Critical review and methodological issues in integrated life-cycle analysis on road networks

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Abstract

Life-cycle management of road network projects traditionally emphasise *material production* and *construction* stages, with less attention given to *usage stage* and functionality improvement. Increasingly there is a need to address: inconsistencies in cost attribute selection; adjusting for uncertainties and costs; clarifying system boundaries; data sources; functional units and regional or temporal applicability of life-cycle frameworks. The current study focuses on a critical literature review of life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) research published in the last decade (post 2008) towards identification of research gaps. Accurately analysing all life-cycle stages, feedback loops, future cash and resource flows, and interlinking performance with overall sustainability can aid the decision-making process towards sustainable alternatives for constructing new, or rehabilitating existing roads. This review finds that the use of recycled materials, base/sub-base stabilisers and asphalt binder replacement has the potential of energy saving (≥ 34% or 3.1 TJ), mitigating landfill disposal issues, and greenhouse gas load reduction (≥ 34.5% CDE). Lack of real world LCCA-LCA application and stakeholder prejudice against recycled material usage are addressable by better stakeholder (decision-makers and road users) engagement via a social component. The proposed enhancements identified in this study can increase LCA/LCCA attraction to policy-makers, planners and users and ultimately ensure a more sustainable asset.

Keywords: road network sustainability; asphalt pavements; life-cycle assessment; recycled materials; GHG emissions.

1. Introduction

Due to unprecedented population growth and ongoing influx of people and businesses towards urban areas, roadways often face traffic congestions causing time-delays, pollutant emissions, added fuel and vehicle operational costs, noise pollution and deterioration of the road networks. Issues such as limitation of funds, lack of political/social interest and subjectivity of opinion dominates the decision-making process to create and maintain infrastructure in perpetuity. Principles of control and system-style life-cycle engineering management are generally under applied. Traditionally, project studies are often conducted during the feasibility stage of an asset's design and much emphasis is placed upon the initial costs. However, the whole costs of low-specification design, construction without adequate quality management systems and sporadic rather than controlled inspection, as well as unstructured operation, maintenance and rehabilitation (OM&R) regimes continue to cause concern (Hood et al., 2018). Significant monetary benefits exist where cost analyses are performed for the entire life of a road network asset (e.g., pavements, highways, bridges and other roadside components) towards increased investment and long-term benefit to users.

Life-cycle cost analysis (LCCA) is the conventional procedure for the evaluation of the financial benefits and returns from any investment by analysing its future expenditures along with the initial costs. Whilst the application of LCCA in road construction has been given considerable attention during the past decades, only limited practical application has been attained so far (Cabeza et al., 2014). Coupled with the principle of cost-effectiveness, is the idea of sustainability which adds to the traditional balance of time, quality and cost of construction investment. Adding sustainability into the equation introduces the comprehensive criteria of evaluating road investment decisions, either for “new” road networks or “rehabilitation” of deteriorating assets, against environmental, social, and even political and administrative perspectives. Roadway projects can then be sustainably and cost-effectively procured, designed, constructed, managed and maintained and then reintegrated or recycled. It means that if the sustainability justifications are added to the economical or monetary criteria, the needs of users can be better met and further benefits may be achieved if the analysis is performed for the entire life cycle of the road network assets.

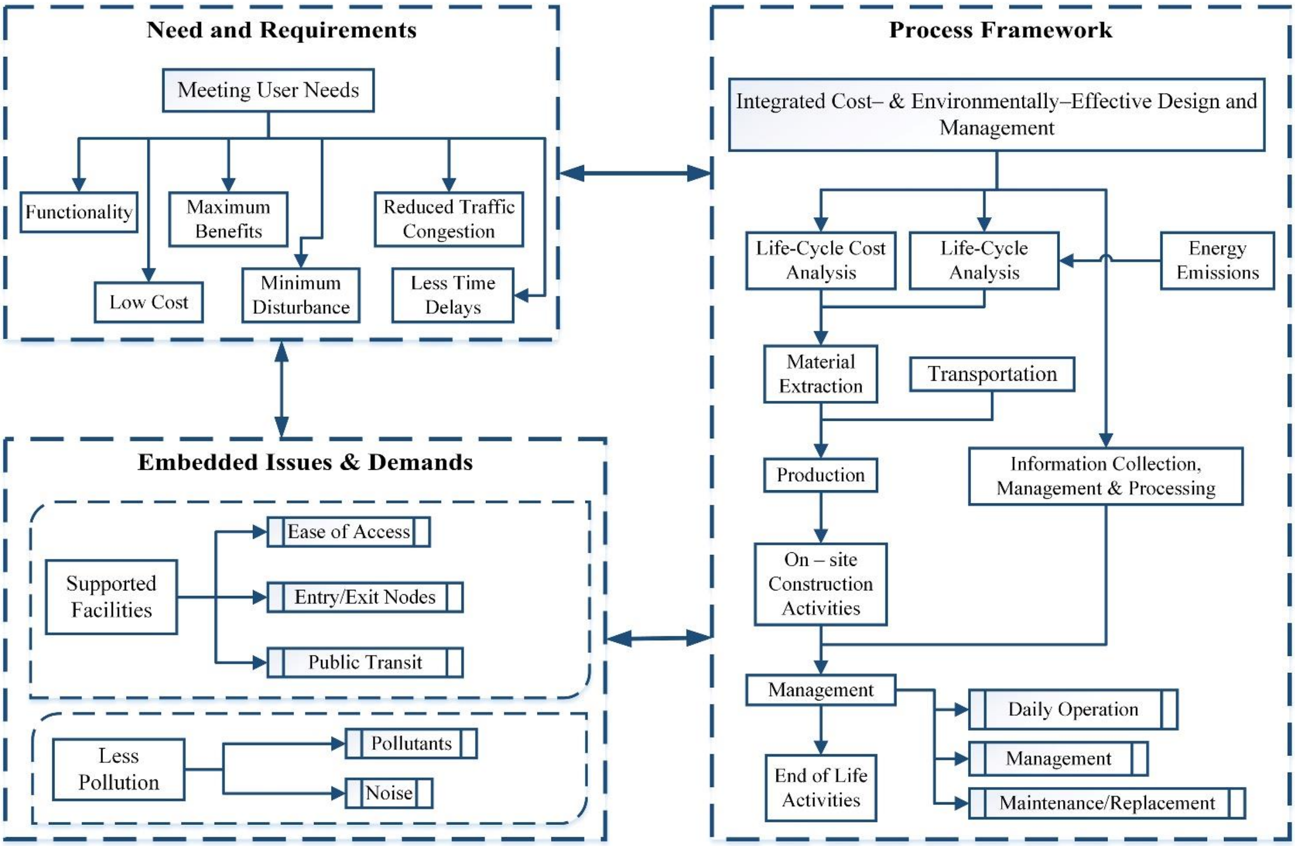

Figure 1 Schematic of processes in infrastructure design and management

Life-cycle assessment (LCA) is a known methodology for evaluating environmental impacts related to energy consumption, greenhouse gas and pollutant emissions of processes and products (ISO 14040, 2006). Any integrated design and management of a typical road network project generally considers three main subjects: identifying the main problem that requires an investment; the embedded hidden issues; and, the problem-solving process or methodology (Figure 1). The success of any road network project, therefore, depends upon the cumulative efficiency of these three primary components, to balance cost and environmental targets and (government) agency’s adherence to code and standards’ legislation.

Integration of the two road infrastructure design and management assessment approaches, LCCA and LCA, and the direction of respective cost and environmental burdens alongside the effect of *vehicle-surface interactions* on fuel consumption and wear and tear of tyres during the usage stage of a pavement require acknowledgement within an analysis framework. It is also essential for government authority decision-makers to consider all design and management aspects, such as; traffic congestion; cost and environmental risks; road ownership and user costs; vehicle operation and ownership cost; currency fluctuations; and, environmental loads during a whole-life of the road asset. However, researcher projects tend to be limited in the number of aspects and scope of the life-cycle stages considered (AzariJafari et al., 2016).

The purpose of the current study is to provide a state-of-the-art review and analysis of the existing literature in the wider field of LCCA and LCA of road network projects to highlight the *critical aspects*, identify the *hotspots* in current processes which can be improved upon to increase the robustness of the frameworks and facilitate the government authority and private planning/consulting stakeholders to *achieve whole-life cost and overall sustainability goals*. Once the critical aspects are identified for achieving overall system sustainability of road and transport projects; the energy, human capital and other resources can optimised to reduce excessive environmental burdens towards cleaner production of road network projects. Literature review *methodology* adopted here consists of collecting peer-reviewed research papers published in the last decade, after 2008 (through Google Scholar and ScienceDirect databases), to review the latest research work conducted on life-cycle management of road network projects. The adopted methodology is roughly based on Guo et al. (2018), expanded to include the most recent and definitive research published on road networks elements; inclusive of pavements, highway (roadside) components and bridges to capture the wider extent of the transport and road research field.

The articles were filtered based on the road elements and life-cycle stages addressed relative to respective cost, pollutants and energy consumption across large-scale projects comparing critical indicators, scope, and framework of peer-reviewed studies to uncover findings that may improve the cost and environmental performance of these road assets. Two sub-stages in the processing stage, LCCA and LCA of individual studies are discussed in context of stakeholder needs, the embedded issues in the study system boundary, and the frameworks proposed for problem solution. This is a significant contribution of the current study as it addresses the three (cost, environmental and social) sustainability issues of road network assets to cover the extent of perceived process problems in management of road network projects.

The main purpose of this paper is to review the state of existing literature and identify the critical processes and stages for effective asset management and life-cycle assessment of road network projects towards overall cost, social and environmental sustainability. Researchers have performed individual extensive reviews of studies on the use of recycled materials (Anthonissen et al., 2016; Balaguera et al., 2018; Gautam et al., 2018) in road projects, attributes for life-cycle costs (Babashamsi et al., 2016), LCA as a project procurement and planning tool (Butt et al., 2015; AzariJafari et al., 2016), significance of traffic/transit load and patterns in the overall life-cycle impact of road networks (Inyim et al., 2016) and the social and policy concerns (Santos et al., 2010; Jiang et al., 2017). On the other hand, studies on quantifying/minimising the environmental burden, e.g., particulate matter pollutants (Pant and Harrison, 2013) and fuel consumed by the traffic (Rahman et al., 2017) were reviewed by other researchers. This paper further develops on the findings of these studies to propose cleaner production of road networks as a policy issue; highlight the significance of life-cycle environmental and socio-economic burden from the vehicles and the use of recycled materials to promote sustainable development. It also presents an overall picture of the energy, cost and resource inflows and outflows across the whole-life of road networks in addition to the critical attributes, data resources for life-cycle analyses, common mitigation, recycling and mixing strategies utilised and standards of practices.

2. Process Framework: LCCA in road network projects

Researchers considering the practical application of LCCA for the design and rehabilitation of road and infrastructure projects, such as Zimmerman et al. (2010) defined this whole-cost application as an evaluation of all anticipated costs incurring during the desired service-life of the asset so that different alternatives can be compared and assessed through equivalent parameters, and a feasible course of actions deduced.

2.1. Conceptual basis and stages in LCCA

The reliability of any LCCA-based (whole-cost) framework or model is influenced by the accuracy of the data collected as well as projection of any future costs that may occur in the considered life-cycle of the asset. The exact determination of future expenditures can often be uncertain due to market variables and risks such as recession and variations in the velocity of distant cash flows (Galí, 2015). Economists as well as asset managers, when accounting for alternate investments during the planning and design of an asset, often discount future costs after *n* years with a constant or variable discount rate to give a more realistic magnitude of the asset's operational, maintenance, user and social costs (including environmental costs) in terms of the present value "PV" (Goh and Yang, 2009). Equation (1) shows this relation for initial costs of C_{in} and costs C_t for a year t if the discount rate is i (American Standard for Testing of Materials (ASTM), 2015).

$$PV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}; \quad \text{for } C_t = C_o(1+e)^t; \qquad \text{Equation (1)}$$

LCCA results for any road design alternative are influenced by the fluctuations in the discount rate and may even be further influenced by local currency inflation and risks (Wu et al., 2017). Discount rates applied by the private agencies usually reflect risk-free annual return rate (akin to government treasury bonds), while public agencies base it on their cost of raising capital. An empirical rule of thumb (Equation (2)) provided by the Royal Institution of Chartered Surveyors acknowledges these factors and may be included in off-the-shelf packages or any LCCA spreadsheet developed for the analysing life-cycle costs occurring at various stages in a road project's life (Whyte, 2015a).

$$\text{Discount rate} = (\textit{Treasury bond return rate} - \textit{Inflation}) + \left[0.5 \times (\textit{Average equity return} - \textit{Treasury bond})\right] \qquad \text{Equation (2)}$$

Additionally, Equation (3) is used to determine the escalated rates in future.

$$A = PV\left\{\frac{\left[i(1+i)^n\right]}{\left[(1+i)^n - 1\right]}\right\} \qquad \text{Equation (3)}$$

$$C_l = C_{ac} + C_{en} + C_{ins} + C_{op} + C_m + C_{rn} - V_r \qquad \text{Equation (4)}$$

The life-cycle cost (C_l) of a road asset can, therefore, be given by Equation (3) (Whyte, 2015a); where: acquisition cost of materials and land is C_{ac}; C_{en} represents energy costs; construction and installation costs are C_{ins} and C_{op} is the asset operational and usage cost. Routine minor maintenance costs are C_m, C_{rn} is the renewal cost, and any salvage or residual value is represented by V_r. The costs are converted to present worth by using Equation (1). This means that the traditional inputs to any LCCA model are fixed, discrete values, discounted to equivalent units to produce preconceived results. The conversion or discounting of future expenditures to present value or worth is a procedure in which the results of a cost analysis over the long-term are uncertain when selecting the best alternative, solely based on an investment-return methodology.

Generally, the common elements of LCCA models developed for road project investment decisions tend to observe a multi-tier procedure (Figure 2), whereas the critical economic indicators are not generally prioritised. Input variables, such as initial costs, operation and occupancy costs, maintenance and repair costs, social and hidden costs, externalities and incomes, analysis period, end-of-life costs and compensation for inflation, depreciation of money with time are fixed, based upon past studies and traditional LCCA approaches (Wennström and Karlsson, 2016) to address cost optimisation problems of road maintenance and pavement design. The need for construction of new roads or rehabilitation of an existing pavement structure forms the basis on which the objectives of a functional product[1] are developed and the scope and boundary of the project are established. The life-cycle inventory data for the specific road design alternatives, i.e., available resources and manpower are assessed next to perform cost computations for the road projects.

[1] The term product used herein is intended to include both goods and services, and is also used in such context by the ISO 14040 guideline (ISO, 2006). A product system model, therefore, represents the processes involved during the entire life-cycle of a product, and respective inflows-outflows of capital, resources and energy.

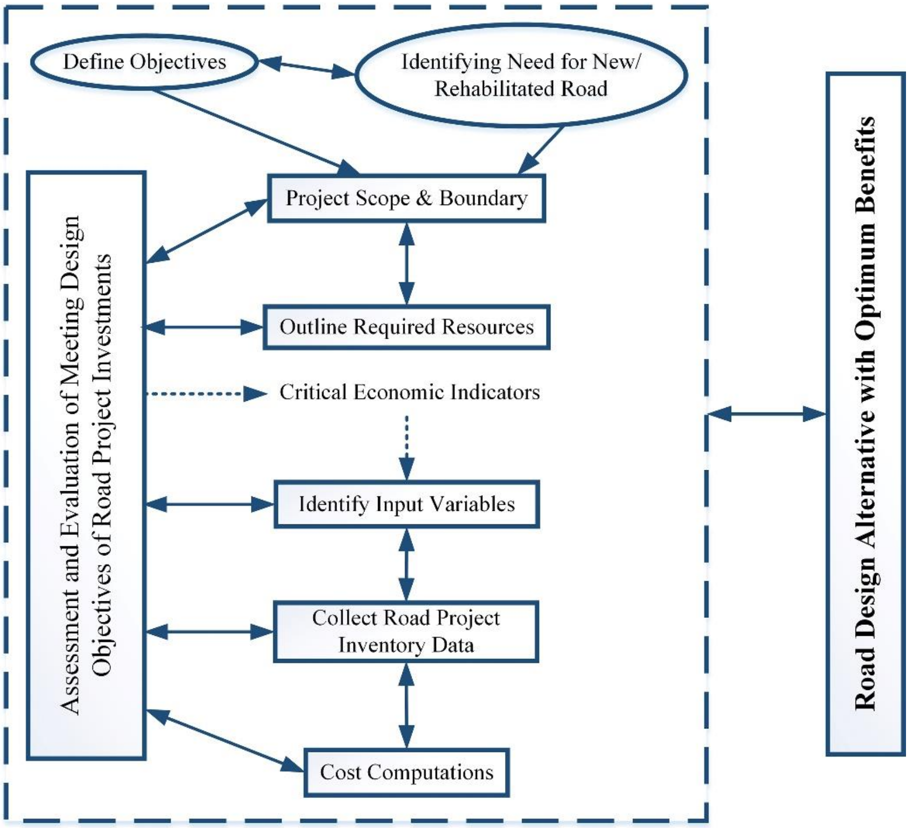

Figure 2 Stages in a conventional LCCA for investment decision-making on road projects

2.2. Cost aggregation: Future cash-flows

The inflows and outflows of resources and critical variables occurring during any of the several stages within a project's estimated life-cycle are synthesised in a database, and the costs for a practicable range of "fit-for-purpose" alternatives are calculated. Whilst costs to mitigate and address technical measures to find environmental compliances for noise and particulate matter are assessed generally, environmental benefit and energy inflows-outflows are reserved for LCA consideration (Section 3). After compensating for uncertainties and discounting cost, preferred fit-for-purpose alternatives are then categorised based upon cost, benefit and feasibility contributions. The alternative with the optimum benefits can then be deduced based upon the impact categorisation produced by the LCCA. It should be noted that LCCA does not yield a direct fixed alternative or prioritise the implemented option (Alqahtani and Whyte, 2013, 2016). Nonetheless, LCCA does aid decision-makers in assessing the need-cost-benefit paradigm for the road asset. The following text covers the recent state of the art studies conducted on the development of LCCA frameworks specifically targeted towards pavements, highways and bridge projects. The discussion below covers LCCA (whole-cost) application across various stages within the asset's life-cycle and the different frameworks proposed in the existing research literature.

2.3. Stakeholder expenses: Costs to users

The concept of getting the most benefits for the least amount of investment is not a novel idea within the domain of the road network projects. Researchers (Jingning, 2015; Mirza and Ali, 2017) have advocated the intermingling of LCCA-effective design and OM&R practices with those of value engineering to improve the decision-making paradigm. Further argument by Alqahtani and Whyte (2016) advocates for the calculation of indirect socio-economical, environmental and road-user indirect costs, such as: accessibility and comfort; accident and safety; time-delays; and, vehicle operational costs due to congestions, detours and work zone conditions. The road network user costs (Equation (4)) have to be added to the assets' life-cycle cost estimates, calculated based on Equation (3), for best estimation of the stakeholder expenses.

$$\text{User costs} = C_{\textit{time-delay costs}} + C_{\textit{vehicle opreration costs}} \qquad \text{Equation (5)}$$

2.4. Stakeholder expenses: Budgetary costs of road agencies

Due to the limitation of the funds available to many municipal agencies, private financing of public infrastructures provides an alternate option. However, in order to attract the private investors, the economic feasibility evaluation should address the involved uncertainties (both cost estimation- and performance-related) and risks (financial and payment, pre- and post-contractual and political risks) when evaluating the potential returns (Giang and Pheng, 2015), as direct correlation between risks and return exists. It is also noteworthy at this stage that the investment goals of private investors may not necessarily align with the political, publicity and administrative objectives of the government municipal authority; and, may be more inclined towards materialising a solid client retention and consumer market expansion.

One notable example, for road and transport projects, is the case of Public Transport Authority of Western Australia, where approximately 65% of public transit and road projects were approved by government stakeholders, despite projecting a negative net present value, a potential rejection marker for private investors (Whyte, 2015a). The government authorities seeking partnership with private investors may fail to convey their objective of maximum social benefits to the investors while campaigning for a higher initial cost for a later return, nonetheless user retention of road projects through expanding transit clients may be more comprehensible. This client or commuter attraction is probably achievable by passenger engagement and need identification so that the government or private capital can be best targeted towards providing services that, not only results in whole-life social benefits from the road and transit asset, but also expand clientele of the services provided by involving users in the decision-making process (Hasan et al., 2018a). Supplementary studies targeting this specific objective of identifying client needs (Hasan et al., 2018b) should, therefore, be performed prior to any design or life-cycle study to ensure the success of the project.

2.5. Maintenance and rehabilitation (M&R) costs

The application of an LCCA framework on M&R projects addressing deteriorating road network elements was explored in a study by Choi et al. (2015a) on highway M&R works. The authors collected extensive data containing 190,000 roadways datasets from the Texas Department of Transportation's pavement information management system regarding 39,000 highway sections and 103 influencing factors to perform regression and cluster analysis. The study noted sensitivity of LCCA analyses to cost indicators and traffic loading and underlying road network peculiarities. Mobility trends, i.e., mode choice of commuters (Hasan et al., 2018a), fluctuate over the road network life-cycle. In order for any transit system to act as a quality service providing platform to its consumers, the infrastructure that supports it must be well-maintained. Cost of maintaining the road network is dependent upon several factors attributed to its contributing elements; e.g., age and thickness of pavement, provision of highways and bridges (facilitating high-speed corridors), perceived traffic congestion during maintenance activities, temporal variations, political, administrative and investment objectives as well as average annual average daily traffic load.

2.6. Frameworks and critical parameters for LCCA

Researchers have long investigated pavements and other elements of a road network and adopted LCCA to compare design alternatives. However, these LCCA studies are somewhat diverse, and present an eclectic mix of parameters deemed critical for achieving cost optimisation when designing or maintaining the road network assets. The breadth of published literature is still lacking in succinct guidelines and indicator databases comparable across the different studies and so, towards the state of the art analyses presented here, Table 1 provides a summary of the key LCCA studies detailing multiple iterations and combinations for road networks projects towards system transparency and a mirroring of stakeholder objectives.

Table 1 Summary of commonly cited studies on LCCA of various elements of road network projects

	Issues addressed				**Cost parameters**						**Uncertainty**					**Time and traffic**			**Design parameters**					
Researchers	Traffic congestion	Cost-risk relation	Pollution	Added–value analysis	Initial cost	Ownership and OM&R	Political & administrative	Return rate & LoS	Future cash-flow	Hidden, social & user	Discount rate	Sensitivity analysis	Lack of past data	Standardised guidelines	Rate of inflation	LCCA time horizon	Longer useful life	Traffic load (AADT)	Thickness	Age and deterioration	Precipitation/freeze-thaw	Annual average temperature	Limited funds	Modular integrated systems
Chen and Ni (2018) **Maintenance & surface roughness: highways and roads**	₽	×	×	₽	✓	↑	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	✓	↑	×	×	↑	×
Lee et al. (2018) **Rehabilitation: highways**	₽	₽	×	×	✓	✓	×	×	₽	↑	✓	×	✓	✓	×	✓	✓	✓	✓	×	×	×	✓	×
Batouli et al. (2017) **Construction & extension: highway**	✓	×	✓	₽	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	₽	✓	₽	✓	✓	✓	×	×	✓	×
Celauro et al. (2017) **Construction & maintenance: roads**	×	×	✓	✓	✓	✓	×	×	✓	×	✓	×	×	×	₽	✓	×	×	✓	✓	×	×	✓	×
Trigaux et al. (2017) **Construction & maintenance: urban and suburban roads**	×	×	✓	✓	✓	✓	×	₽	✓	✓	✓	✓	×	×	✓	✓	✓	✓	₽	✓	×	×	₽	↑

Simões et al. (2017) **Micro-surfacing Preventive maintenance: roads**	×	×	✓	✓	✓	↑	✓	Ք	✓	✓	✓	×	×	×	✓	✓	✓	✓	✓	✓	×	✓	✓	×
Wu et al. (2017) **Preventative maintenance: pavements**	✓	✓	×	×	✓	✓	✓	×	Ք	✓	✓	✓	Ք	×	✓	✓	×	✓	✓	✓	×	×	×	×
Jannat and Tighe (2016) **Maintenance & rehabilitation: highway**	Ք	×	Ք	×	✓	✓	×	Ք	✓	×	✓	×	✓	✓	×	✓	✓	✓	✓	✓	×	×	✓	×
Wennström and Karlsson (2016) **Rehabilitation: pavement**	×	×	×	×	✓	✓	×	×	✓	✓	×	×	×	×	×	×	×	✓	×	×	×	×	×	×
Choi et al. (2015a) **Rehabilitation: highway**	×	×	×	×	×	×	×	×	×	×	×	✓	×	✓	×	×	✓	↑	×	↑	↑	↑	×	×
Han and Do (2015) **Maintenance simulation: highways**	Ք	✓	✓	✓	×	✓	↑	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	×	✓	×	×	✓	×
Qiao et al. (2015) **Maintenance and climate change cost: highways**	×	×	↑	×	✓	✓	✓	Ք	✓	✓	✓	✓	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×
Du et al. (2014) **Procurement: bridges**	×	×	✓	✓	Ք	×	×	×	×	×	×	✓	×	×	×	✓	✓	×	×	Ք	×	×	×	×
Goh and Yang (2014**)** **Sustainability cost: highways**	✓	×	✓	×	×	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	×	×	×	×	×
Mirzadeh et al. (2014) **Construction and rehabilitation: roads**	✓	✓	×	✓	✓	↑	✓	✓	✓	✓	Ք	✓	×	×	✓	✓	✓	✓	✓	Ք	×	×	Ք	×
Noori et al. (2014) **Reflective cracking mitigation: roads**	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	✓	✓	✓	✓	✓	×	×	×	×

Safi et al. (2014) **Procurement: bridge**	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Goh and Yang (2009) **Sustainability: roads**	✗	✗	✓	✗	✗	✓	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗

***<u>Key</u>*:** ✓ *= used/addressed,* Ꝑ *= partially addressed, needs further work,* ✗ *= Unaddressed/Needed,* ↑ *= recognised as the leading factor*

2.7. Summary and gaps from the reviewed Roads LCCA frameworks

Real world project-level analysis of the 18 studies cited above, finds adherence to numerous respective (varied) guidelines and industry norms from around the world, as key to an LCCA methodology for roads. For simplification of analysis complexity, it is suggested that any proposed LCCA framework should include prominent items from the key variable groups identified in the table above. The exact variable selection is dependent upon the complexity of project, expert appraisal, and severity of the required cost optimisation endeavours. Following these guidelines, detailed document analysis of the above published literature shows that:

- *Ownership and OM&R costs* form part of a cost parameter matrix in a majority of the essential roads' studies (~75%). The cost to acquire the road network asset on part of the municipal agency is critical for the decision-makers analysing completeness cost of the project, however, consistency in cost analysis needs to be maintained to include the OM&R cost, as a higher acquisition cost may be justifiable by a reduction in the future management and operation expenditure later.
- *Risks* associated with road network investments are explored in only three studies where they are the primary focus of the analysis. Capital investments are affected by several interdependent factors such as temporal variations, traffic growth patterns, fluctuations in discount rates and deterioration of pavement material which creates an inherent cost risk perceivable by decision-makers. Transparency of any applied LCCA framework is susceptible to an appropriate acknowledgement of the involved risks in the cost allotment to different project design alternatives.
- *Uncertainty and market fluctuations* were acknowledged in almost all (~80**%**) of the key road's whole cost studies. Recommendations made on the basis of a LCCA framework are not only susceptible to the adopted *discount rate* (acknowledged in ~70% of research) and *inflation rate* (considered in ~40%) of the analysis currency, but, also susceptible to uncertainty as a result of a lack of historical data or low "quality" data collected for analysis. On the other hand, an abundance of past data of construction and rehabilitation activities can present a variety of options to the decision-makers for any potential road network projects. Due to perceived misalignment between various government and public stakeholders on the best course of action, a general lack of trust and uncertainty on LCCA results is still noted to exist in real world projects.
- *User costs and hidden social costs* were generally addressed (60%), however, more emphasis was placed on agency-side costs of ownership and maintenance (75%). Nonetheless, user costs may be critical for future studies; recent work by Wennström and Karlsson (2016) attributed a majority of costs towards the road users as illustrated in Figure 3. Decisions to constrain the scope of analysed variable constructs to agency-side parameters may be attributed to a general lack of data at the various life-cycle stages of the asset under consideration.
- *Political and administrative issues cost* and *dollar-value (i.e., fiscal translation) of pollutant generation* (taking lead in only one study) need to be included in the LCCA framework as environmental sustainability

not only mirrors overall design objectives of embedded projects' needs, but also increase the robustness of the LCCA process. Partially inspired by the marginal monetary utility maximisation principles of economics, optimising the per-dollar value of road networks is an important parameter for municipal authorities, and so easily comprehensible by the general public. A dollar value of pollutants generated as a result of human activities (i.e., roads here) per tonne of greenhouse gases (GHG), human productivity lost and costs in recuperating from adverse health impacts affect the robustness of any LCCA framework and can greatly help to rank valuation of the different project alternatives.

- Implemented LCCA processes also need to be attentive to *future cash-flows, traffic load patterns, limited funds* available to the agency, *time horizon* of the analysis and cost associated with different aspects of each primary road network element. Constrained budgets and sustainability goals of municipal agencies necessitate the use of transparent frameworks accounting for cash-returns and dynamic traffic flows in addition to maintaining (limited) controls on mass mobility to achieve future-proofing.

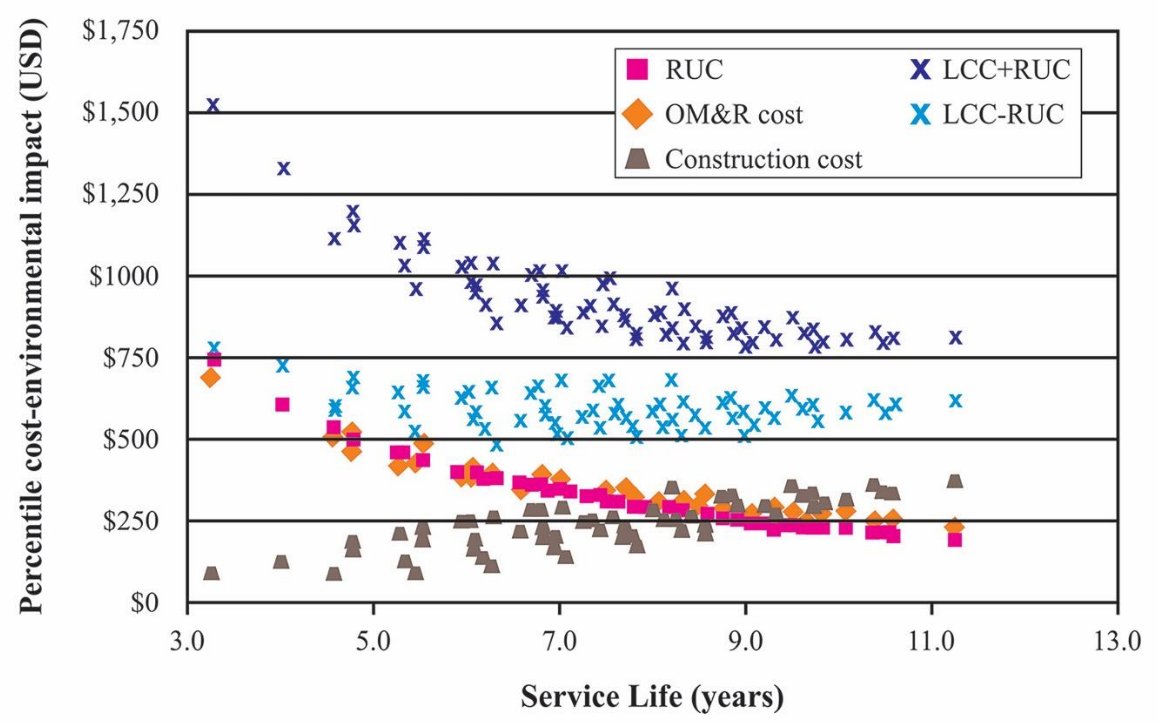

Figure 3 Percentile trade-off between cost-environment of road projects (adapted from Wennström and Karlsson (2016))

Generally, government authorities commissioning design and performing decisions on maintenance and operation of road assets need decision support tools throughout the assets' life-cycle to optimise the costs. LCCA considers all costs occurring during the effective project life, however, these costs need to be properly discounted to net present value and market fluctuations, uncertainties and risks should be acknowledged in project-specific LCCA models or spreadsheets developed to compare the cost components. These factors may also be significant when comparing the use of recycled materials (Hasan et al., 2016a) during any stage in the road assets' life-cycle, often motivated by environmental goals and reducing "eco-loading" of the construction activities. For example, Whyte (2015a) compared virgin materials (virgin limestone, hot/warm-mix asphalt) against recycled materials in a heavily trafficked Western Australia road. The general conclusions proposed more environmentally friendly options as slightly cheaper provided the application cannot be precluded by haulage. As these costs largely target the *ownership, operation, maintenance and rehabilitation costs* to the *government agency*; costs to road users in terms of direct vehicle operation cost, value of time lost in congestion around construction zones or under-capacity roads incapable of handling large traffic loads, not least the indirect impact on human health and environmental toxicity, need to be accounted for (further discussed in Section 3.4). Nonmonetary scores such as the environmental and social benefits may produce a larger difference between the virgin and recycled material options, often justified through LCA analysis tools.

3. Process Framework: LCA in road network projects

Life-cycle assessment (LCA), initially coined by SETAC in 1990 (Fava et al., 2014), is the methodological evaluation of environmental weightings of a product by systematic quantification of impacts such as resource consumption and depletion, eutrophication, climate change, ozone depletion, noise pollution and other direct and indirect implications of human activities on the ecosystem (ISO 14040, 2006; SAIC, 2006; Svoboda, 2006) generated over the entire life-cycle; or "cradle to cradle/grave".

3.1. Conceptual basis and phases in life-cycle assessments:

The conceptual basis for LCAs has been developed over decades with the I/O evaluation of net energy analysis and then assessing production processes both directly and indirectly responsible for generation of energy and waste emissions (Green and Lepkowski, 2006). LCA adopts a life-cycle perspective to quantify the resource and energy consumption and wastes (e.g., GHG) emitted in the environment, which increases interest in developing an LCA-based framework for built assets (Sharma et al., 2011). The process framework largely based upon SETAC and ISO 14040 asserts that the sustainability assessment of a product must acknowledge impact across three dimensions; economic, environmental and social. Four distinctive systematic phases of an iterative LCA approach are: outlining goal and scope, compilation of life-cycle inventory (LCI), life-cycle impact assessment (LCIA) and the last phase of interpretation.

Goal and scope outlining involves the identification and report of the extent of a product system including the processes expected later in its life-cycle. A familiar feature of this phase in the description of a functional unit[2], system boundaries[3], categories of impact (e.g., social, economic and environmental) and alternative scenarios. *LCI compilation* is the tabulation and quantification of the collected information regarding the energy

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[2] As defined by ISO 14040, "A functional unit is a measure of the performance of the functional outputs of the product system", and may use quantification of materials or the service provided, e.g., a roadway is intended for transportation of people and goods and may have extended sub-functions of providing less congested, quicker, smoother and easier transportation depending upon its design.

[3] Recommended cut-off criteria for constraining the elements to be modelled for representation of a product system, based on energy/resources, and environmental impacts.

and resource exchanges (inflows-outflows) with the environment and waste emissions over the project's life in a product system (Whyte, 2015b). After the compilation, the *LCIA phase* involves conversion of inventory into systematic estimates of environmental impacts weighted and evaluated based upon analytical indicators. The last phase of *interpretation* is actually an iterative process in practice, in the sense that it follows and precedes the three other LCA phases after every consecutive iteration of the assessment process. Even though the primary focus of LCA is to provide analysts with quantitative data on environmental impacts associated with the processes upstream, decision-makers are often encouraged to conclude recommendations based upon LCIA and inventory data in conjunction with the sub-functions and impact categories and not just the magnitude of the energy/resource flow and waste generation.

3.2. Data collection, data quality check, material control and product declarations

One of the primary challenges in real-world application of any LCA methodology is defining the scope, source and quality of the LCIA inventory data that needs to be collected for identifying the environmental burden generated across the different stages of a road network asset. Industrial confidentiality related to upstream case-specific historical data and the cost of gathering high quality and detailed LCA data for a construction project (Treloar et al., 2004) may be challenging for any road agency in applying LCA for decision-making process. On the other hand, uncertainties in the collected LCIA data may be detrimental to the calculated environmental performance of the different alternatives for the road asset case study being analysed by the road management agency. These issues with data collection, quality check and system boundaries were further highlighted by Yu et al. (2018). They note that as the existing pavement LCA studies rely on different energy intensity values data resources to calculate the energy consumption associated with concrete and/or asphalt pavement production, the estimated values may lead to fluctuations. Moreover, scarcity of certain construction materials and local resource depletion concerns in a case study region, transportation distance, mixing techniques, equipment and heating etc., may also influence the corresponding calculations.

Such issues, identified prior to conduction of an LCA study increases the stakeholder confidence and ensures adequate decision-making process for best road alternative selection. Primary data sources should be used where possible and missing data may be complimented by secondary resources from peer-reviewed literature as prevalent in the research on road materials (e.g., Moretti et al. (2017)). The system boundary, including selection of road life-cycle stages, may be based upon the standardised performance data sheets such as environmental product declaration standards. Environmental product declarations (EPDs) are international third-party verified standardised (ISO 14025, 2006; CEN EN 15804, 2013; ISO 21930, 2017) data sheets for the environmental performance of different impact categories regulated by product category rules (PCRs); i.e.; climate change (global warming potential) value, ozone depletion value and acidification potential etc.; of the road alternatives. In a standardised LCA methodology, the government road management agency defines the PCRs *prior to* conduction of an LCA. Studies such as Baker et al. (2016) have used Type III, i.e., product-specific, EPDs to define LCA boundary report the LCA study results.

3.3. *Construction material selection: LCA approach in pre-construction stages*

The traditional aim behind conducting LCAs is to improve the overall performance of a product in terms of environmental impacts, and as such an earlier estimate in design and construction procurement procedures may produce benefit. Pavements, highways and bridges form a critical portion of the road networks. Therefore, they account for a significant part of energy/resource consumptions, emission of GHGs such as CO_2, CO, NO_x, O_3 and black carbon and other volatile organic compounds generated by the road network projects. Fuglestvedt et al. (2008) have observed that the global radiative forcing corresponding to the pavements alone for the year 2000 were 150 mW/m^2 and since industrial times, road networks may have accounted for approximately 31% and 15% of the total ozone and carbon dioxide forces due to human activities, from material extraction and production stages to the final salvage or reuse. Figure 4 below, highlights some of the key energy burden work. Biswas (2014) in his study comparing the use of recycled materials against virgin materials in roadway construction in Australia, found that 180.6 tonnes of CDE and 10.67 TJ energy was consumed during an urban pavement's life-cycle, while Choi et al. (2015b) found 4390.774 tonnes CDE for a JRCP pavement consuming 49.8 TJ energy.

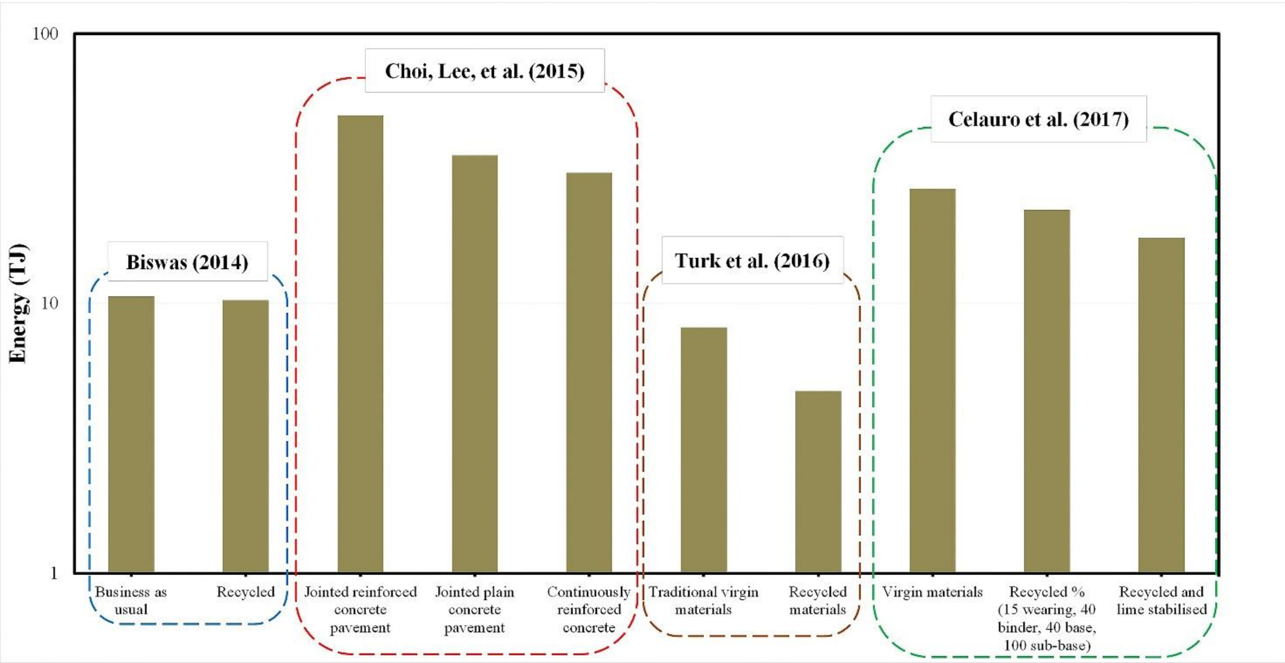

Figure 4 Life-cycle energy burdens of roadways (log scale)

Figure 4 and Figure 5 incorporate a recent study by Turk et al. (2016) which found the use of recycled material as a decreasing factor in energy consumption (by 3.4 TJ) and global warming potential (by 20 tonnes of CDE). The potential is further realised in the later study by Celauro et al. (2017), where different options with a gradually increased replacement of virgin materials by the recycled options demonstrated improved performance in energy usage (Figure 4) and carbon load (Figure 5) categories.

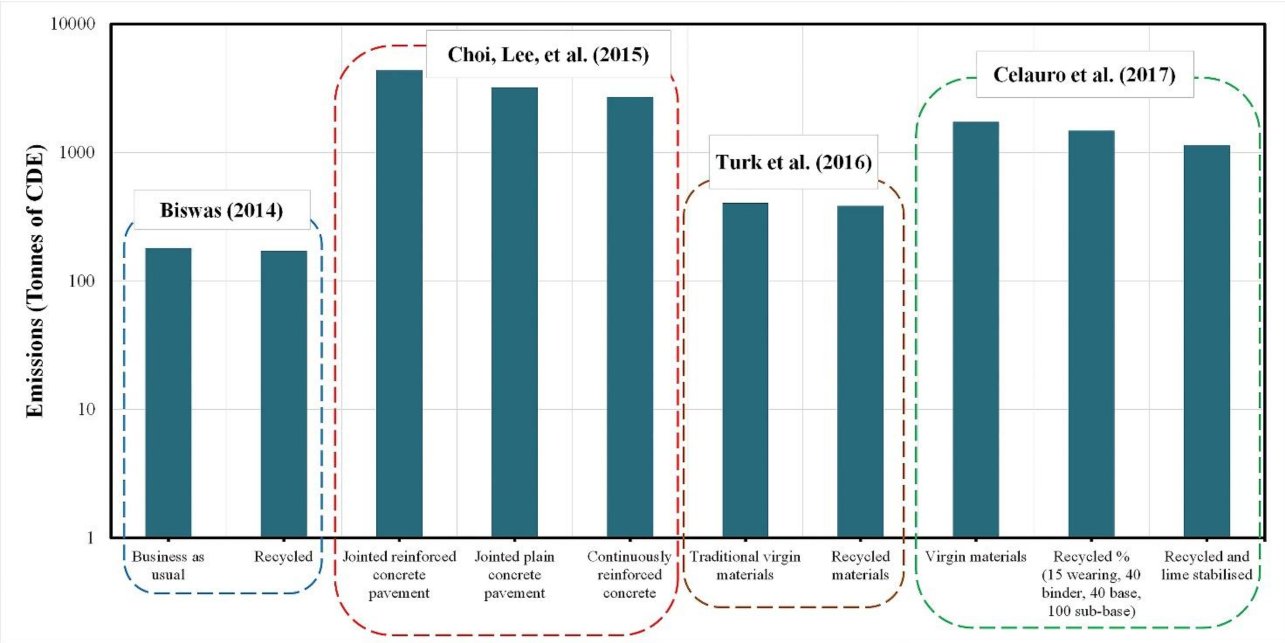

Figure 5 Life-cycle global warming potential of roadway (log scale)

3.4. Applying LCA in construction, usage, maintenance and rehabilitation stages emissions

Past trends in developed countries such as the United States have exhibited around 17% increase (EPA, 2016) in transportation sector GHG emissions in the year 2014 compared to the 1990 appraisals. The EPA (2016) study found the transportation sector as the second highest polluter in the USA. Similar results have been estimated for developing countries (Sadri et al., 2014; Dang and Sui Pheng, 2015) as well as G8 and European countries (Andersen et al., 2013). The operation of road networks and respective fossil fuel consumption costs escalate the financial and environmental impacts from the relatively lower early stage burdens, making roads a hot topic in green infrastructure initiatives. Several factors contribute to the energy consumption and waste emissions associated with the operation of road networks.

Usage stage impacts to road users and mass mobility implications of any early stage decisions as well as the larger system-wide effects, critical to end-consumers, need to be addressed. This aspect is specifically significant for the real-world success of any LCA-based endeavour for high traffic volume roads as the construction and OM&R activities have been noted to account for less than 5% of the consumed energy during the whole-life of a road network, whereas the usage stage traffic volume can account for more than 95% (EAPA/Eurobitume, 2004; Araújo et al., 2014). The study by Araújo et al. (2014) on use of recycled materials in pavement construction, operation and maintenance noted that depending upon traffic volume, the GHG emissions due to traffic operating on the roads are 1000 times larger, with energy consumption 700 times higher, during usage stage compared to the construction stage. This alone intensifies the importance of accounting for the usage stage in LCAs. However, it should be noted that this dominance of usage stage impacts in the LCA results is influenced by the traffic volumes supported by the road. For example, in the study by Santos et al. (2015) comparing low (AADT ~ 300) and high (AADT ~ 2000) traffic volumes, usage stage only accounted for 10-21% of the emissions, whereas material choice and construction methodology dominated the life-cycle impacts of the studied pavements.

In addition, in-place recycling of pavement material may further increase the environmental benefits during construction and rehabilitation stages. Turk et al. (2016) have found that cold in-place recycling can reduce the acidification load by 18% and energy consumption by 16% during pavement construction and maintenance on a high traffic (AADT ~ 2500) Slovenia road without significantly compromising on the service life. Recycling construction waste as road aggregates have gained popularity (Hasan, 2015). However, the mechanical properties and stability of roads constructed with recycled materials could be of concern to the different stakeholders because of its status as fit-for-purpose (Hasan et al., 2016b). The technical performance of using recycled materials as pavement base layer was analysed in another study on low traffic volume roads by Lopez-Uceda et al. (2018) with recycled pavement aggregates and Portland cement-fly ash binder mix. They found that the mixed recycled aggregate base exhibited 2.5 MPa tensile strength and 20 MPa compressive strength and may only be suitable for constructing roads with heavy vehicle AADT < 50. Moisture resistance, fatigue, rutting and stiffness of pavements constructed or rehabilitated with recycled materials was studied by Dinis-Almeida et al. (2016) and (Pasandín and Pérez, 2017). They found that even though recycled aggregates increase the absorptive behaviour (demanding more bitumen content), the mixtures exhibited adequate tensile strength, fatigue resistance and moisture resistant similar to the virgin material sample, even for warm-mix asphalt pavements. Furthermore, Miliutenko et al. (2013) note that hot in-place recycled can be applied for low-heavy traffic road types and showed additional 3 GJ equivalent/tonne and 0.02 tonne CDE of asphalt waste savings compared to in-plant recycling.

3.5. Frameworks and critical attributes for LCA

Researchers utilising different LCA frameworks have identified contributors like the construction material used, traffic volume and delays, quality of pavement or road design among others over the entire life-cycle of any road network project. Compared to the infancy of LCA and the uncertainties in its functional units, boundary and inventories, LCCA has been widely researched and, often, been a part of roadworks and pavement policy-making under various regulatory agency guidelines (Rangaraju et al., 2008). Integrating LCCA tools within the LCA toolbox can aid decision-makers further by assigning an economic perspective along the environmental context, bringing the question of resource and energy conservation into the picture of cost benefit, thus combining two dimensions of sustainability.

A review by AzariJafari et al. (2016) recognised the diversity of the alternates available to the decision-makers assessing investment incentives from pavement projects. Inconsistency of LCA frameworks, applied across several components of the larger transit system as well as different stages of the pavements themselves were noted. However, an integrated LCA modelling approach to handle the broader life-span of the projects can still yield value-added future-proofing results. Reviews are often specifically aimed at addressing research challenges, with less emphasis on the real-world case studies; yet, this state-of-the-art review notes that work completed highlights the inconsistent selection of functional units and life-cycle stages in different research as among the primary challenges for future wider research or any eventual industry application. Sensitivity of LCA recommendations to the material choices and construction strategies, environmental burdens arising later in the road project's life-cycle (e.g., lighting requirements, carbonation and albedo) were also credited to the type of material used during construction and rehabilitation. Depending upon the system boundary definition, noise is also sometimes included among the environmental burdens (Sánchez et al., 2018). Conversely, other researchers (Oltean-Dumbrava et al., 2013) have instead included in road LCA studies as part of the social indicators.

Furthermore, the source and quality of LCA data (as well as the consistency, transparency and flexibility of applying the LCA recommendations to different design alternatives for diversified road network projects) may also influence the adoption rate of the LCA frameworks by the decision-makers. Table 2 below summarises this work's LCA roads secondary research and provides key variables' weightings thus far.

Table 2 Scope and methodology of selected LCA-based studies on road network projects

Study reference	Roadway element typology	Functional unit	System boundary	Scenarios analysed	LCI database and resources
Moretti et al. (2018)	Asphalt concrete road	3.75 m wide dual lane, 1 m × 4 m cross-section, 1.5 m wide shoulders	- Raw material extraction - Production and processing - Construction	**Trench *vs.* embankment** road sections. **30-100 km** transportation **distances**.	- *Material transportation:* European Commission (2012) and European Commission (2014). - *Asphalt concrete production:* Moretti et al. (2017). - *Cement production:* Associazione Italiana Tecnico Economica Cemento (2016). - *Bitumen and fuel:* Eurobitume (2011). - *Aggregates:* Officina dell'Ambiente (2013) and Union Nationale des Producteurs de Granulats (2012).
Bloom et al. (2017)	Urban highway re-construction	2.4 km	- Raw material extraction - Production and processing - Construction	**Recycled** materials: concrete aggregates; asphalt pavement (base course and hot-mix asphalt); asphalt shingles (**partially replacing binder**); blast furnace slag and fly ash (**partially replacing Portland cement**).	- *Quantity take-offs:* Local agencies and design plans. - *Environmental impacts:* Compared outputs from two emissions modelling software; PaLATE (option 1) and SimaPro (option 2).
Celauro et al. (2017)	Asphalt pavement (urban road)	1 km, single carriageway. 30 years analysis period	- Production and processing - Construction - Maintenance and rehabilitation	Five scenarios **varying**: **virgin**, **recycled *and* lime stabilised** materials. Maintenance plans: **repaving wearing** course ***vs.*** maintenance of **all courses**.	- *Unit materials:* Regional Council Office for Infrastructure and Mobility (2013). - *Emissions calculation:* Local resources and PaLATE.
Chen et al. (2017)	Cement and asphalt roads	No specifically defined	- Raw material extraction - Production and processing - Construction	Low to high volume traffic roads	- *Minerals, aggregate and asphalt GHG emissions:* Zhang and Liu (2015) and Wang and Wei (2015). - *GHG factors:* Regional data and Zhao et al. (2016)
Karlsson et al. (2017)	Urban road re-construction	7.5 km 3-lane road	- Construction - Maintenance and rehabilitation	Two alternatives: **reconstruction** of **entire road *vs.*** only **reconstructing end** and **start**.	- *GHG emissions and energy use:* Goedkoop et al. (2009), Lundberg et al. (2013) and Toller et al. (2014). - *Material and other environmental factors:* Stripple (2001) and other local resources.

Butt and Birgisson (2016)	Asphalt road (theoretical cases)	1 km, 3.5m lane construction and maintenance (after 15 years). 25 years life span	- Production and processing - Construction - Maintenance and rehabilitation	Four scenarios: **Two unmodified asphalt mix aggregates *vs.* adding warm mix asphalt**.	- *GHG emissions:* Local resources, EAPA/Eurobitume (2004) and Klöpffer (2006). - *Energy consumption:* ECRPD (2010), Sheehan et al. (1998) and Stripple (2001).
Butt et al. (2016)	Asphalt road	1 km, 3.5 m wide. 1 km, 4 m wide. 20 years design life	- Raw material extraction - Production and processing - Construction	Two case studies with different pavement cross-sections.	- *Asphalt production energy use:* Local contractors. - *Fuel, electricity mix and other material consumption data:* Stripple (2001).
Turk et al. (2016)	Regional asphalt concrete road	40,000 sq. m pavement rehabilitation (20 years design life) of road serving 2500 AADT	Rehabilitation activity encompassing; - Raw material extraction - Production and processing - Construction	Traditional **virgin materials *vs.* recycled** (stabilised asphalt concrete) materials.	- *Fossil fuel, asphalt binder, virgin aggregates, recycled stabiliser and material transport:* GaBi 4.0 database. - *Portland cement dataset:* Josa et al. (2004), EPD (2012), EPD (2015) and Ammenberg et al. (2015). - *Asphalt mix production:* Mladenovič et al. (2015).
Anastasiou et al. (2015)	Urban concrete pavement with asphalt overlay	7.3 wide dual lane low traffic 1 km road and 40 years' service life	- Raw material extraction - Production and processing - Construction - Maintenance and rehabilitation - End-of-life	Various scenarios comparing different percentages of recycled and virgin materials.	- *Material consumption:* Marceau et al. (2007) and Eurobitume (2011). - *Greenhouse gas emissions:* IPCC (2008)
Choi et al. (2015b)	Rigid highway pavement rehabilitation	1 km long & 14.8 m wide. 50 years life span	- Production and processing - Construction - Maintenance and rehabilitation - End-of-life	Compared pavement types; **continuously reinforced concrete** (30 years' service) ***vs.* jointed plain concrete** (20 years' service) ***vs.* jointed reinforced concrete** (15 years' service).	- Unit cost data collected and miscellaneous data sources through Carnegie Mellon University (2011).
Santos et al. (2015)	Typical Portuguese flexible pavement	1 km of 4 main (3.75 m) lanes & outer, inner shoulders (3 m, 1.5 m). 40 years analysis period	- Raw material extraction - Production and processing - Construction - Maintenance and rehabilitation - Operation and usage - End-of-life	**Two** classes of **AADT**, **16** types of **hot-mix asphalt** and **asphalt concrete** pavement structures and the **3 foundation types** from the Portuguese pavement design catalogue.	- *Electricity, coal and crude oil:* Dones et al. (2007). - *On-road vehicles, construction equipment and material transport:* EEA (2009). - *Production of HMA:* US EPA (2004). - *Aggregates:* Jullien et al. (2012). - *Bitumen and bituminous emulsion:* Eurobitume (2011).

Biswas (2014)	Asphalt road	100 m, over 100 years	- Raw material extraction - Production and processing - Construction - Maintenance and rehabilitation	**Virgin materials *vs.* recycled** (only as: concrete rubble for base, crushed limestone sub-base and recycled asphalt wearing course).	- *Limestone and hot-mix bitumen:* Whyte (2015b). - *Equipment and energy data:* RMIT (2007) database. - *Recycled concrete and crushed rock base:* Mitchell (2012) and RMCG (2010).
Du et al. (2014)	Bridge procurement	Whole bridge (dimensions based on scenarios) over 100 years life	- Raw material extraction - Production and processing - Construction - End-of-life	Five bridge design options.	- *Material and quantity data:* local contractors. - *Environmental inventory data:* From Ecoinvent v2.2 public database for the local conditions.
Yu and Lu (2014)	Overlay pavement section	10 km, 4 lanes	- Pavement albedo during operation and usage	**Portland cement concrete *vs.* hot-mix asphalt overlays**.	- Based on empirical relations proposed by Bird et al. (2008), Muñoz et al. (2010) and Susca (2012).
Yu and Lu (2012)	Rehabilitation of Portland cement concrete pavement	1 km overlay. 40 year service life	- Raw material extraction - Production and processing - Construction - Operation and usage - End-of-life	**Hot-mix asphalt *vs.* Portland cement concrete *vs.* crack seat overlays**.	- *Material consumption:* Marceau et al. (2007), Stripple (2001) and Meil (2006). - *Transportation of materials:* Wang (2011). - *Construction equipment*: EPA NONROAD 2008 model. - *Fuel consumption:* EPA (2005) and Amos (2006).
Wang et al. (2012)	Rehabilitation of rural road segments	Not explicitly defined as compared rolling resistance effect for different case studies	- Raw material extraction - Production and processing - Construction - Operation and usage	**34,000 AADT** (2-lanes) ***vs.* 3,200 AADT** (4-lanes) **asphalt** roads ***with* capital preventive maintenance** strategies; ***vs.* 86,000 AADT** (2-lanes) ***vs.* 11,200 AADT** (2-lanes) **concrete** roads ***with* concrete pavement restoration.**	- *Cements, aggregates and concrete:* Stripple (2001), Meil (2006), Dones et al. (2007) & Marceau et al. (2007). - *HMA and rubberised hot-mix asphalt:* Stripple (2001) and Meil (2006) and USLCI database by NREL (2011). - *Oil manufacturing and feedstock:* Dones et al. (2007).
Cass and Mukherjee (2011)	Highway concrete pavement rehabilitation	Per lane mile of CO_2 equivalent	- Equipment manufacture - Raw material extraction - Production and processing - Construction	Two modelling approaches; **with *and* without SimaPro** in the emissions calculations.	- *Material and equipment inventories:* Field data using Info Tech. Inc.'s Field Manager® software. - *Emissions:* SimaPro 7 and e-Calc emissions calculator.
Lee et al. (2010)	Asphalt highway road surface	4.7 km long section	- Raw material extraction - Production and processing - Construction	**Traditional** *AASHTO* pavement design ***vs.* recycled** (foundry sand subbase, fly ash stabilised pavement material base).	- *Emissions and inventory:* PaLATE and EPA (2009). - FHWA's RealCost v2.5 for cost calculation.

The potential for uptake of a (newly) developed LCA framework based upon the real world studies tabulated above (Table 2) is particularly important for advocating the practicable usage of sustainable approaches such as the use of recycled materials for construction and maintenance of road network projects. Research has shown that utilising recycled and waste material for road construction reduces environmental impacts, landfill pressure and extraction costs but that, negative perception by stakeholders, regarding poor performance of such materials and high cost, hinder large-scale practical application (Huang et al., 2007). The critical review study by Wang et al. (2018) attempted to provide extensive coverage and summary of significant findings in the current recycling technologies for road network projects. Several of the tabulated authors above claim that the recycled material inclusion during construction and maintenance activities remains promising for reducing energy load and GHG emissions compared to use of virgin materials.

Leachate generated from constructed road base using recycled techniques and feedstock energies were minimal when paralleled with overall life-cycle benefits. However, recycling techniques such as terminal blend, dry and wet rubberised and recycled asphalt mixing; and, use of slag and fly ash as pavement stabilisers were often deemed critical to meet the cost and environmental goals of municipal authorities. In addition, the cost performance and variation in the environmental impacts from use of recycled materials during the entire life-cycle, particularly the usage stage need to be identified. More studies based on real-world data and problem handling for actual road network and transit system projects are helpful for government and public stakeholders to correctly visualise the benefits of recycled materials. Necessarily, it raises the question of accurately comparing the various mixing techniques, materials, recycling ratios and construction strategies across different alternatives.

This state-of-the-art analysis of past research via the document-analysis, secondary research approach presented goes towards developing a LCCA/LCA framework to aid the decision-making process. The selected pool of key literature has been reviewed in Table 2 to reflect the critical aspects of LCA methodology, use of recycled and alternate materials and establishment of LCA inventories. The crucial recycling techniques and data resources that may be useful to any future studies or industry applications are summarised in the above table. Comparison of functional units and system boundaries complimented by the required datasets is also provided to aid the decision-makers, project planners and managers and various public and private actors interested in the sustainable design and management of road networks.

3.6. Summary and gaps from the reviewed LCA frameworks

The studies presented in Table 2 attempted to analyse the (cost and) environmental load reduction performance of the strategies adopted by the local authorities for the construction and management of road networks. For the application of any LCA frameworks in road network projects, specifically to move further towards real-world use, the following paragraphs aim to recapitulate the current state of research and provide suggestions.

- A general *lack of dynamic user traffic patterns* and *"consumer" impact assessment* are argued here to represent serious constraints to future application(s) of LCA frameworks. Likewise, very few research papers attempted to *integrate the system-wide impacts* across all the life-cycle stages, which is argued here as needed due to the considerably long-term usability of road networks. Unless proper integration can be achieved in the framework and reasoning behind indicator, functional unit and system boundary selection, becomes more transparent, LCA recommendations of project alternatives remain open to subjective interpretation which can deter uptake.
- *Selective analysis* of life-cycle stages occurred inherently in a majority of studies albeit *only one study* (Santos et al., 2015) considered feedback loops, energy and GHG feeds from the entire road life-cycle. Recycling or end-of-life was the second most neglected stage; only *three studies* included environmental load from this stage. Frequent maintenance and rehabilitation schedules of the deteriorating road surfaces was addressed by *four studies*, while extraction of raw materials was added to the framework parameters in *nine studies*. Production and processing benefits of recycled against virgin materials were examined in *eleven studies* and construction stage(s) was considered by all of the studies except the pavement albedo study where it was out of the research scope. Nowadays, real-world scenario representations and improvements of stakeholder confidence in LCA frameworks, require that parameters from all stages of the road network life-cycle are needed to capture the magnitude of cost and environmental benefits of recycling.
- *For comprehensive LCA framework* considering all stages (Santos et al., 2015), a majority of the data was either assumed based on existing literature or calculated from an amalgamation of regional and foreign unit costs, emissions and energy feed datasets. Regarding the foreign datasets, significant research is available along with calculators from European and US-based resources, which may be applicable to other regions. However, this may produce methodological challenge in the applicability and sensitivity of results.
- *Shortages of local and actual case and region-specific data resources for some regions around the world* hinder the application of LCA frameworks in both research and industry projects as majority of the existing datasets and life-cycle frameworks are developed from US and European case studies and the difference between the system advancements, production/construction laws, norms and regulations and technical process are varied between regions (Santos et al., 2017). However, this may be resolved by collecting local LCI resources and comparing the data flexibility of existing studies for missing datasets to deduce how they (in isolation or collectively) can be applied to handle the missing data.
- *Asphalt recyclability* is arguably one of the most significant findings of most studies leading to loss of stored feedstock energy with wear and tear. Repaving or on-site recycling of asphalt rephrases

the asphalt vs. concrete recyclability archetype analysis due to the difference in perceived usability as sub-base for the new road constructed over the completely deteriorated structure.

- *Energy feeds, cost and emissions from transferal waste resources* such as blast furnace slag and fly ash to partially replace cement binders in concrete or asphalt-concrete pavements are argued here as key aspects. Some researchers (Silva et al., 2015; Hoy et al., 2017) suggest that recycling and reuse of materials may result in some strength loss due to aging, such that extracted recycled materials required to be stabilised by industrial wastes (Hasan et al., 2015). It is argued here that any future developed LCA frameworks should acknowledge positive mapping of transferred waste reuse credits, and require explicit recognition that recycling waste outputs divert away from landfilling sites.

3.7. Normalisation and weighting for LCA interpretation

Due to the diversity in material choices available for road construction, ranging from virgin materials (asphalt and concrete), mixing technique (hot, warm and cold); several environmental impacts of varying magnitudes and units are generated across the different life-cycle stages. For example, climate change is generally expressed as "kg CO_2 equivalent", whereas acidification is expressed as "kg SO_2 equivalent" and normalisation provides a common reference point (Stranddorf et al., 2005) for planners. The normalisation values that are used for interpreting the LCIA results for the different geographical regions around the world are presented in Table 3, as a concise reference point for future works. The values and units are based upon the data from the updated ReCiPe model.

Table 3 Annual normalisation factors for some environmental impact categories (adapted from Bengtsson and Howard (2010) and Huijbregts et al. (2017))

Environmental impact categories (unit)	**Normalisation Factors**		
	Global	**Europe**	**Australia**
Climate change (*kgCO_2 equivalent/year*)	3.36×10^{13}	4.49×10^{12}	6.21×10^{11}
Ozone depletion (*kg CFC-11 equivalent/year*)	2.29×10^{8}	1.02×10^{7}	4.17×10^{4}
Fossil fuel depletion (*kg of oil equivalent/year*)	7.84×10^{12}	7.23×10^{11}	-
Acidification (*kgSO_2 equivalent/year*)	2.56×10^{11}	1.79×10^{10}	2.67×10^{9}
Terrestrial eco-toxicity (*kg 1,4-DB equivalent/year*)	4.96×10^{10}	6.50×10^{9}	1.90×10^{9}
Freshwater eco-toxicity (*kg 1,4-DB equivalent/year*)	2.77×10^{10}	5.43×10^{9}	3.71×10^{9}
Marine eco-toxicity (*kg 1,4-DB equivalent/year*)	4.11×10^{12}	1.18×10^{12}	2.62×10^{14}

Human toxicity (*kg 1,4-DB equivalent/year*)	$8.83x10^{12}$	$2.08x10^{12}$	$6.96x10^{10}$
Eutrophication (*kg P equivalent/year*)	$1.76x10^{9}$	$1.93x10^{8}$	$1.39 x10^{8}$
Particulate matter (*kg PM equivalent/year*)	$8.55x10^{10}$	$6.93x10^{9}$	$9.82x10^{8}$
Photochemical oxidation (*kg NMVOC equivalent/year*)	$3.45x10^{11}$	$2.64x10^{10}$	$1.61x10^{9}$

It may be further argued that the current environmental objectives of the country may assess the environmental consequences of the construction decision differently due to perceived importance of each impact category and may prefer assigning scores or weightings, based on expert opinions. For example, some of the environmental categories occurring during the life-cycle stages of a road project are illustrated below in Figure 6 (Bengtsson et al., 2010). Compared to the normalisation factors, the weighting values are highly dependent upon the specific objectives of a regional agency, socio-demographics of the expert panel used for assigning the weighting values and the sampling size. In general, impact weighting generation and prioritisation uses the methods available for multi-criteria decision-making (MCDM) such as analytic hierarchy process (AHP) and fuzzy rankings.

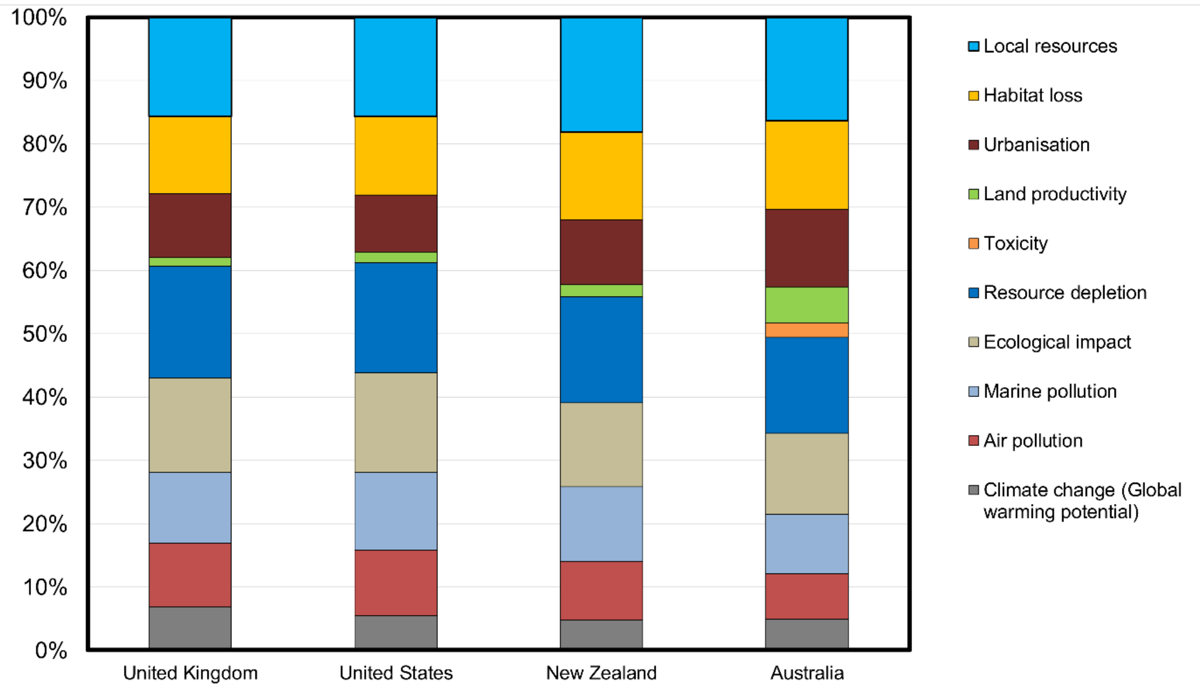

Figure 6 The average weighting factors for some of the life-cycle impact categories (adapted from Lippiatt (2007), Bengtsson et al. (2010) and Abbe and Hamilton (2017))

4. Requirements, needs and demands: summarising the social component

Growth in population inherently requires residents' mobility and accessibility within a city that is serviced by its extensive road networks. Traditionally these road networks are designed to facilitate rapid personal travel and are built around private automobile transit. For example, Chester et al. (2010) have stated that the infrastructure in most cities in the United States is centred on automobile travel. As urban road networks mature, agencies are forced to seek a trade-off between high maintenance of existing facilities versus road network expansion costs due to increased usage. Indeed Chester et al. (2010) further propose developing growth models based on historical data to highlight the transferal occurrences where investment focus of urban agencies shifts to maintaining existing road networks from constructing new and alternate strategies extrapolated from present usage. The limited maintenance funds of municipal agencies are stretched by the elevated road network deteriorations due to traffic congestion and pavement surface wear and tear. This inhibits the functionality, durability and ability of road networks as the maximum benefit provider to the users. Linear combinations of all cost and environmental components across the modules of the road network projects need to be balanced against the user mobility and benefit to commuters.

Transport agencies encourage modal shift towards public transport to reduce private automobile travel and increase the functionality and benefit-provision performance of road networks (Gray et al., 2016). In order to achieve this, the municipal transport agencies should focus upon perceiving transit as a competitive service that provides users with a quality service, supported by efficient road networks. Amirgholy et al. (2017) noted that, similar to any consumer product, a quality public transport service and supporting road network comes at high capital and environmental cost to the management public authority agency. Any future study on life-cycle management of road network projects must then evaluate the supported transit and related mobility modules as a marketing and consumer behavioural problem. In this way, a dynamic LCCA/LCA package integrating user needs, mobility trends, road network projects and mass-transit, can aggregate multi-level cost, energy and environmental flows. Thus not only will such a tool indicate increases in the functionality and user adoption of the project alternatives proposed by the municipal agencies, but also make the sustainable design and management of road network projects conceivable to the decision-makers, project planners and other stakeholders.

5. Conclusions and future research directions

Due to the limited capital funds available to municipal authorities and the higher effect of cost uncertainties on profit compared to environmental performance, the importance of cost parameters requires highlighting during decision-making. The diversity of initial cost optimisation literature in the earliest reported studies on road network project assessment is a testament to the relative importance of initial cost. Since the 1970s, whole-life approaches to optimise cost over the entire project life has been extensively discussed and several LCCA frameworks and attributes have been proposed.

This state of the art review paper summarised the existing literature attributes to overcome the issue of real-world adoption and subsequently links and consistency with the respective environmental analyses. National and international interest on reducing environmental burdens and energy input loads of construction projects has generated LCA tools as a knowledge quantification toolbox. LCA has been used in a number of road network projects to examine and enhance the cost and environmental future-proofing performance of design, operation, maintenance and recycling decisions. Due to this reason, both cost and environmental frameworks have been reviewed in this study recognising that in the future LCCA frameworks must be embedded in the more holistic LCA frameworks.

The current review study examined 36 (extensively) and 97 (supporting) life-cycle cost, and environmental articles, from peer-review journals targeting research on design, management and recycling of actual real-life road network assets. The findings show that:

1. The interest of stakeholders and researchers in "sustainable" road and transit has increased in recent years. However, a majority of studies were conducted in limited geographical contexts (USA and European) or constrained focus to only a few stages of the road network life-cycle. Regarding the cost component, several attributes have been proposed by research to achieve cost optimisation of road network projects through LCCA-based comparison of design alternatives (refer to Section 2.6).
2. User and embedded social costs of road network projects are significantly higher than the initial capital investments and should be given preference (Figure 3 results above). User adoption, dynamic traffic growth patterns, future cash-flows and user-accorded benefits should be targeted to present the local authority transport planners with the opportunity of reducing the analysis uncertainties due to decision-maker and user prejudice. The challenges and future research directions are elaborated in Section 2.7.
3. The time period of analysis examining life-cycle burdens of different project alternatives for road networks and the highly subjective nature of the somewhat intangible benefits obtained as a result of investments, no matter how difficult to quantify with a deterministic approach, must also be incorporated and measured explicitly.
4. The use of *recycled and industrial waste materials* has demonstrated a potential in increasing cost performance, environmental benefits and resource savings compared to use of virgin materials, mechanical and fit-for-purpose performance of pavements build with recycled materials should also be investigated for the traffic, distress and fatigue levels.
5. A side-benefit of utilising recycled and waste materials in road projects is preventing groundwater contamination and leachate generation in the aquifers located close to landfills, particularly in developing countries.
6. The GHG emissions from construction design alternatives of road network projects utilising recycled materials was comparatively less than virgin materials' utilisation, for example, (Celauro et al., 2017) revealed a maximum of 34.5% CDE reduction (as Figure 5 in Section 3.3).

7. Resource and energy loads of pavements constructed by material mixes containing lime-stabilised and recycled materials (Celauro et al., 2017) was 34.21% or 3.1 TJ lower than virgin materials alternatives as shown in Figure 4 of Section 3.3.
8. The *LCIA results* may be presented in a more comprehensible form using normalisation factors and expert-assigned weighting scores in the *interpretation* phase. Stakeholder interest can be addressed through meeting user needs, agency objectives and proper stakeholder engagement through the incorporation of the social component into LCA tools (as discussed in Section 4).

The eight items above represent the way forward for a real-world application of life-cycle analysis in road network projects.

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