Institute (JARI) provided this data to the authors through a direct communication.

Material	E_P [MJ/kg]	Form of material
Carbon fibre	286	
Glass fibre	30	Assembled roving
Epoxy	137.1	
PET	69.4	Bottle grade
PUR	101.5	
PVC	56.7	

3.5. Results

The optimisation was performed for two different objective functions, one taking only the use-phase energy (USE) into account and one based on the production- and use-phase energy (LCE). The resulting optimal design variables are shown in Table 4 for the three different driving distances studied. Table 5 shows the corresponding objective function values as well as the total mass of the sandwich panel. For all solutions the limiting constraint is the displacement in the distributed global loading case, see Fig. 5.

The resulting design variables, when only the use phase is optimised, tend to a solution with minimum mass for all three driving distances. This is achieved by having both face sheets made out of 100% carbon fibre and a core composition which together with enough distance between the face sheets (i.e. core thickness) provides a high enough bending stiffness for all functional constraints to be satisfied. In all three solutions, the core is composed out of a mix of mostly the softer lighter PUR foam and some of the stiffer heavier PVC foam. The PET foam, which is heavier and softer than the PVC, is not selected by the optimiser at all. For the short distance driving scenario, the production energy is almost three times higher than the driving. For the medium distance driving, they are about equal and for the long distance usage the driving energy is twice the production.

For the LCE optimised solution the three driving scenarios strongly influence the balance in the resulting configurations. The composition of the core is a mix of PUR foam and to a lesser extent of PVC foam. The face sheets are made out of a mix of glass fibre and carbon fibres, and the upper and lower face sheets are furthermore not identical in the material fractions obtained. Additionally, the fraction of carbon fibre in the face sheets is increasing with distance driven in order to reduce the impact of the drive phase energy E_U. The lightest panel appears, as could be expected, in the solution pertaining to the longest driven distance.

From the results presented above, it is clear that the choice of the life cycle energy as an objective function, changes the design even in this simplified example. While the actual resulting configurations themselves are perhaps unimportant, the fact that they do actually differ is of considerable significance.

Based on the results in Table 5, also shown in Fig. 7, some quite interesting observations may be made already for this simplified vehicle component case study. Three distinct features emerge when analysing the results in Table 5. The total energy consumed is in all cases lower when optimising for the LCE. In order to save

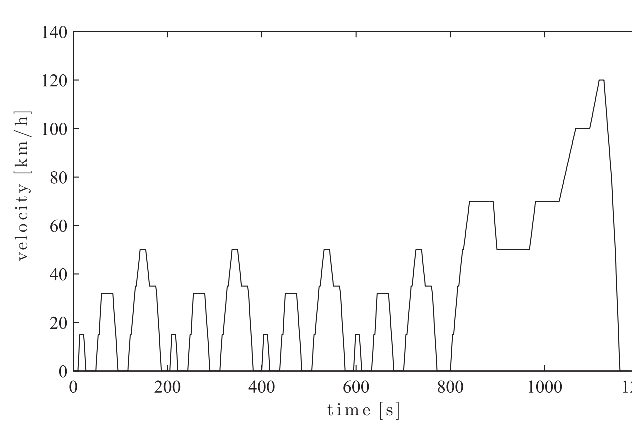

Fig. 6. The New European Drive Cycle (NEDC).

Table 4
Resulting optimal design variables of use-phase energy and life cycle energy optimisation for three driving distances.

Distance	60,000 km		180,000 km		360,000 km	
Variable	USE	LCE	USE	LCE	USE	LCE
$V_{1,CF}$ [%]	100	25	100	23	100	27
$V_{1,GF}$ [%]	0	75	0	77	0	73
$V_{2,CF}$ [%]	100	25	100	23	100	31
$V_{2,GF}$ [%]	0	75	0	77	0	69
$V_{c,PET}$ [%]	0	0	0	0	0	0
$V_{c,PUR}$ [%]	89	87	89	88	89	89
$V_{c,PVC}$ [%]	11	13	11	12	11	11
t_1 [mm]	0.10	0.13	0.10	0.14	0.10	0.14
t_2 [mm]	0.27	0.25	0.27	0.27	0.27	0.25
t_c [mm]	45	55	45	55	45	54

Table 5
Results of use-phase energy and life cycle energy optimisation for three driving distances.

Distance	60,000 km		180,000 km		360,000 km	
Function	USE	LCE	USE	LCE	USE	LCE
E_P [MJ]	680	540	680	540	680	550
E_U [MJ]	230	250	690	740	1380	1470
E_L [MJ]	910	790	1370	1280	2060	2020
m [kg]	4.8	6.3	4.8	6.3	4.8	6.0

energy, a reallocation of space is made. Furthermore, the LCE optimised solution is in all cases the heavier of the two, thus emphasising the fact that minimising mass in order to save energy used for driving might lead to a sub-optimal design from a holistic life cycle point-of-view. It illustrates the point made in Section 1, that gains in one part of the design can be offset in another, i.e. see in Fig. 7 how the lower energy in the use phase for the USE optimised cases relative to the LCE cases (achieved by minimising mass) is lost in the production phase.

The actual size of the reduction in life cycle energy depends on the distance driven, and decreases with increasing distance. For the short distance case, see Fig. 8, the reduction is more than 10%; for the medium distance case it is slightly less than 10%; while the reduction for longer distances is around 2%. The production energy is remarkably stable in all usage profiles.

Furthermore, the different optimal configurations found for the USE and LCE objective functions, illustrate that one way to adjust the balances is to allocate space differently. In the LCE solutions, in order to minimise the total energy, the panel occupies a larger volume compared to the USE configurations. The thickness of the

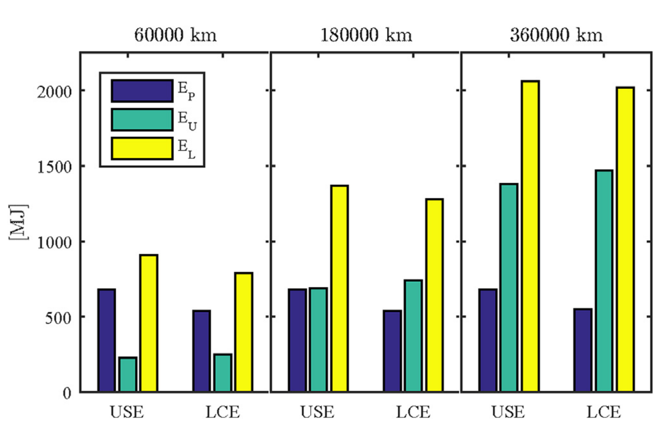

Fig. 7. Energy results from the optimisation.

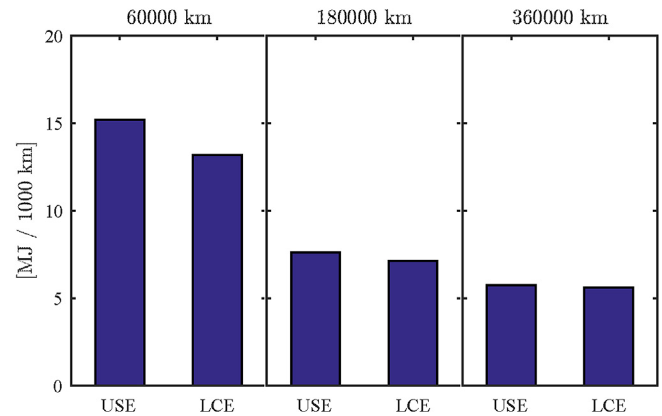

Fig. 8. Normalised life cycle energies.

core has increased by about 20% for the LCE solutions compared to the USE solutions as a means of keeping the weight as low as possible. While this is an efficient way to save as much mass as possible (consistent with general sandwich theory), the interesting outcome here is that it opens up for an increased use of the low-energy heavier glass-fibre laminates in the face sheets. This results in around a 20% reduction in production energy for the LCE solutions compared to the USE solutions.

The core composition is similar in all the cases investigated, with a large portion of low-density PUR foam blended with the stiffer PVC to obtain a sufficiently high stiffness to uphold the functional constraints of the panel. In all the cases investigated the PET foam is eliminated from the design, despite having a significantly lower production energy than the PUR, as its engineering properties are less suited to the design constraints.

4. Discussion

A life cycle energy optimisation (LCEO) methodology has been presented, which integrates life cycle energy as an environmental proxy into a multidisciplinary design optimisation framework. This is an enabler to integrative multifunctional environmentally-driven design. The proposed methodology has been demonstrated to work on a simple example in the previous section. This illustrated the benefits of the method, but also gives an indication of the challenges that must be overcome in its continued development. These are discussed further in this section.

The methodological framework works across system-level scales and this enables the design to possess a self-organising character. It is much less dependent on existent knowledge than the conventional design process and is therefore better suited to early-stage design. Macro-scale solutions are allowed to emerge from micro-scale rules and so the design has a much more bottom-up character. This leads to results that would perhaps not be arrived at through a deliberate top-down design approach. For example, the fact that the lower life cycle energy design in the previous section is thicker and heavier is perhaps unexpected. This is in keeping with the previous multi-functional design results, where the results contained almost organic-looking structures (see (Cameron et al., 2009, 2014; Cameron, 2011)) that are quite different from traditionally designed structural components.

These cross-scalar connections are formulated mathematically with a view to higher system levels, i.e. the life cycle energy of the overall system. This is well suited to identifying improvements and driving the solution towards some global objective. The mathematical modelling as a function means information is available about the gradient of this function, and this points the direction towards a more optimal solution. This is in contrast to the conventional reductionist approach where there is no overarching connecting model for the performance.

The methodology explores cross-functional connections within a system, which can be exploited to find more optimal solutions. It brings together modules from all relevant disciplines and joins them together through a quantifiable environmental proxy function. This is in contrast to examining individual disciplines while interfacing with other technical or environmental constraints, heuristics and assessment results. Note that in this multifunctional framework it is more natural to integrate environmentally related functions directly in the design, than in the top-down one-function-at-a-time approach.

Ideally functional interactions would be mapped out and modelled in detail so they could be explored in a quantitative manner in early-stage design, and a solution found that is globally optimal for all functions. However, such an approach can quickly become very demanding of resources, to the point of becoming practically impossible (not withstanding the fact that the present fully computerised approach can go far beyond the capabilities of the human mind to simultaneously evaluate such large-scale complex interactions). Therefore, it is important to identify which interactions are most critical to overall performance of the system or larger sub-systems (still bringing together many sub-functions), and to model these with an appropriate level of fidelity. The level of detail modelled can be tailored for different stages the overall design process progresses and applied iteratively, with the aim of finding the best answers for as much of the overall system as possible as early as possible. This also includes an identification of which functions act locally (e.g. load carrying) and which act globally (e.g. thermal, acoustic, energy), so as to ensure that the appropriate functions are internalised within the design. Further work is needed to understand the limitations of the methodology in this regard. However, even if exploring the whole vehicle system and all its functions simultaneously is impractical, exploring larger sub-systems and functional sets will still improve the optimality.

The methodology focusses on optimising for life cycle energy, and not the more traditional transport related functions. This means a life cycle environmental function is directly explored within the design and related to other vehicle functions. This significantly shifts the optima landscape (Rohlfshagen and Yao, 2013) for the design from more traditional solutions. Once transport constraints are satisfied, the optimiser is free to find the best solution from an environmental perspective. This switch from the conventional view of vehicle functionality could potentially move vehicle design in a very different direction and lead to a new design paradigm. The presented methodology does integrate the production and end-of-life within its framework, but better models will need to be included to give more realistic and accurate results. Similarly, financial costs could be included in the same way as the transport related functions. These would act to constrain the optimiser so that financially infeasible solution are not arrived at.

Some more assessment is needed into the robustness of life cycle energy as a proxy for environmental impacts and to verify its effectiveness. The assumption here is that the design with the lowest life cycle energy is superior from an overall environmental impacts perspective. However, this remains to be verified when more realistic case studies are undertaken. There may well be certain impacts that are not captured by the proxy. Also, the strength of the correlation with specific environmental impacts is likely to change depending on the type of energy used. Although fossil fuel energy is likely to remain significant in the transport sector (Capros et al., 2014), moves towards greater use of nuclear or renewable sources are likely result in a move in impacts from emissions-related to waste, land use, etc. The sensitivity of the proposed methodology to such changes could be investigated further. Overall though, it seems reasonable to expect that minimising life-cycle energy use should result in beneficial environmental outcomes.

Finally, concepts such as multifunctional body panels (Cameron et al., 2014) must be developed, which are conducive to multifunctional solutions. The starting concept may inadvertently constrain the functions that may be included and the solutions that may be achieved. The starting concepts must therefore be broad enough to allow the optimiser to work within as large a solution space as possible. However, there is a significant research gap regarding how multifunctional concepts can emerge in a bottom-up or holistic design approach. Understanding the connectivity and interaction of functions on local and global scales, and their repercussion for solution concepts would be a valuable contribution to designing better multi-functional solutions.

5. Conclusions

In this paper a life cycle energy optimisation methodology has been presented and applied in a proof-of-concept example, which looks at the low-energy design of a vehicle sub-functional unit, i.e. a sandwich panel for use as a car roof. The design has been optimised for use-phase energy and for life cycle energy. Although the purpose of the case study was not to perform a real design, it nevertheless serves to illustrate the difference between choosing life cycle energy and use-phase energy as an optimisation objective function. The methodology is successful in achieving a design, which meets the functional constraints and requires less energy over its life cycle. The life cycle energy optimised design has, depending on the driving scenario, between a 2% and 10% lower life cycle energy compared to the use-phase optimised design.

The methodology appears to be very promising. Further work is required to test the robustness of solutions for more complex design cases, with greater numbers of functional constraints, an improved production energy model and with end-of-life considerations included.

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