INTEGRATED DECISION-SUPPORT FRAMEWORK FOR SUSTAINABLE FLEET IMPLEMENTATION

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Abstract

Issues regarding fossil fuel depletion, climate change and air pollution associated with motorised urban transportation have motivated intensive research to find cleaner, greener, and energy-efficient alternative fuels. Alternative fuel vehicles have a pivotal role in moving towards a sustainable future, with many already deployed as public transport fleet. Unlike private vehicles, the process of evaluating and selecting the appropriate fuel technology for the taxi fleet, for instance, can be demanding due to the involvement of stakeholders with different, often conflicting objectives. While many life cycle models have been developed as decision-support tools for evaluating vehicle technologies and fuel pathways based on multiple criteria, the different perspectives of fleet operators, policymakers and vehicle manufacturers may create a barrier towards the adoption of eco-friendly low carbon fleet. At present, the search for one optimal solution that performs the best in all aspects is difficult to achieve in practice. Therefore, there is a need for an integrated tool that can align the different priorities of economic, environmental and social perspectives of decision makers.

This research aims to develop a computer-based framework that can be used as a shared justification tool to support multi-stakeholder decision making. The main contribution is the implementation and applicability testing of the framework via a probabilistic life cycle analysis with satisficing model. The model was initially tested and evaluated by representative third-party users from the transport industry. When demonstrated in an illustrative taxi case study, results from the life cycle analysis show constant compensation and trade-offs between the criteria. Subsequently, this thesis provides an example of how the satisficing choice model seeks a satisfactory solution that adequately meets the multiple objectives of decision makers. Also, the research provides insights for other research and industry efforts in developing tools to support decision making towards sustainable development practices.

Keywords: Alternative fuel, decision-support, satisficing choice model, life cycle, taxi fleet

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List of Abbreviations

3Ps	People, Profit and Planet
AFLEET	Alternative Fuel Life Cycle Environmental and Economic Transportation
AFV	Alternative fuel vehicle
B20	20% blend of biodiesel ratio to diesel
BEV	Battery electric vehicle
CAPs	Criteria air pollutants
CBA	Cost benefit analysis
CFCs	Chlorofluorocarbons
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CTG	Cradle-to-grave
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food & Rural Affairs
E85	85% blend of ethanol ratio to petrol (or other hydrocarbon fuels)
EJ	Exajoule

eLCA	(environmental) Life cycle assessment
EoL	End-of-life
EU	European Union
EV	Electric vehicle
fLCC	Financial (conventional) life cycle costing
GHGs	Greenhouse gases
GJ	Gigajoule
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HC	Hydrocarbon
HCFCs	Hydrochlorofluorocarbons
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
Kg	Kilogram
KM	Kilometre
LCA	Life cycle analysis
LCC	Life cycle cost
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCM	Life cycle management

LCSA	Life cycle sustainability assessment
LCT	Life cycle thinking
LDVs	Light-duty vehicles
MCDA	Multi-criteria decision analysis
MJ	Mega joule
N_2O	Nitrous oxides
NGV	Natural gas vehicle
NOx	Nitrogen oxides
NPV	Net present value
OECD	Organisation for Economic Co-operation and Development
PDF	Probability distribution function
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
PV	Present value
SCC	Social cost of carbon
SD	Sustainable development
SETAC	Society for Environmental Toxicology and Chemistry
s-LCA	Social life cycle assessment
SOx	Sulphur oxides
SPC	Shadow cost of carbon
TBL	Triple-bottom-line

TCO	Total cost of ownership
TfL	Transport for London
TTW	Tank-to-wheel
UN	United Nation
UNEP	United Nations Environmental Program
VOC	Volatile organic hydrocarbon
WHO	World Health Organisation
WTT	Well-to-tank
WTW	Well-to-wheel
ZEC	Zero Emission Capable

THESIS OUTLINE

This thesis documents the development of a framework and its applicability testing as a tool for evaluating alternative fuel technologies from a life cycle perspective, to inform multi-stakeholder decision making. The overall structure of the study takes the form of eight chapters. To guide the reader, the thesis is outlined as follows (Fig. 1):

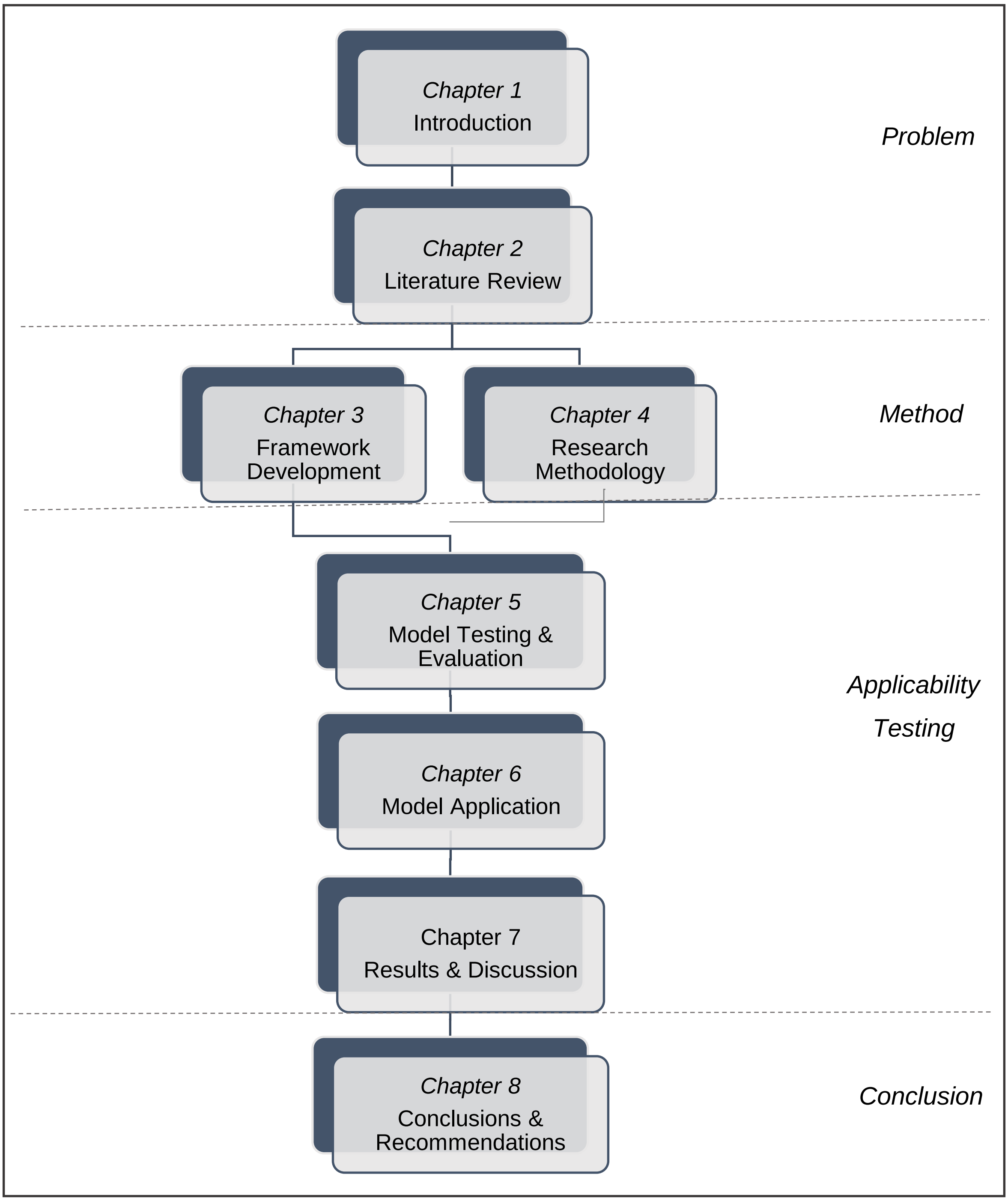

Fig. 1: Overall structure of the thesis (source: author)

Chapter 1: Introduction

This chapter introduces the concept of sustainable development (SD), its challenges due to rapid urbanisation and how the use of alternative fuels in public transportation fleet can help reduce the negative impacts of conventional, petroleum-based vehicles. Then, the chapter highlights the background and context to the research problem, outlines the aims and objectives, the research questions, the scope of the research and the expected outcomes. The main research significance and overview of the methods are also presented in brief.

Chapter 2: Literature review

Chapter Two begins with a brief overview of the recent development in alternative fuels technologies for road transportation. It then proceeds to look at how life cycle methodologies are applied to support decision making in this context. Next, the chapter presents a critical review on recent studies that evaluate and compare fuel technologies from a sustainability perspective, taking a life cycle approach. The findings from the review inform the gap that needs to be filled by this present study, whilst the information gathered is also used to guide the process of developing and demonstrating the framework.

Chapter 3: Framework development

Based on the gaps identified in the earlier chapters, the third chapter is concerned with the methodology and theoretical framework proposed in this thesis. The chapter presents the conceptual framework, then elaborates the working procedures of the decision-support tool. The process flow is presented in a graphical layout, to illustrate how the tool works according to what it is designed for.

Chapter 4: Research methodology

This chapter describes the methodology for gathering the data required for implementing and testing the framework. The approach and procedures of inquiry are elaborated based on the philosophical views, before the specific data collection and analysis methods are explained. Finally, issues of validity, reliability, and research ethics are also briefly discussed before the summary is presented.

Chapter 5: Third party user testing and evaluation

Chapter 5 presents the results of user testing and evaluation by third-parties (external), from whom the feedback is collected using survey questionnaires. The lessons learned are useful to improve the framework/model further, prior to applying it in a case study, using real data.

Chapter 6: Model application in a case study

This chapter is dedicated to the application of the tool using sample data collected from a representative case study. The model is placed into perspective in a typical case example of alternative fuel technologies evaluation, to inform decision making in a context of taxis in rapidly growing cities. A case study is elaborated in order to get the model operational, using data related to taxi fleet operations in Kuala Lumpur, Malaysia. The step-by-step process carried out by the tool is described by highlighting the scope, input parameters, and assumptions used for the case study modelling.

Chapter 7: Results and discussion

Chapter 7 presents the findings of research which has been divided into five parts: I - Results of the survey for collecting empirical data; II – Results of the inventory analysis; III - Results of the comparative life cycle analysis; IV – Results of the trade-off with satisficing; and finally, V – Results of uncertainty analysis.

Chapter 8: Conclusions and recommendations

In this final chapter, the aim and objectives are restated, and the main conclusions are presented in accordance with the research objectives. Then, the main research contributions are summarised. Finally, limitations of the study are highlighted to provide recommendations for future work.

CHAPTER 1: INTRODUCTION

1.1. Introduction

The aim of this chapter is to provide the background and context to the research problem, which is the rationale for undertaking the study. The first section describes the main issues surrounding urbanisation, particularly in relation to the transport sector, and highlights some of the current practices towards sustainable transportation. This is followed by a discussion regarding the need for evaluating fuels and technology choices from the perspective of sustainability, taking a life cycle approach. Then, the motivation for undertaking the research and the problem statement are introduced. Next, the aim and objectives, research questions, scope of study and expected outcomes are highlighted. Finally, the significance of the research and a brief overview of the methods are summarised.

1.2. Transport and sustainability

1.2.1. Urbanisation and sustainable development

Recent decades have seen a rapid increase in the global urban population, and this trend is expected to continue in the years to come. The United Nations (UN) reported that 54% of the world's population lived in urban areas in 2014, compared to the situation in the 1950s, when only 30% of the world's population was urban (United Nations, 2014). By the year 2050, about two-thirds of the global population is expected to live in urban areas (Walker and Marchau, 2017). Present day urbanisation is mostly concentrated in the Asia-Pacific region, which has seen its urban population grow faster than in any other region, and is expected to reach a 50% urbanisation rate in the year 2026 (UN-ESCAP, 2013). Malaysia, for instance, has undergone massive changes in recent years. It was ranked at 49th in 2014, in terms of population size and ranking of urban agglomerations with more than five million inhabitants, and experienced a 3.3% average annual increase between 2010 and 2015 (United Nations, 2014).

The fast-growing urbanisation over recent decades is unprecedented, hence it is becoming extremely difficult to ignore the challenges and risks that come with it. According to the Organisation for Economic Co-operation and Development (OECD), up to 70% of global energy consumption and greenhouse gas (GHG) emissions are attributable to urban areas, despite these areas occupying less than 5% of the world's landmass (OECD International

Transport Forum, 2015). As cited in Faria *et al.* (2012), the International Energy Agency (IEA) forecasted that global crude oil consumption will be 102 MMbbl/d (million barrels of oil per day) in 2030, representing a 27% growth from 83 MMbbl/d in 2009. The present trend will lead to much bigger problems in the future if the concerns on the depletion of fossil fuel resources are not mitigated and managed with sustainability in mind. While the process of urbanisation in Asia is unstoppable and will continue in the coming decades, opportunity still exists to set the course on a more sustainable path. The United Nations (UN) has urged Asia-Pacific countries to enhance participation, transparency and consensus among stakeholders for the management and planning for urbanisation in a sustainable way (UN-ESCAP, 2013).

The term "Sustainable Development (SD)" was initially introduced in 1987 during the World Commission on Environment and Development, chaired by Norwegian Prime Minister, Mrs. Gro Harlem Brundtland (UNEP Setac Life Cycle Initiative, 2009). Another term that relates to this concept is known as *Sustainability*. Although there have been many cases of confusion between the two terms, Heijungs, Huppes and Guinée (2010) define *Sustainability* as the property of a thing being sustainable. A "thing" in this statement can be a product, process, technology etc., while being "sustainable" is when it can be maintained in a specific state for an indefinite (or very long) time.

Almost a decade after the Brundtland definition of SD was launched, the concept of Triple Bottom Line (TBL), coined by John Elkington in 1994, emerged (Elkington, 1998). The TBL concept was introduced in order to translate SD as an organisational language and to bridge the gap between theory and practice at corporate level. According to the United Nations Environmental Program (UNEP), Elkington's TBL definition is seen as similar to the 3P approach: People, Planet and Profit (or Prosperity), as it takes into account the three pillars of the environment, economy and society (United Nations Environmental Program (UNEP), 2011), as shown in Fig. 2. It entails reconciling all the three pillars, in which each dimension involves a complex system of different and sometimes conflicting objectives and interests (Bortolazzo, Cavallazzi and Valente, 2018).

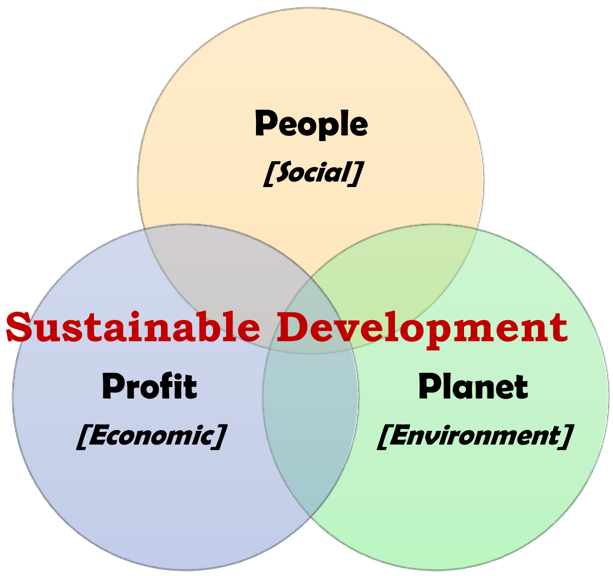

Fig. 2: The three pillars of sustainable development (adapted from United Nations Environmental Program (UNEP), 2011)

1.2.2. Risks and implications for the transport sector

It has been generally acknowledged that the dynamic changes in demographics resulting from rapid urbanisation have contributed to economic growth, enhancing standards of living and efficiency in many ways. However, the higher standard of living in modern cities has accentuated the externalities of road traffic and mobility problems, due to a rapid increase in the demand for motorised transportation, resulting in congestion, parking space, use of energy, and emissions (UN-ESCAP, 2013; Bakker *et al.*, 2017; Walker and Marchau, 2017). This is a critical issue in many modern developing cities, including Malaysia, in which the Kuala Lumpur-Klang Valley area is confronted with an overload of traffic flow inward-outwards of central Kuala Lumpur (Jaafar *et al.*, 2014). Of particular concern is the fact that these vehicles are mostly petrol-powered, emitting greenhouse gases (GHGs) and criteria air pollutants (CAPs), which cause vulnerability to climate change and harmful effects on human health as presented in Table 1.

Globally, the transport sector produces 25% of energy-GHGs related emissions, of which more than 70% come from road transport vehicles (Ashnani *et al.*, 2015). The continuous emissions of GHGs has resulted in increased global temperature and dramatic climate change, which not only affects economic activities and the environment, but also has adverse effects on human health (Franchini and Mannucci, 2015). The increased temperature or global warming due to motorised vehicle tailpipe emissions has claimed more than 150,000 lives per year and caused numerous prevalent diseases (Thomas *et al.*, 2014; Khreis, May and Nieuwenhuijsen, 2017). Another recent projection for the year 2030 shows that the situation will worsen if climate change mitigations are not implemented, causing 38,000 more deaths amongst the aging population due to heat exposure, 48,000 amongst children because of diarrheal disease, in addition to a level of mortality of 60,000 and 95,000 due to malaria and under-nutrition (stunting) in children, respectively (Franchini and Mannucci, 2015).

Meanwhile, concerns about the environmental sustainability of the transport sector extend beyond GHG emissions and include pervasive air pollution (Leather, 2009). Besides environmental effects, air pollution is ranked at number four in terms of the world's fatal health risks; it has caused one in every ten deaths in 2013, costing the world's economy US$225 billion in lost labour income, and US$5.11 trillion in welfare losses (World Bank and Institute for Health Metrics and Evaluation, 2016). The World Health Organization (WHO) estimated that globally, air pollution caused seven million premature deaths in 2012, which is equivalent to one in eight of the total number of deaths (OECD, 2015). 88% of these mortality risks occurred in low-and middle-income countries (Ashnani *et al.*, 2015), where 90% of the population was exposed to harmful air pollutants. At any rate, these risks of premature deaths are remarkably significant, setting the context in which any mitigating actions and improvement initiatives should also be evaluated from an air quality-related human health effects perspective.

Table 1: Road transport vehicle emissions and their impacts (adapted from Litman, 2017)

Emission	Description	Sources	Harmful Effects
GHGs			
Carbon dioxide (CO_2)	A product of combustion.	Fuel production and tailpipes.	Climate change.
Carbon monoxide (CO)	A toxic gas caused by incomplete combustion.	Tailpipes.	Human health, climate change.
CFCs and HCFC	A class of durable chemicals.	Air conditioners and industrial activities.	Ozone depletion, climate change.
Methane (CH_4)	A flammable gas.	Fuel production and tailpipes.	Climate change.
CAPs			
Fine particulates (PM_{10}; $PM_{2.5}$)	Inhalable particles.	Tailpipes, brake lining, road dust, etc.	Human health, aesthetics.
Road dust (non-tailpipe particulates)	Dust particles created by vehicle movement.	Vehicle use, brake linings, tyre wear.	Human health, aesthetics.
Lead	Element used in older fuel additives.	Fuel additives and batteries.	Human health, ecological damage.
Nitrogen oxides (NOx) and nitrous oxide (N_2O).	Various compounds, some of which are toxic, all of which contribute to ozone depletion.	Tailpipes.	Human health, ozone precursor, ecological damage.
Ozone (O_2)	Major urban air pollutant caused by NOx and VOCs combined in sunlight.	NOx and VOC.	Human health, plants, aesthetics.
Sulphur oxides (SOx)	Lung irritant and acid rain.	Diesel vehicle tailpipes.	Human health and ecological damage.
VOC (volatile organic hydrocarbons)	Various *hydrocarbon* (HC) gases.	Fuel production, storage & tailpipes.	Human health, ozone precursor.
Toxics (e.g., benzene)	Toxic and carcinogenic VOCs.	Fuel production and tailpipes.	Human health risks.

1.2.3. Towards sustainable practices in the transportation sector

Recognising the risks and implications of transport, as discussed earlier, which can to a large extent be attributed to inefficient use of user-owned, fossil-fuelled dependent vehicles (Walker and Marchau, 2017), recent statistics by Bloomberg show that almost 80 percent of the global auto market is currently pushing the phase-out of petroleum-based vehicles (Fickling, 2017). There is a growing body of literature that recognises the importance of energy-efficient and low-emission vehicles, as they provide an opportunity to make transport more sustainable. These vehicles are termed as "Alternative fuel vehicles (AFVs)" throughout this thesis, which refer to the vehicles that use fuels or technologies other than the conventional petrol or diesel. At the same time, although the research and development of AFV technologies looks promising, in a move towards a low carbon mobility future, the implementation is mostly driven by governments through regulations, taxation, incentives and subsidies. By way of illustration, emissions standards of 95g/km CO_2 emission were imposed on passenger car fleets in Europe effective in the year 2021, and 78g CO_2/km in 2025 (Boston Consulting Group, 2017).

Meanwhile, China, which represents one-third of the world's car market, is working on a schedule to end the sales of fossil-fuel-based vehicles, following the moves of France and UK which bans the sale of new diesel and petrol cars from 2040 (Bloomberg News, 2017). The country's vice-minister of industry and information technology, Xin Guobin said in 2017, during an industry forum that a deadline for automakers to end sales of fossil-fuel-powered vehicles will be set, becoming the biggest market to do so. The announcement is particularly remarkable in driving the industry stakeholders, besides governments, companies and organisations, to play more influential roles.

In light of recent evidence illustrating the effects of poor air quality and urban air pollution on public health, it is valuable to integrate financial and environmental outcomes with social health aspects in a strategic sustainability assessment context. A study by Ogden, Williams and Larson (2004) shows that air pollutant damages are concerns of economic importance that are comparable to the climate-change risk from GHG emissions. In England, the chief medical officer has recently urged the government to put more stringent national standards in place in order to combat air pollution and reduce its threat to human health (Laville, 2018). The need for considering air pollution as a health issue has been highlighted, instead of just as an environmental concern. Following the TBL concept, sustainable practices can be implemented through harmonious synergies and a balanced treatment of economic, social and environmental responsibilities. Hence, it is crucial that these three aspects are incorporated in the evaluation of AFV technologies, to ensure that organisations can remain profitable without endangering the environment and society. A more detailed account of AFV technologies for public transport fleets is given in the following section.

1.2.4. The use of alternative fuels in public transport fleets

As previously stated, various scientific literature has widely discussed the potential of energy-efficient and low-emission vehicles. The shift is seen as a way to reduce GHG emissions and oil consumption (Nanaki and Koroneos, 2013), therefore help to mitigate climate change and combat air pollution. However, a much-debated question is whether the reduction benefits can compensate for the higher costs of renewable fuels or advanced technologies. Cost-competitiveness plays a major role in and is a particularly important aspect in developing countries, which have relatively lower income levels compared to more developed nations (González Palencia, Araki and Shiga, 2016). According to a report by the Green Car Congress, just 2.5 percent of new vehicles sold in 2017 across the world were battery electric, plug-in hybrid, or fuel-cell vehicles, with another eight percent being hybrid-electric or natural-gas powered; the others still came from either petrol or diesel fuel-powered vehicles (Boston Consulting Group, 2017).

Nesbitt and Sperling (2001), Nanaki and Koroneos (2013), and Ribau, Silva and Sousa (2014) claim that a way to increase the penetration and diffusion of new technologies in the transportation sector is through vehicle fleet implementation. Vehicle fleets are often targeted as strong and attractive first markets due to their big scale, fuel consumption, and high vehicle turnover (Nesbitt and Sperling, 2001; Haller *et al.*, 2007; Campíñez-Romero *et al.*, 2018). These authors argue that the travelling routes and the infrastructures for a fleet (like taxis) are better defined than in a personal vehicle. For easier penetration and to increase the diffusion of AFVs, the public transport sector can act as a testbed or niche market for new technologies (Aldenius and Khan, 2017). Besides this, public transport fleets usually operate under the purview of national and local authorities, thus are more compliant with government mandates and initiatives (Wikström, Hansson and Alvfors, 2015; Campíñez-Romero *et al.*, 2018). In the UK, for instance, the Department for Environment, Food and Rural Affairs (DEFRA) has set out more stringent action plans to tackle air pollution and improve air quality, detailing how 33 local authorities will implement new measures to reduce harmful road transport emissions.

All things considered, it is not surprising that alternative fuel technologies have been implemented for public transport vehicles worldwide, such as the electric taxis in London and New York (Castel-Branco, Ribau and Silva, 2015), compressed natural gas (CNG) taxis in Malaysia (Ong, Mahlia and Masjuki, 2012) and China (Wang *et al.*, 2015; Hao *et al.*, 2016), as well as the CNG buses in the Republic of Serbia (Milojević, 2017). Due to the intensive operations and high mileage of taxis, which can be more than seven times the mileage of an average private vehicle, such as in Singapore (Reuter et al., 2014), taxis are comparatively more polluting than other passenger vehicles in the city (Campíñez-Romero *et al*., 2018). According to Campíñez-Romero *et al.*, (2018), the ratio of taxi fleets per inhabitant in London, New York and Madrid is 2.65, 3.68 and 4.75 respectively. A news release by the Low CVP (Low Carbon Vehicle Partnership) reported that there are over 290,000 licenced taxi and private hire vehicles across England and Wales, plus 23,000 in Scotland (The Low Carbon Vehicle Partnership, 2018). Although the taxi population is relatively small amongst the 31.3 million licensed vehicles in Great Britain, their high mileage and proximity to public areas contribute significantly to poor air quality, which impacts on human health (Low CVP, 2018). Transport for London (TfL), on its website, stated that taxis contribute 16% of all road transport NOx in central London, hence exhibit a great potential to facilitate the improvement of urban air quality.

Besides recent industry-related evidence, an extensive body of literature and past studies has proven the significance of implementing sustainability strategies for vehicles that travel longer distances, such as taxis, as they can maximise the benefits from fuel-efficient and low-emissions vehicles (Zhao, Doering and Tyner, 2015; Baek, Kim and Chang, 2016; Peng, Fan and Xu, 2016; Hao *et al.*, 2017). Henceforth, replacing high mileage conventional taxis with these alternatives should be one of the first steps taken to improve the current conditions. In the United Kingdom, a Low Emission Taxi Guide was published by the Low Carbon Vehicle Partnership (Low CVP) and the Energy Saving Trust (EST), which aimed to provide guidance for local authorities and the taxi companies regarding best practice on the implementation of policy measures, initiatives and incentives to accelerate the adoption of ultra-clean taxi and private hire vehicles (The Low Carbon Vehicle Partnership, 2018). By way of example, TfL has introduced new licensing requirements to phase out diesel taxis with Zero Emission Capable (ZEC) taxis and a delicensing scheme, offering a payment of up to £5,000 plus grant funding of up to £7,500 off the price of a new ZEC taxi. This is to incentivise and to encourage the switch to ZEC vehicles sooner than planned, which should be implemented elsewhere in countries and cities around the world.

1.3 Research motivation and problem statement

The motivation for this research comes from an observation of the current and ongoing trends in the transportation sector, as reported in the literature. A review of literature on industrial practices has shown that transport decision makers tend to focus on a specific objective. Taking taxis in Nanjing, China, as an example, most decisions related to fleet operations, including the fuel types, are made by taxi drivers who either own the fleet or obtain a lease from the taxi company (Wang *et al.*, 2015). A study by Saukkonen, Laine and Suomala (2017) revealed that the reasons that have triggered the taxi companies to switch to natural gas vehicles (NGVs) in Finland are mainly from a business or profitability point of view, such as the expected lower fuel costs (fuel savings) and lower taxation. Being privately owned, like any other company fleet, the benefits of AFVs, such as their ability to reduce vehicle emissions or enhance the company's "environmental image" does not mean much to the fleet manager, who is mainly accountable for keeping the vehicles operating at the lowest cost (Nesbitt and Sperling, 2001). Wang *et al.* (2015) revealed that besides cost, taxi drivers' decisions are also influenced by "intangible costs" such as the inconvenience of refuelling, whilst they tend not to care much about the environmental impact of the fuel.

Whilst the current practice may satisfy the targeted goal and priority of each decision maker, this narrow, single-centric evaluation is inadequate and no longer relevant in the move towards SD. Given that the evaluation process is often conducted separately, using different tools and methodologies, analysis results are often viewed with different lenses. As the shift to AFV technologies is directed towards vehicle fleets within public authorities, fleet managers and operators need to balance stakeholder pressure such as environmental considerations and legislative compliance involved in such implementation (Haller *et al*., 2007; Jasiński, Meredith and Kirwan, 2016). Within the context of public transport, the decision-making process would involve increased complexity and dissimilar interpretations by the various stakeholders with different needs, goals, interests and priorities, which may at times be conflicting (Thabrew, Wiek and Ries, 2009; Jasiński, Meredith and Kirwan, 2016). Moreover, there are very few tools that integrate the evaluation of multiple criteria within a unified, single platform for supporting decision making. There is also a lack of an integrated decision-support tool and assessment framework that can provide holistic evaluation of AFV technologies, addressing different priorities of economic, environmental and social perspectives of decision makers. This limitation is illustrated in Fig. 3.

The scientific literature shows that life cycle analysis (LCA) has been applied quite extensively in the transport sector, to assist decision makers prior to implementing any strategies. Based on the examples of case studies from all over the world, as presented in the UNEP guideline (United Nations Environmental Program (UNEP), 2011), LCA methods can be applied everywhere and for all products, to provide useful findings for decision makers. Nevertheless, Norris (2001) argues that the traditional segregation between environmental assessment and economic analysis has limited the influence and relevance of LCA for decision making, as the important relationships and trade-offs between the economic and life cycle environmental performance of alternative decision scenarios are not taken into consideration. When evaluating options, each stakeholder group cannot simply ignore the aspect that is viewed as being of major importance by the others, even though they consider that to be a minor (less important) one.

The various scientific literatures have unanimously acknowledged that a clear domination of one particular fuel or powertrain technology in all criteria is rarely the case. For instance, none of the technologies can dominate the others and perform the best in every aspect evaluated. In conflict multi-objective problems, it is often not possible to have a single solution that simultaneously optimises all objectives, hence requiring trade-off solutions that represent a balance between the objectives (Ribau, Silva and Sousa, 2014). Given that the optimised solution is difficult to be implemented in real practice (Zhao, Ercan and Tatari, 2016), an optimisation model is mainly developed to evaluate choices at the design and conceptual stages, with the use of computer programming methods and algorithm in order to generate the “best case” or optimal result e.g., Castel-Branco, Ribau and Silva (2015); Onat et al. (2016). Research to date has tended to focus on applying an optimised fleet mix for future portfolio of AFVs under various scenarios (see for instance; Ercan *et al.*, 2015; Zhao, Ercan and Tatari, 2016; Romejko and Nakano, 2017) and to enable decision makers to see the possible appropriate combination of drivetrain based on different weights of decision criteria, where the selection is defined by the criteria that the evaluator thinks are most important (MacLean and Lave, 2003; Ashnani *et al.*, 2015).

It is now well established from a variety of studies that trade-offs need to be explored to find a reasonable balance between the multi-dimensionality of stakeholders’ interests, objectives and priorities (Hackney and De Neufville, 2001; Bai and Labi, 2009; Luk, Saville and MacLean, 2016). However, it is still not known whether optimising is practical and feasible for evaluating currently available AFV technologies involving decision makers with conflicting objectives. Read *et al.* (2017) argue that the alternative that is selected unanimously, considering the priorities of all decision makers, tends to be the most stable solution, instead of the optimal solution. The proposal behind this thesis is that for the framework to be effectively used as a tool to support collaborative or consensus decision making in sustainable fleet implementation, an alternative strategy and evaluation procedures must be explored.

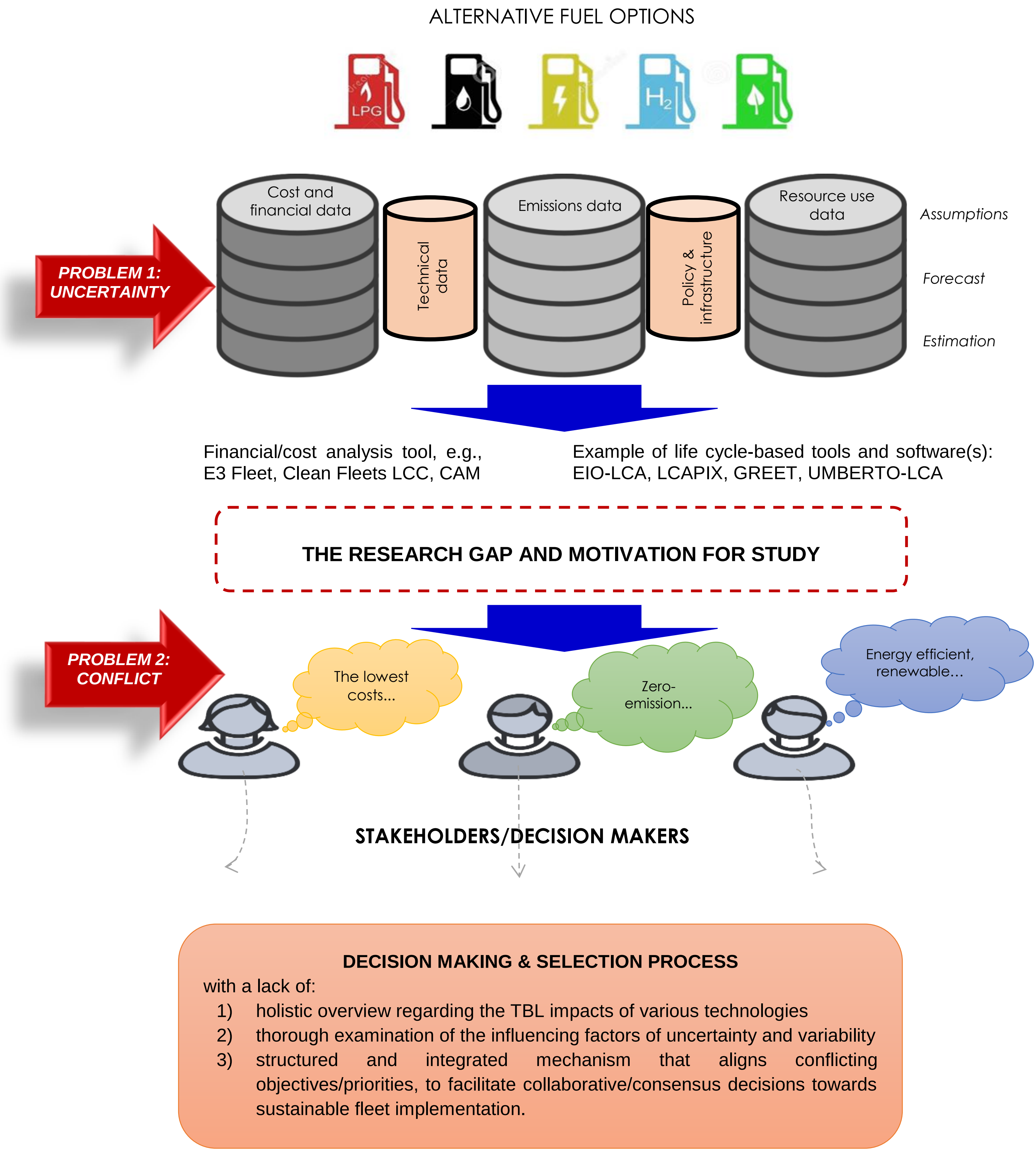

Fig. 3: Current practice and limitations in transport decision making (source: author)

1.4 Research aim and objectives

As stated in the problem statement, a few limitations with the evaluation and decision making of AFV technologies have been identified. Subsequently, the primary aim of this study is to develop an integrated justification platform for evaluating those choices, so that it can effectively be used to inform stakeholder decision making (ideally through a collaborative or consensus process) for supporting sustainable fleet implementation.

To achieve this aim, the following objectives were established:

Objective 1: Develop a theoretical understanding of the methodologies for evaluating AFV technologies from a TBL perspective, and a new framework suitable for integration into the life cycle model.

Based on the field of interest, firstly a literature review is performed to gain knowledge and theoretical understanding of life cycle methods which serve as the core fundamental for the assessment procedure presented in this thesis. An investigation needs to be carried out to identify the attributes of AFV technologies and suitable approach for evaluating them, in accordance with the scope and aim of this research. These aspects are reviewed in Chapter 2 (Literature Review). Based on the knowledge gained from the review, a new framework is formulated and presented in Chapter 3. Accordingly, the next objective is formed.

Objective 2**:** Implement the computer-aided framework using test simulation models.

Based on the proposed methodology, the framework is implemented on a computer platform (hereby referred as the “tool”). Finally, to provide exemplary evidence and demonstrate that the framework is both feasible and applicable for solving industrial-based and real-world problems, the third objective is established.

Objective 3: Apply the model for evaluating currently available fuel/powertrain technologies in a taxi context, to support multi-stakeholder decision making.

The tool is made operational and tested using real data (collected and analysed using the methods and techniques as explained in Chapter 4) from a representative sample. Prior to applying the model in a case study (Chapter 6), it is evaluated by third party users, as presented in Chapter 5. The results from the experimental case study modelling and simulation are then presented and discussed in Chapter 7 (Results and Discussion).

It is expected that by meeting all the objectives listed above, the aims of this research will have been realised (Chapter 8). Accordingly, this research is conducted according to the scope outlined in the next section.

1.5 Scope of research and expected outcomes

Given the amount of work and time required for conducting this research, from the conception of the decision-support framework and the data collection for making the tool operational, the scope of this research was limited to the development of an integrated tool that evaluates currently available alternative fuel technology choices for taxis in a representative city. The tool is designed for comparing various fuel-powertrain technologies in terms of their TBL impacts and making satisfactory trade-off, to facilitate towards collaborative decision making of industry stakeholders e.g., fleet operators, regulators, policy makers, vehicle manufacturers. The scope and expected outcomes of this research are illustrated in Fig. 4, with specific contributions highlighted within the red dotted lines.

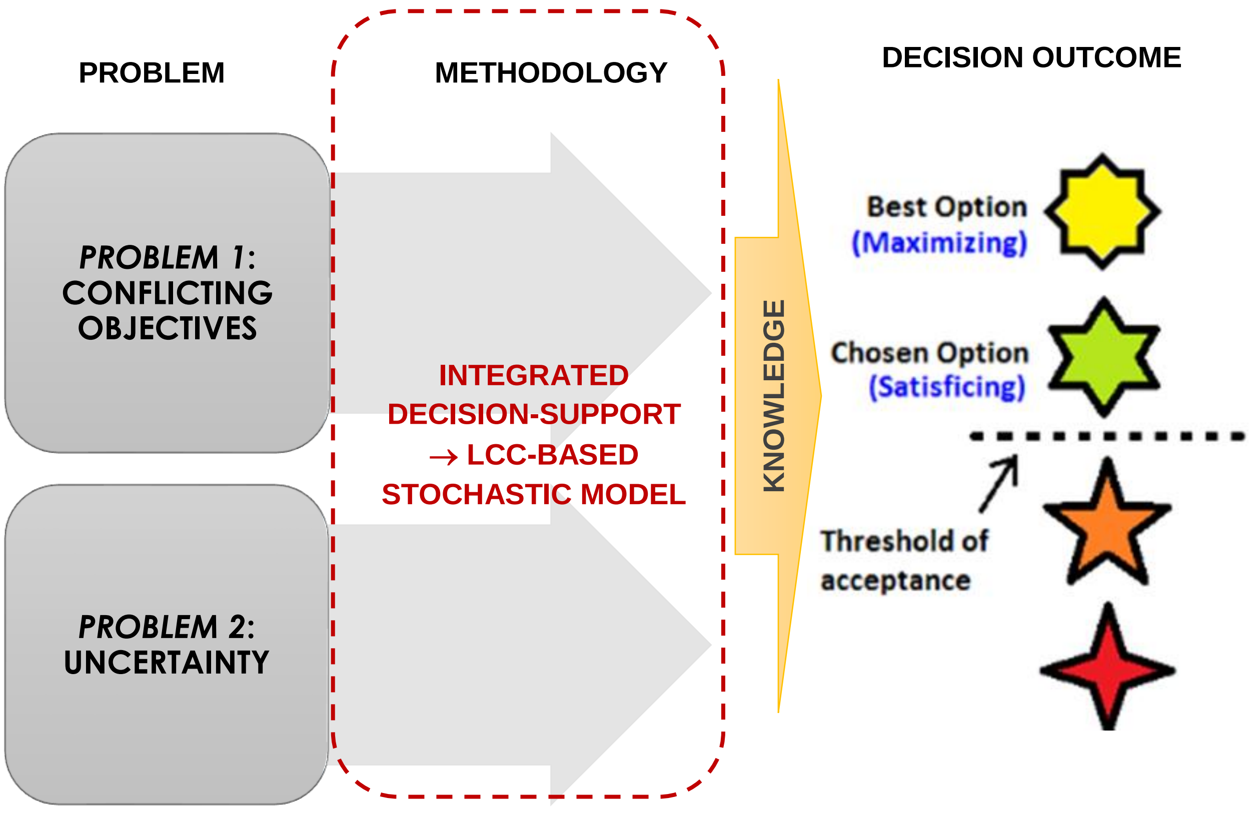

Fig. 4: Scope of research and expected outcomes (source: author)

Based on the scope above, the focus of this research is to provide a shared platform that could be used by multiple users from different background and expertise, to inform the search and decision making of technology choices towards sustainable fleet implementation. As an integrated justification platform, it is important that the tool provides knowledge through a presentation of outputs using a common language (that can be understood even by the non-experts). It is also crucial to establish a methodology that is not only robust but practical and simple to implement, otherwise it will hardly transcend from theory to practice. Henceforth, the overarching key principle is simplification which is in accordance with the recommendation by Sala, Farioli and Zamagni (2013), who stressed the importance of having a method that is *"applicable in the day-by-day, simple in its application but methodologically robust"*. Therefore, it is of great necessity to fill this knowledge gap with a simplified decision-support tool that does not require complex programming methods and algorithms to quantify and produce the outputs, plus the use of a familiar dimension, to enable greater clarity to be achieved. The main reason for developing such a tool is triggered by the need to communicate the results clearly, making the decision-making process easier despite the different area of expertise of stakeholders who may or may not have the knowledge and experience in LCA or sustainability assessment.

This research distinguishes itself from previous work in several ways. The research significance is highlighted next.

1.6 Research significance

In summary, this research is important because:

- The evaluation of AFV technologies in fleet planning has become more complex and requires the integration of a life cycle perspective, although such holistic approaches are scarce in the literature (Mennenga, Thiede and Herrmann, 2013).
- Little work has been conducted to assess the trade-offs between selecting various fuels/powertrains for taxis and the resultant costs for the fleet owners, along with the associated carbon footprint impact (Castel-Branco, Ribau and Silva, 2015).
- Many models have been developed to evaluate the economic, environmental and societal benefits of AFV technologies; nevertheless, they are not interlinked to stakeholders' decision making (Al-alawi and Coker, 2018).

- The need for a clear, systematic and standard approach for integrating the economic, environmental and social impact assessments still remains unfulfilled (Gundes, 2016).
- A specific and comprehensive study addressing the effect of multiple uncertainties is still lacking in existing studies (Fan, Peng and Xu, 2017).

Although fundamentally the integrated approach of probabilistic life cycle modelling has been adopted in other field of research, most LCA of AFV technologies only yield single, fixed deterministic values. Most importantly, none of the existing framework has incorporated the theory of "satisficing" for making the trade-off between multiple aspects. On contrary, it is observed that life cycle-based optimisation models can be found in the recent literature (see, for example, Castel-Branco, Ribau and Silva, 2015; Ercan *et al.*, 2015; Zhao, Ercan and Tatari, 2016; Romejko and Nakano, 2017; Figliozzi, Saenz and Faulin, 2018). In contrast to optimisation, there is much less information and limited research effort devoted to incorporating satisficing strategy within a decision-support framework. The experimental work presented in this thesis provides one of the first investigations into how the Satisficing Theory from bounded rationality concept is incorporated as part of a decision-support framework.

To the best of the researcher's knowledge, no research has been found that has developed and applied a probabilistic, TBL-based life cycle model that evaluates the sustainability performance of AFV technologies for taxi fleet. On one hand, the taxi sector represents an interesting and good example of complex decision making, involving stakeholders with different or conflicting priorities. Valdivia *et al.* (2013) claim that the integrated life cycle approach encompassing multiple sustainability indicators is especially pertinent for resource-limited developing countries that often pay little regard to GHG and local CAP emissions. Therefore, this research focuses on the application of framework/tool in a typical case example of rapidly growing cities that are currently experiencing urban mobility problems and lack of emission control, which would benefit from the use of tool such as developed in this study. On the other hand, the research can help to show the potential benefits of the deployment of AFVs for intensively-used taxi fleets. Hence, it deserves an explicit investigation, as studied in this thesis.

The contributions of the research are explained further in the final chapter (Chapter 8).

1.7 Research process in brief

Following the aim and objectives, this research has been carried out in a 3-step procedure, as shown in Fig. 5. The first step involves a literature search for exploring the existing theories and concepts, and how they can be incorporated into the framework. Then, the framework and its working procedures are established, then implemented on a computer platform (Step 2). Step 3 is focused on the demonstration of the model with experimental modelling and simulation using real data, based on a typical case example of taxi fleets. Prior to applying the model with a sample dataset collected from a representative taxi population in a case study, the model is tested and evaluated by third parties - someone other than the researcher, who will then provide feedback in a simple survey form. This initial testing was conducted to ensure that the model is functional, which help to confirm whether the model has been built right, and/or its behaviour are reasonable (thus provide evidence for necessary corrections).

For the input parameters and baseline assumptions used in the model, a quantitative research method was adopted for data collection because the data are quantitative. Data collection has been divided into two parts. The first part uses a survey questionnaire to gather empirical data related to taxi operating profiles from taxi operators and drivers, since the information is lacking in the literature. The second part of the data collection uses secondary data from both published and unpublished materials (e.g., a government statistical report, manufacturer's documents, valid database, etc.) to establish baseline assumptions on fuel characteristics, emissions, fossil energy resources, market conditions etc. The model then uses the quantitative data and input parameters collected from both sources to produce outputs, that provide knowledge on how to make satisfactory trade-offs.

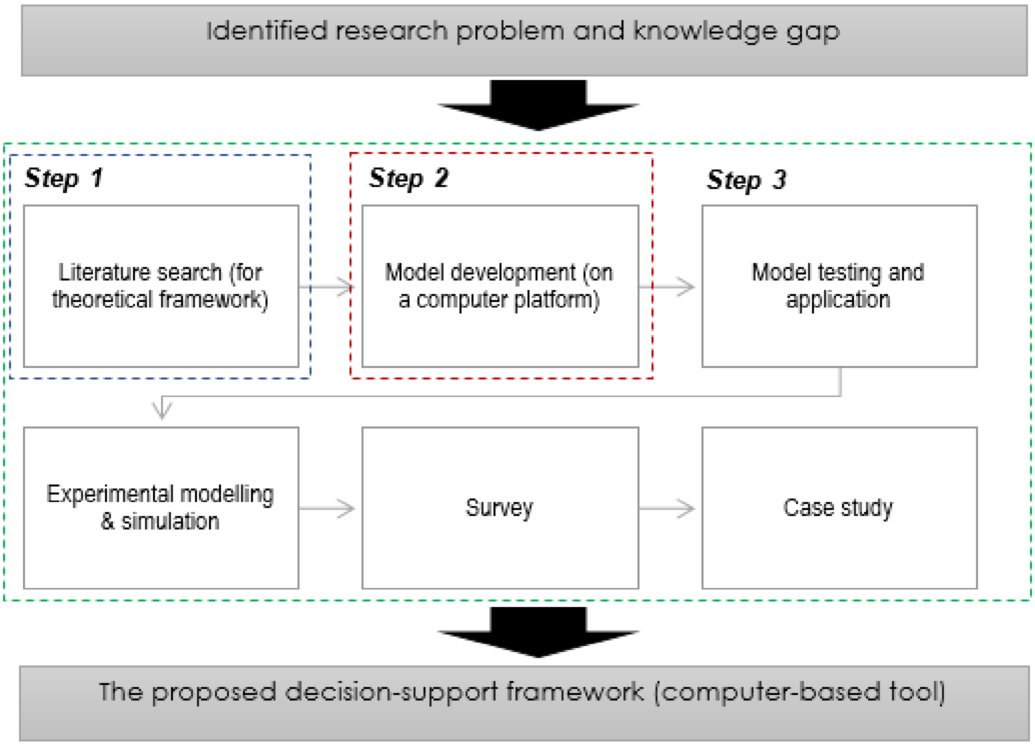

Fig. 5: Research process in a 3-step procedure (source: author)

1.8 Summary

In summary, the background information on urban transport implications affecting the economy, environment and society has been presented in this chapter. To capture the impacts in a holistic context, the aggregation of sustainability TBL measures is widely seen as necessary when evaluating AFV technology options, ideally considering the whole life cycle. Following this, the gaps in the existing studies and shortcomings of the current practices have been highlighted. All in all, this research fulfils the gap by proposing an integrated decision-support framework implemented on a computer platform. After the realisation of the aims and objectives of the research, the key outcome of this study is the proof of concept for the integrated tool that informs the trade-off performance between AFV technology choices, to support collaborative decision-making process towards sustainable fleet implementation. The next chapter of this thesis presents the review of existing literature within the context of AFV technologies evaluation and decision making, to identify gaps for improvement and to guide in the development of a computer-based framework and modelling tool, as described in this thesis.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The aim of this chapter is to review the literature, to reveal some of the problems with existing methods and practices as stipulated in Chapter 1. The understanding of the above problems and the findings from the literature review are prerequisites for the formulation of the research objectives and the proposal of a computer-based framework, presented in Chapter 3.

2.2 A brief overview of AFV technologies for road transportation

Concerns over the issues of fossil fuel depletion, climate change and poor air quality have primarily driven the government and related agencies in accelerating the uptake of AFVs. Various laws and regulations have been imposed upon public and private organisations since the late 1980s, requiring them to incorporate low-emission AFVs into their fleets (Nesbitt and Sperling, 2001). At present, various kinds of alternative fuels and advanced powertrain technologies are available in global automotive markets. The term powertrain is referred to as "a group of components that generate mechanical power and deliver it to the road, and include the internal combustion engine (ICE) and/or/ electric motor, transmission, drive shaft, differential and drive wheels" (Faria *et al.*, 2012). As discussed in MacLean and Lave (2003), the attractiveness of alternatives depends on whether the fuel-engine combinations are more superior than their conventional counterparts. For a start, AFVs must be more economically efficient over their service life (thus satisfying consumer needs). Apart from cost-effectiveness, environmentally benign vehicles are desired, hence satisfying the interests of regulators and public (society) as a whole.

In general, AFVs are claimed to help in mitigating unintended environmental and health damages caused by GHGs and CAPs, as well as in decreasing the high levels of fossil fuel dependency around the world (Tong *et al.,* 2017). The common perception of the superiority of AFVs concerns their ability to lower environmental impacts, yet some studies have found that it remains debatable whether AFVs provide significant benefits over conventional ICEVs from the holistic perspective of sustainability and on a life cycle basis (Noshadravan *et al.*, 2015). Having said that, studies that are limited to a certain stage of the life cycle, or constrained to a single dimension, only tell half of the story, thus the outcome could be misleading. This is why a life cycle treatment is imperative, to account for a more comprehensive account of impacts throughout the entire life cycle of the fuel-vehicle system. Effective and credible measurement tools are thus crucial for the assessment of these multiple aspects (Jasiński, Meredith and Kirwan, 2016).

This section provides a brief overview of some of the most significant breakthroughs with respect to the currently available AFV technologies for motorised road transportation, and their development during the past decade.

- **Electric vehicles (EVs)**

Battery electric vehicles (BEVs) are a typical type of EVs that only have an electric motor powered by a battery, which means that they do not rely on any other sources, unlike the hybrids. In contrast, hybrid EVs (HEVs) are powered by a combination of electricity stored in batteries and fuel stored in a tank. In general, the BEVs provide many benefits in comparison to conventional fossil fuel vehicles. Compared to their predecessor technologies of petrol or diesel ICEVs, BEVs are more energy-efficient and produce zero tailpipe emissions (Faria *et al.*, 2012), thus can contribute significantly in improving air quality and subsequent public health impacts in areas where they are driven. The true effectiveness of BEVs is, however, conditioned by several factors. Comparative life cycle studies between BEVs and conventional ICEVs have shown that vehicle electrification can reduce GHGs; however, the magnitude of the savings potential depends to a large extent on the source of electricity used to charge the vehicle, the energy mix for the electricity generation, and on how electricity is produced and distributed in the respective location (Karabasoglu and Michalek, 2013; Rusich and Danielis, 2015; Ma *et al.*, 2017).

In some cases, BEVs would continue to damage the environment and human health and the impacts are comparable or even worse than some advanced ICEVs if the electricity comes from carbon-intensive, fossil fuel sources (Rusich and Danielis, 2015; Bicer and Dincer, 2017). In studies comparing BEVs in countries where the electricity generation relies heavily on coal power, such as in China (Wu and Zhang, 2017) and Australia (Wolfram and Wiedmann, 2017), the total life cycle/footprint emissions of GHGs is estimated to be higher than conventional ICEVs. In the latter study, it was concluded that BEVs only contribute to emission reductions if a larger share of renewable sources can be achieved in Australia's electricity grid. In places where the electricity generation is heavily dependent on fossil fuels or non-renewable sources, BEVs are found to have a much higher burden compared to conventional vehicles. This implies that from a carbon footprint perspective, vehicle electrification is beneficial only to a certain degree, as in the case of Azmi and Tokai (2016); Onn *et al.* (2017); and Wolfram and Wiedmann (2017).

In another study by Bicer and Dincer (2017), the life cycle comparison of human toxicity, GHG emissions and ozone layer depletion has not positioned BEVs as the most favourable option when compared with hydrogen and methanol-fuelled vehicles. Despite having no direct CO_2 emission during the operation stage, through the process of battery production and the disposal, BEVs have still raised some concerns about causing damage to the environment, as battery production caused 31%–46% of the total BEV production impact, whilst the battery EoL treatment contributed to 14%–23% of the total EoL treatment (Ager-Wick Ellingsen, Singh and Hammer Strømman, 2016). Based on the results from various earlier works, it can be concluded that the sustainability performance of BEVs depends on the production process of electricity, i.e., from generating the electricity and from producing the fuels to enable the electricity's generation (fuel cycle), as well as the manufacturing and maintenance stages (vehicle cycle). In this regard, both the fuel and vehicle cycles should be considered for estimating the overall emission impacts of BEVs.

Besides considering the impacts of emissions and carbon footprints, there are other issues concerning BEVs that require further consideration. Currently, BEVs are relatively more expensive to purchase than conventional fossil-fuelled vehicles (Rusich and Danielis, 2015), hence many operators are still contemplating whether to switch to vehicle electrification. Taxi operators, for instance, will only transition their fleets and invest in BEVs if it is economically viable (Carpenter, Curtis and Keshav, 2014). Without incentives or tax credits for purchasing the vehicles, BEVs are not economically competitive, due to the high initial costs (Zhao, Doering and Tyner, 2015), which are mostly due to expensive battery costs, which account for approximately 40% of the BEV's purchase price (Rusich and Danielis, 2015). Despite the higher initial investment, BEVs have lower operating and maintenance costs (Freire and Marques, 2012), because electricity is a cheaper form of fuel than petroleum. In view of this, evaluating BEVs from a life cycle perspective of total cost of ownership (TCO) is particularly important.

Another drawback of BEVs, as frequently highlighted in the scientific literature, is their limited range of distance and "fuelling/charging" time (Faria *et al.*, 2012). This would make BEVs an inconvenient choice for long distance or mileage-intensive driving, such as taxi drivers who drive many kilometres per day, and who do not want to lose time in charging their taxis while they could transport passengers and earn money. These issues can be solved by the hybrid version, HEV, which has similarity in its operation and autonomy to the conventional ICEV (Castel-Branco, Ribau and Silva, 2015). HEVs made their debut in the US not as AFVs per se, because they still operate on fossil fuel, but as more fuel-efficient vehicles that also have relatively low pollutant emissions (Lipman and Delucchi, 2006). HEVs have been found to be advantageous when implemented for public transportation, hence the presence of many hybrid-electric taxis, such as in New York and Sao Paulo (Castel-Branco, Ribau and Silva, 2015). Hybridising EVs can reduce GHG emissions substantially (Patil *et al.*, 2016), and the Plug-in Hybrid Electric Vehicles (PHEVs) provide further emissions reductions than HEVs, at levelized costs of 50% higher (Sengupta and Cohan, 2017).

Overall, these different configurations of BEVs, HEVs and PHEVs provide benefits in reducing dependence on fossil fuels and emissions, and with the continuous development of electric powertrain technologies hope remains that they will be cost-competitive in the future.

- **Biofuels**

Biofuels are another promising alternative for fossil fuels, being a renewable energy source solution for transport fuels. There are currently two main types of biofuels - bioethanol and biodiesel, which can be used in internal combustion engines (ICE) either in their pure form or mixed with fossil fuels. Bioethanol refers to the first generation of biofuels, which can be produced from multiple renewable resources such as corn, wheat, soy, and cellulose from wood chips, grasses, etc. (Koch, Fowler and Fraser, 2011). Meanwhile, biodiesel is a second generation biofuel derived from animal fats and vegetable oils (Mat Yasin *et al.*, 2017). Biodiesel is generally a transesterified-vegetable oil that has been adapted to the properties of conventional diesel. It has been accorded much interest, given its potential in reducing PM, HC and CO emissions, as reported in the published studies (Tsolakis *et al.*, 2017). On the contrary, these authors also revealed that most studies have reported that biodiesel slightly increases NOx emission, although some discrepancies exist – depending on several factors such as engine technology, operating conditions, engine maintenance and biodiesel composition.

Due to its functional similarity to petroleum-based fuel, biodiesel may be mixed with commercially available diesel fuel and can be used directly in any mineral diesel engine with minor or no modifications (Koch, Fowler and Fraser, 2011; Mat Yasin *et al.*, 2017). For instance, the 20% blends of biodiesel with conventional diesel fuel (known as B20) can generally be used in unmodified diesel ICEVs. The main advantage of biofuels, as highlighted in many studies, is due to its ability to shift away from being an almost entirely oil-dependent transportation. For instance, Mat Yasin *et al.* (2017) discussed and summarised the benefits of biodiesel as having unlimited sources, having comparability of fuel properties with conventional diesel, is biodegradable, of low toxicity and is environmentally friendly. The potential reduction benefits vary in the literature, but biodiesel is claimed to provide reductions in CO_2 and CO emissions of between 62% and 36% (Shahid, Minhans and Che Puan, 2014).

Meanwhile, amongst the major disadvantages of biofuels, are the issues concerning their feedstock and production process when using energy crops, food prices and availability (Koch, Fowler and Fraser, 2011), lower engine speed and power, higher fuel consumption (up to 10%) compared to conventional diesel, and limitation of use in cold climate areas because of poor to low temperature flow performance (Mat Yasin *et al.*, 2017). According to Caliskan (2017), environmental issues are the main concern regarding the use of biodiesel, while the economic and technical issues are secondary.

Despite the potential of replacing fossil-based fuels, these bio-based fuels constitute a small percentage in the share of energy supply to the transport sector. Only 2.5 EJ of biofuels are used out of the 100 EJ total global final fuels used in the sector (Ahlgren, Börjesson Hagberg and Grahn, 2017). Therefore, governments and intergovernmental organisations such as the European Union (EU) have introduced policy targets, which aim at increasing future biofuel use to 20% by 2020 (Mat Yasin et al., 2017). The share was expected to be at least 6% by 2010; however it only achieved 4.4%, mostly due to socioeconomic problems generated in Europe and in developing countries by the production of feedstock (Osorio-Tejada, Llera-Sastresa and Scarpellini, 2017a). In Malaysia, the use of biofuel was encouraged in the National Bio-fuel Policy of 2006, with the government using 5% of palm methyl ester blended with 95% diesel (B5) for its fleet (Shahid, Minhans and Che Puan, 2014).

In terms of its usage in the overall automotive market, pure ethanol is not currently used as a transportation fuel but rather as a gasoline additive, typically at 10% maximum ethanol content (E10) as the common fuel blend (Koch, Fowler and Fraser, 2011). Meanwhile, E85 (85% ethanol, 15% gasoline) can be used in specially designed “Flex Fuel” vehicles to displace conventional fossil fuels. As for biodiesel, it was expected to play a much bigger role in the displacement of fossil fuels, yet it will likely only be in the blends of B5 and B20, due to constraints on raw product availability.

- **Natural gas vehicles (NGVs)**

Due to the abundance of gas reserves and increased production, the use of natural gas in various end-use sectors has expanded worldwide, including in the U.S., in which 3% of energy sources are consumed by the transportation sector (H. Cai *et al.*, 2017). Natural gas has been widely and profitably applied in compressed form - CNG - in many countries, mainly in urban light-duty vehicles (LDVs), either with dedicated or bi-fuel systems. According to Imran Khan (2017), CNG is the most favoured and used alternative fuel in the world. Besides CNG, liquid natural (LNG) is another form, typically used in heavy-duty vehicles (HDVs), using dedicated or dual-fuel systems (Osorio-Tejada, Llera-Sastresa and Scarpellini, 2017b).

Across the literature, several studies have revealed that CNG is a better choice of fuel compared to petrol, from an economic and environmental perspective. CNG and LNG are typically cheaper than petroleum fuels, hence natural gas vehicles (NGVs) offer greater lifetime fuel cost savings for extensively used fleets with high mileage (Osorio-Tejada, Llera-Sastresa and Scarpellini, 2017b). In terms of reducing climate impacts, results from comprehensive LCA studies of different fuels for LDV show that CNG engines may reduce GHG emissions by up to 30% compared to conventional petrol ICEVs (Shahraeeni *et al.*, 2015). As for LNG, a comparative study in Song *et al*. (2017) concludes that life cycle GHG emissions can be reduced by 8% if diesel HDVs are replaced with LNG HDVs in China. This is despite the higher direct energy consumption and the life cycle energy use of LNG (7.4% and 6.2% respectively). In contrast to this finding, however, an Australian study (Ally and Pryor, 2007) discovered through LCA that CNG buses produce higher global warming potential (GWP) from GHG emissions than diesel buses, due to the lower fuel efficiency resulting in more energy used per distance travelled. However, CNG buses were found to reduce pollutant emissions associated with smog, acidification, and soil/water contamination (Khan, 2018). These emissions are reduced by 21% for VOC, 20% for PM, and up to 44% for NOx and SOx (Rose *et al.*, 2013), hence lowering the risk of air pollution. Besides these benefits, the availability factor due to widespread resources and mature fuelling infrastructures (Osorio-Tejada, Llera-Sastresa and Scarpellini, 2017a) have made NGVs continue to be relevant as alternatives to conventional vehicles.

- **Hydrogen fuel cell vehicles**

Hydrogen fuel cell vehicles (HFCVs) were introduced into the market as the plausible Car of the Future, because of their promise in addressing major environmental and oil supply insecurity risks (Ogden, Williams and Larson, 2004). Nevertheless, currently, a major finding of HFCVs is that they are not yet competitive on a life cycle cost basis without internalising externalities associated with air pollutant and GHG damages, and oil supply insecurity risks. A number of studies have discovered that HFCVs will not be financially competitive (Perera, Hewage and Sadiq, 2017), at least until 2110 (Ito and Managi, 2015). As this present study is focused on developing a decision-support tool for evaluating currently available technologies, HFCVs are not described further in this section.

Over the course of the next few years or decades, there might be a breakthrough in new technology, which will change the outlook of future sustainable transportation. The adoption of currently available AFV technologies for fleet operations is discussed next.

2.3 The evaluation and decision making of AFV technologies for fleet operations

The different attributes of AFV technologies has made the evaluation process challenging and time-consuming. When deciding the right fuel-technology system for fleet operations, ideally every decision maker would seek to find the best performing choice in all criteria. Thus, it could take a lengthy process of negotiation and extensive effort to reduce the disagreement on the results before reaching an agreeable solution that would satisfy all the parties involved. Adding to the complexity of the decision-making environment is the level of uncertainty and unknowns that has undeniably discouraged many organisations from implementing AFV conversion plans (Haller et al., 2007).

Much of the current literature on sustainable fleet operation pays particular attention to the superiority and advantage of AFVs over conventional petroleum-based vehicles, either from economic, environmental, or technical points of view. From policy makers' perspectives, the costs and benefits of mitigation are often prioritised, focusing on metrics such as GHG emissions or CO_2eq related impacts (Yaduma, Kortelainen and Wossink, 2013). On the other hand, an economic cost analysis is naturally more important to fleet owners and operators (Castel-Branco, Ribau and Silva, 2015), since business decision makers tend to focus more on maximising profits and reducing operating costs (Mennenga, Thiede and Herrmann, 2013).

Across academic research and scientific literature, a number of studies have placed emphasis solely on reducing fossil fuels consumption - for instance, Ashnani *et al.* (2015) - while others have concentrated on evaluating the emissions, climate and/or air quality-related impacts on human health and the environment (see, for example, Tessum, Hill and Marshall, 2014; Bohnes, Gregg and Laurent, 2017). The economic and financial benefits of AFV technologies are analysed in Lin *et al.* (2013); Letmathe and Suares (2016); and Kara, Li and Sadjiva (2017), based on the total cost of ownership (TCO) from a consumer point of view.

Due to the growing interest in the topic of SD and the development of AFV technologies in the last decade, several different sustainability assessment and decision-support tools have been developed to provide stakeholders and decision makers with an increased awareness and better understanding of the potential impacts on the 3Ps. As a result, several studies have attempted to include multi-dimensional TBL aspects to incorporate the different objectives of decision makers. It is inherently important for organisations and stakeholders within the transport sector not to ignore the interconnected economic, environmental and social aspects; they can recognise them by viewing them from a holistic point of view. By way of example, while legislators emphasise the importance of combating climate change and air pollution, the taxi companies would probably want to take advantage of the benefits they could gain whilst making their fleet operations more sustainable.

Despite numerous sustainability measures presented in the literature, Jasiński, Meredith and Kirwan (2016) argue that there is no single and unique approach for a complete and integrated sustainability assessment of vehicles. The assessment and comparison process may sound straightforward in theory, but the implementation is more complex, as it involves a wide range of attentions and different attitudes of decision makers (Sehatpour, Kazemi and Sehatpour, 2017). The use of multiple methods has also led to increased complexity and dissimilar interpretations by the various stakeholders (Thabrew, Wiek and Ries, 2009). Previous studies such as Ribau, Silva and Sousa (2014) have revealed that the results of multi-criteria, sustainability-oriented assessment often show conflict between the cost and energy consumption, or the costs and emissions of AFV technologies. Although this leads to more complexity in the decision-making process, the preferred option should be determined through a consensual process (Shmelev and Van Den Bergh, 2016). These authors argue that decision making in a highly complex system requires stakeholders to find a consensus on the priorities and constraints. The unbiased and transparent information on economic, social, and environmental costs and benefits is assumed to promote a democratic process of agreement and consensus between stakeholders (Thabrew, Wiek and Ries, 2009).

When evaluating options based on multiple criteria, trade-offs are most certainly unavoidable, which is an issue that needs to be clarified. This is particularly important for public transport fleet decision making involving public authorities and businesses, such as for valuing a product that is environmentally positive but socially questionable (Valdivia *et al.*, 2013). Hu *et al*. (2004) concluded that the life cycle economic, environment and energy assessment could provide an important tool for policy makers to better understand the trade-offs between economics and environmental effects as well as energy, in order to achieve the most efficient use of energy resources. Trade-off analysis creates an interesting “game” in decision making, as it can aid decision makers to make a quick prediction of the impacts of each alternative decision to ultimately make a choice (Bai and Labi, 2009). According to these authors, the term “trade-off” has wider meaning in practice: it is not restricted to a single aspect but can be between groups of aspects.

A trade-off can be generally defined as “a barter situation that involves losing a quality or aspect of something in return for gaining a quality or aspect of another”. Trade-off analysis is useful in the process of decision making in many fields. There are several types of trade-offs; however, decision makers are typically interested in the criteria trade-off, when the assessment involves multiple and conflicting objectives (Bai and Labi, 2009). In the field of AFV technology assessment for transport fleet decision making involving multiple criteria, some potential trade-offs exist. Basically, a trade-off involves losing one aspect of something in exchange for gaining another different aspect. There are many types of trade-off that can be encountered in transport fleet decision-making practice, such as a trade-off between impact categories and criteria performance.

As emphasised in MacLean and Lave (2003), comparing the assessment results for AFV technology choices is difficult. According to these authors, the lack of comparability between the different technologies that are reported in most of the studies has restricted meaningful quantitative comparisons, even for the basic metrics such as energy use and GHG emissions. Meanwhile, the findings from an interview with 21 Dutch transport politicians presented in Annema, Mouter and Razaei (2015) conclude that decision makers are particularly keen on appraisal tools that show clearly the important trade-offs of a transport policy. Understanding the trade-offs is important to determine, for instance, which of the vehicle technologies are the most cost-effective at reducing emissions and/or fossil fuel use.

2.4 Life cycle thinking concept for integrated assessment of technology choices

When making selections, some form of deliberation and evaluation process is crucial for the decision makers, as they are influenced by the existing scientific evidence (Rusich and Danielis, 2015). Considering the consequences of transport, the choice of fuel/powertrain technologies demands a thorough assessment from a life cycle perspective, covering the whole vehicle-fuel system. Generally, LCA refers to a compilation of input and outputs associated with the cost and negative impacts. However, the distinctions between the different terminologies of life cycle methods are not always clear, because they are often substituted in the current literature. The terminology of life cycle methods is used interchangeably at times in the literature. Although the names and abbreviations can be similar, the “life cycle analysis” (LCA) and (environmental) life cycle assessment (addressed as eLCA in this thesis) are, in fact, two different things. To avoid confusion and misconceptions, the term LCA used in this thesis refers to a general analysis based on a life cycle approach, whereas the eLCA has a very specific application in (environmental) life cycle assessment. Without limiting this discussion to eLCA as defined in this thesis, LCA has the potential to fulfil the need for an integrated analysis supporting sustainability.

Within the context of AFV technologies, it is now well established from a variety of studies that the comprehensiveness of a decision-support tool can be achieved by undertaking analysis from a full life cycle perspective, covering both the vehicle and fuel cycles (Sharma and Strezov, 2017). Although the vehicle operation stage (when fuel is being used) dominates the amount of energy consumed during its life cycle (46%-76%) and the GHG emissions generated (67%-74%), the manufacturing and end-of-life (EoL) stages cannot be ignored (Viñoles-Cebolla, Bastante-Ceca and Capuz-Rizo, 2015). Thabrew, Wiek and Ries (2009) argue that taking a life cycle perspective enables inter-linkages of upstream and downstream activities, associated costs, benefits, and the stakeholder involvement to be emphasised in building sustainable strategies. Thus, it eliminates the assumptions that technologies with zero tailpipe emissions, like BEVs, have no environmental impacts (Garcia and Freire, 2017).

To provide a profound understanding of life cycle methods in terms of their fundamental principles and how they can be used effectively as sustainability-oriented decision-support systems, further descriptions of these methods and a review of their applications are made below.

2.4.1 An introduction to life cycle methods

The concept of LCT predominantly refers to a cradle-to-grave, holistic approach that examines the impacts of a product from the start of its life as raw materials, through production and distribution, its use, repair and maintenance, until final disposal or recycling (United Nations Environmental Program (UNEP), 2011). LCT has been considered a valuable support in sustainability evaluations, despite not being considered as a reference method for sustainability assessment (Sala, Farioli and Zamagni, 2013a). Applying LCT provides a means of incorporating the concept of sustainable development into the evaluation of products and services (Sala, Farioli and Zamagni, 2013b) by measuring it with a scientific approach. It provides a better understanding of alternative choices and makes informed selections for the long term possible (Rose *et al.*, 2013).

A “Life Cycle Initiative” was launched in 2002 by UNEP/SETAC (a collaboration between the United Nations Environment Programme and the Society for Environmental Toxicology and Chemistry). This international life cycle partnership promotes LCT and enables users from every part of the world to put the concept into effective practice, particularly in developing countries (Valdivia *et al.*, 2013). One major achievement of the initiative has been the development of methods and techniques through life cycle management (LCM). LCM is not a single tool or methodology, but rather an integrated and “organisational dimension of the life cycle approaches” for managing the total life cycle of goods and services towards more sustainable production and consumption (UNEP/SETAC, 2007; UNEP Setac Life Cycle Initiative, 2009). Fundamentally, it connects between various operational concepts and tools in order to produce valuable knowledge about the consequences of business operations.

According to Finkbeiner *et al.* (2010), the life cycle perspective is essential for the three dimensions of sustainability in order to achieve reliable and robust results. This is particularly important because the life cycle approach eliminates false conclusions and provides a fair comparison of options, recognising and avoiding shifting of problems into the future (Kloepffer, 2008). The role of the life cycle approach has evolved throughout the years and at present, there is growing demand for the existing methods to move towards an integrated approach that supports the new challenge of sustainability. According to Testa *et al*. (2011), the integration of environmental aspects in a cost management tool ensures that business decision making is made considering not only costs but an increasing awareness of the potential burdens on the environment and human health, which occur in all stages of the life cycle. LCM and its associated tools have been generally accepted by the scientific community for delivering eco-efficiency and sustainability-oriented assessments (Kloepffer, 2008; Sala, Farioli and Zamagni, 2013a). Their scopes have been broadened in order to deal with the three pillars of economic, environmental and social factors in a holistic context for sustainability assessment (Sala, Farioli and Zamagni, 2013a). The background information of life cycle methodologies that was established to deal with each pillar is presented next.

2.4.2 Life cycle sustainability assessment

This section uncovers the fundamental nature of the life cycle tools within a sustainability-oriented assessment for supporting decision making.

a) (environmental) Life cycle assessment (eLCA)

Of the three life cycle methodologies, eLCA is the most established and the only method that is internationally standardised (Kloepffer, 2008), with ISO 14040 and 14044 (Finkbeiner *et al.*, 2010), which govern the requirements necessary for conducting analysis. According to the ISO standard, eLCA is defined as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". It is a well-known decision-making framework and is widely applied to quantify the environmental impacts of a product or process on a cradle-to-grave (CTG) basis, from raw material production until the EoL (N. C. Onat *et al.*, 2017). Due to the comprehensiveness of its scope, LCA is useful to avoid problem-shifting, such as from one phase of the life cycle to another, from one region to another, or from one environmental problem to another (Testa *et al.*, 2011).

Following the UNEP guideline (United Nations Environmental Program (UNEP), 2011), eLCA includes the phase/procedural steps as per the International Standard ISO 14040-14043 as follows:

- *Goal and scope definition (Setting the goals and boundaries of the system - ISO 14041)*
- *Inventory analysis (Data collection - ISO 14041)*
- *Environmental impact assessment (impact assessment – ISO 14042)*
- *Interpretation of results (the findings of the inventory analysis and the impact assessment are combined together - ISO 14043)*

Besides the four main steps above, there are optional stages of standardisation and weighting which can be performed to aggregate the results of the various categories of impact in a single index, for example expressed with a score, to assess the environmental impact of the studied system as a whole (Testa *et al.*, 2011). These additional steps are claimed to display a high level of subjectivity, thus do not enjoy unanimous consensus amongst scholars and practitioners in the international scientific community.

From a review of the literature, there are mainly three different types of LCA approach that have been used in many studies. The definition of each approach is provided according to what has been described in Onat, Kucukvar and Tatari (2014):

1) Process-based LCA (P-LCA) - often used to analyse the environmental impacts of certain phases, e.g., manufacturing, transportation, use and end-of-life, without looking at the components within the supply chain;
2) Input-output based LCA (IO-LCA);
3) Hybrid LCA, which is the combination of (1) and (2).

Within the context of transport sustainability assessment, eLCA has been carried out to quantify the environmental aspects including life cycle emissions and energy consumption of various AFV technologies at both midpoint and endpoint level. The existing literature also presents some examples of combining the environmental and economic dimensions of life cycles, by applying eLCA along with the life cycle costing tool as described next.

b) Life cycle costing (fLCC)

Life cycle costing is the oldest amongst the three life cycle techniques (United Nations Environmental Program (UNEP), 2011). The concept has been applied since the 1960s, to consider all the costs of developing, installing and using a system throughout the entire lifetime (Eisenberger and Lorden, 1977). However, it is yet to be a fully recognised and accepted standard, as only a "Code of Practice" for the technique is currently available. In terms of terminology, "life cycle costing" and "whole life costing (WLC)" are used interchangeably in the literature. Regardless of the different terms used by various authors, what is consistent is its role in providing insight regarding all future costs (Emblemsvåg, 2003). This technique was originally developed from a strict financial cost accounting perspective, to estimate the total life cycle cost of a procurement process, which include acquisition and life cycle ownership (Dhillon, 1989).

Unlike the eLCA, life cycle costing does not have a similar impact assessment step, since the aggregated cost data provide a direct measure of impact (United Nations Environmental Program (UNEP), 2011). From the examination of literature and from analysing different applications carried out in recent years, this technique has evolved into a more comprehensive method by taking into account the environmental and social aspects. The inclusion of the three pillars of sustainability within the life cycle costing concept has enabled the environmental and social impacts to be included in the LCC calculations (Swarr *et al.*, 2011; Testa *et al.*, 2011; United Nations Environmental Program (UNEP), 2011; Hoogmartens *et al.*, 2014). From here onwards, it moves from a mere economic analysis tool to assuming a key role in supporting sustainable development strategies.

Following the work of SETAC-Europe Working Group on Life cycle Costing (Swarr *et al.*, 2011; Testa *et al.*, 2011), guidelines and a code of practice were published describing the life cycle costing method. In the guideline provided by UNEP, life cycle costing is described as a technique that combines all costs that are directly related to a product over its entire life cycle (from resource extraction over the supply chain to use and disposal) and external relevant costs and benefits anticipated to be privatised (United Nations Environmental Program (UNEP), 2011). Consequently, three different types of LCC assessments were described in the document: the conventional (financial) LCC, Environmental LCC and Social LCC (referred as *f*LCC, *e*LCC and *s*LCC respectively, in this thesis), as illustrated in Fig. 6.

- **Conventional (business/financial) *f*LCC** (the areas included within the blue line):
    - A common method of cost analysis that focuses on financial costs, to support business decisions in procurement and investment
    - Incorporates private costs and benefits
    - Requires the establishment of cost categories and principles in the measurement procedure to be established in advance
    - Characterises the functional unit by a single product only.
- **Environmental LCC (*e*LCC)**:
    - Includes external relevant costs anticipated to be privatised (the areas included within the red line in Fig. 6). For example, if CO_2 is enforced then LCC will reflect these costs in the calculations of total costs incurred by the user or owner.
- **Societal LCC (*s*LCC):**
    - includes the external costs related to society, representing the areas included within the green line in Fig. 6).

Based on the UNEP guideline, the environmental and societal versions of LCC enable the non-financial aspects such as climate impact and human health damage due to emissions to be monetised as external costs or externalities (United Nations Environmental Program (UNEP), 2011). By including these external costs, the perspective of the analysis from that of the private consumer can be shifted to that of society as a whole, as the impacts are predominantly borne by the public (Lipman and Delucchi, 2006). These techniques can be a very flexible tool for sustainability-oriented assessment. Since they deal with monetary units, the use of a common unit allows a huge amount of information included in the analysis, due to the integration between multi-dimensional aspects to be processed and simplified.

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Fig. 6: Scope of application of different techniques for quantifying LCCs (United Nations Environmental Program (UNEP), 2011, p.15)

Although the life cycle costing tools can be used independently to rank different investment alternatives and help decide on the best option, a synergy and combination with LCA brings added value to LCM, which essentially enhances the application of life cycle approaches for decision making (Jeswani *et al.*, 2010). As a result, profound sustainable solutions can be identified and implemented.

c) Social LCA

Social LCA (s-LCA) is developed from *e*LCA, to cover the last pillar of sustainability. There are very few studies found in the literature that consider the social aspects from a life cycle point of view. The selection of criteria for undertaking s-LCA still remain as one of the main challenges when implementing the complete TBL sustainability analysis for sustainable transportation. According to Jeswani *et al.* (2010), s-LCA is more suitable for qualitative studies where it does not involve the quantification of measures and could be highly subjective.

It is worth mentioning that s-LCA is not fully developed as a methodology just yet and poses several challenges (Finkbeiner *et al.*, 2010; Gundes, 2016), although guidelines were established by UNEP/SETAC that present key elements to consider and provide guidance for the goal and scope, inventory, impact assessment and interpretation phases of s-LCA (UNEP Setac Life Cycle Initiative, 2009). Having shared the same fundamental basis of LCT, the framework detailed in the s-LCA Guidelines is in line with the ISO 14040 and 14044 standards for eLCA. It also provides the necessary basis for the development of databases and the design of software that will ease the implementation of s-LCA in practice.

From a review of past studies within the context of transport and/or AFV technologies evaluation, the application of s-LCA is relatively more limited compared to LCC or e-LCA. It is mainly adopted along with LCC and e-LCA as part of the Life Cycle Sustainability Assessment (LCSA), rather than used individually. The concept of LCSA is described next.

d) LCSA

The scope of the LCT approach has been extended to incorporate the perspective of sustainability, which allows the economic, social and environmental criteria to be assessed and integrated within the same framework. While attempting to develop a new life cycle-based sustainability analysis tool, Heijungs, Huppes and Guinée (2010) discovered that eLCA, along with other similar models (like fLCC), is in fact an integrative framework that provides a place for the integration of trans-disciplinary knowledge from different fields. A new method known as life cycle sustainability assessment (LCSA) emerged from this integration, which has been discussed in Zamagni (2012) and Sala, Farioli and Zamagni (2013a). This integration has led to the development of an interdisciplinary framework known as life cycle sustainability assessment, or LCSA (Heijungs, Huppes and Guinée, 2010; Zamagni, Pesonen and Swarr, 2013). LCSA is described in Guinee *et al.* (2011) as *"a framework of models rather than a model in itself: a transdisciplinary integration framework for disciplinary models and methods, selected and interlinked for addressing and answering a specific life cycle sustainability question"*.

The concept of LCSA was initially proposed by Kloepffer (2008), followed by Finkbeiner *et al.* (2010). It is highly promoted by UNEP/SETAC as a tool to help make more informed choices about sustainable options. A guideline entitled "Toward a Life cycle Sustainability Assessment" was published by UNEP/SETAC in 2011, showing how the economic, social and environmental risks of a product can be quantified and incorporated into a sustainability impact assessment (Valdivia *et al.*, 2013). The emergence of LCSA is believed by many to be a promising approach to transparent, robust and holistic decision making (Sala, Farioli and Zamagni, 2013a). The LCSA framework is referred to as a framework for future LCA, as it expands the scope of an environmentally-oriented framework to cover all three dimensions of sustainability (people, planet, and prosperity) (Guinee *et al.*, 2011). It combines three life cycle methods as described earlier (fLCC, eLCA and s-LCA). Heijungs, Huppes and Guinée (2010) considered that these individual life cycle approaches can be viewed as three ways of looking at the same system. The term framework is used for LCSA, as it is "a transdisciplinary integration framework of models rather than a model in itself" (Guinee *et al.*, 2011).

Despite the advantage of implementing LCSA, the lack of a practical framework and computational structure to guide towards its operationalisation has been widely discussed in the literature (Heijungs, Settanni and Guinée, 2013). In a much earlier study, Finkbeiner *et al.* (2010) concluded that the existing LCSA model needs to address issues concerning the weighting of, and trade-offs between, the three sustainability indicators. Due to the methodological differences between the life cycle methodologies that formed the framework of LCSA, the integration is difficult, hence the development of LCSA has not gone beyond theoretical discussions. The different methods/tools share the same life cycle basis, but they vary in terms of methodological elaboration and the question(s) they address (Guinee *et al.*, 2011).

Despite the importance of LCSA in delivering sustainability decision-support (Hoogmartens *et al.*, 2014), there remains doubt as to whether a combination of eLCA, s-LCA, and fLCC as per the original framework of Kloepffer (Kloepffer, 2008) would lead to a more comprehensive sustainability assessment (Tarne, Traverso and Finkbeiner, 2017). The concept of LCSA has been widely acknowledged within the scientific community, however its application in real case studies has been very limited and isolated (Osorio-Tejada, Llera-Sastresa, & Scarpellini, 2017; Valdivia *et al*., 2013) and methodological improvements are still needed (Valdivia et al., 2013; Zamagni *et al*., 2013). The challenges of LCSA are mostly addressed in conceptual studies rather than empirical works, with limited practical examples and the use of integrated approaches (N. Onat *et al.*, 2017). Furthermore, most LCSA or sustainability-oriented life cycle studies found in the literature are either qualitative or review, such as Tarne, Traverso, and Finkbeiner (2017) and Onat, Kucukvar, Halog, and Cloutier (2017). Despite the growing consensus within the scientific community and the theoretical development of LCSA, this critique still holds until today.

Through the LCT approach, the life cycle tools as described above can provide valuable information to support knowledge-based decisions towards sustainable practices, which can be applied for evaluating AFV technologies.

2.5 Evaluating AFV technologies from a life cycle and TBL perspectives

The search for renewable and sustainable energy sources for transport continues, which has led to increasing literature focusing on the holistic evaluation of AFV technologies, from sustainability perspective. Despite abundant literature, there are much less studies that have attempted to incorporate the multi-dimensional TBL aspects within a unified framework. As a result, it is almost impossible to draw general conclusions about the best performing alternative, given that the results are dependent on what factors are considered. Considering the importance of taking a life cycle perspective, the literature review is focused on relevant studies related to the performance of AFV technologies in terms of multiple aspects, that were conducted from the perspective of life cycle. A brief description of these studies is provided in Table 2. As shown in this summary, most articles have focused on LDVs and private passenger vehicles, whilst taxis are relatively understudied as compared to buses. In terms of the geographic context, the literature review revealed that most studies have been conducted in the developed regions (in particular Europe and North America). This finding suggested the lack of practical application of life cycle methods in the context of developing countries, hence the gap that can be filled by this study.

In consideration of the pressing need for sustainability-oriented assessment to inform decision making, it is fundamental to establish the criteria that reflect the multi-dimensional attributes of AFV technologies which correspond to the cost-effectiveness, environmental protection, as well as health and social well-being. Noori, Gardner and Tatari (2015) argue that the importance of including these aspects is generally understood by policy makers, scientists and manufacturers, hence should always be the standard practice when evaluating AFV technologies. Some of the most critical socioeconomic indicators of sustainable transportation are contribution to gross domestic product (GDP), life cycle cost, employment, public welfare and human health (Onat *et al.*, 2016). Meanwhile, CO_2 emissions and climate change, particulate matter formation (PMF), photochemical oxidant formation (POF) are amongst the most considered environmental indicators.

Despite the need to incorporate the TBL concept into the LCA of AFV technologies, the literature review has discovered that only a few studies have attempted to assess AFV technologies using the LCSA framework (Onat, Kucukvar and Tatari, 2014; Romejko and Nakano, 2017). Overall, there is a general lack of consistency in terms of the methods and approach, nevertheless, the *e*LCA and *f*LCC have been applied extensively to undertake a comparative assessment of economic and environmental impacts over the full life cycle.

Table 2: Review of related literature published from 2008-2018 (source: author)

	Type of the study	Reference	Geographical context	Short description of the articles comparing AFV technologies in terms of multiple aspects, from a life cycle perspective
1	LDVs and private passenger vehicles *(21 articles)*	de Souza *et al.* (2018)	Brazil	Evaluated and compared the environmental impacts of vehicles, based on WTW for 5 different scenarios (alternatives): ICEVs fuelled by petrol, hydrous ethanol, mixture of petrol and hydrous ethanol (flex-fuel vehicle), PHEV and BEV.
		Bicer and Dincer (2017)	Canada	Evaluated the life cycle impacts of hydrogen, electric and methanol driven vehicles on the environment and human health, using ozone layer depletion, GWP and human toxicity indicators.
		Bohnes, Gregg and Laurent (2017)	Copenhagen, Denmark	Quantified the life cycle environmental impacts of 5 powertrain technologies (ICEV, BEV, HEV, FCV, range-extended EV) based on 4 deployment scenarios, between 2016−2030.
		Gao and Winfield (2012)	United States	Analysed the life cycle energy consumption, GHG emissions and ownership costs for various advanced vehicles (EV, HEV, PHEV, EREV, FCV) throughout their lifetimes.
		Hao *et al.* (2017)	China	Examined the life cycle cost and GHG emissions of conventional vehicles, HEVs and BEVs, and compared their cost-effectiveness for reducing GHG emissions.
		Ruffini and Wei (2018)	California, US	Compared FCEVs with BEVs and ICEVs, through LCCA of future FCEV adoption and the vehicles' TCO, including the infrastructure cost and the externality cost of carbon emissions.

		Miotti, Hofer and Bauer (2017)	Europe	Assessed the environmental impacts (climate change, terrestrial acidification, human toxicity, photochemical oxidant formation, and particulate matter formation) and costs of FCVs over their entire life cycle, to compare against BEVs and ICEVs.
		Perera, Hewage and Sadiq (2017)	Canada	Evaluated the financial feasibility and environmental impact of the EVs and HFC light duty with a spatial based life cycle approach, to identify the emissions and costs of AFVs and ICEVs.
		Sharma and Strezov (2017)	Australia	Assessed the environmental and economic life cycle impacts of alternative transport fuels and against conventional fuels (diesel, petrol, LPG, CNG, biodiesel, ethanol, HFC and electricity).
		Tagliaferri *et al.* (2016)	Europe	Evaluated the life cycle environmental performances of BEVs and HEVs and compared against diesel ICEVs, in terms of climate change, fossil resources depletion and human toxicity.
		Yazdanie *et al.* (2016)	Switzerland	Compared the energy demand, GHG emissions, and costs for full electric, hybrid, and fuel cell powertrains over the energy and vehicle production, operation, maintenance, and disposal.
		Mitropoulos and Prevedouros (2015)	United States	Provided a detailed LCA of vehicles in terms of life cycle emissions and costs, which includes external costs (emissions and time losses), with societal and consumer life cycle costs.
		Noori, Gardner and Tatari (2015)	United States	Evaluated the life cycle cost, environmental emissions and water footprint of ICEVs, petrol HEVs, petrol PHEVs, petrol EREVs and EVs) under uncertainties, to find the optimal combination of drivetrains in different U.S. regions for the year 2030.

		Rusich and Danielis (2015)	Italy	Estimated the TCOs and social LCCs of 66 car models with different fuel/powertrains (petrol, diesel, bi-fuel CNG, bi-fuel LPG, hybrid, BEV) based on the life cycle energy consumption and environmental emissions, calculated monetarily as external costs.
		Zhao, Doering and Tyner (2015)	China	Examined the economic competitiveness and emissions of BEVs in comparison to ICEVs, using benefit-cost analyses from the perspectives of consumers, society and GHG emissions.
		Onat, Kucukvar and Tatari (2014)	United States	Evaluated the macro-level economic, social, and environmental impacts of alternative passenger vehicles (HEVs, PHEVs, BEVs), using LCA and economic input-output analysis.
		Hawkins *et al.* (2013)	Europe	Assessed conventional and EVs based on five life cycle environmental impact categories, to inform the life cycle merits of EVs relative to ICEVs (production, use, and end of life).
		Karabasoglu and Michalek (2013)	United States	Compared the potential of hybrid, ER-PHEV, and BEV to reduce lifetime cost and life cycle GHG emissions under various scenarios and simulated driving conditions.
		Nanaki and Koroneos (2013)	Greece	Compared the currently available conventional, hybrid and EV (in different electricity generation scenarios-high, medium and low carbon) based on economic and environmental criteria.
		Faria *et al.* (2012)	Europe	Evaluated the economic and environmental balances for BEV, PHEV and HEV versus ICEV, based on the life cycle ownership cost, energy consumption and associated emissions.
		Kantor *et al.* (2010)	Ontario, Canada	Evaluated the life cycle impacts of PHEVs, FCVs and fuel cell PHEVs in terms of six major stressors for climate change, acidification and urban air quality.

2	Buses *(7 articles)*	Tong *et al.* (2017)	United States	Assessed alternative fuel options (diesel, B20 or B100, diesel hybrid-electric, CNG or LNG, and battery electric bus) based on life cycle ownership costs (for buses and infrastructure) and environmental externalities caused by GHGs and CAPs emissions.
		Lajunen and Lipman, (2016)	Finland, United States	Evaluated the lifecycle costs and CO_2 emissions of different types of city buses (diesel, CNG, hybrid electric, fuel cell and electric buses)
		Ally and Pryor (2016)	Australia	Compared the diesel, diesel-electric hybrid, CNG and HFC buses on a TCO basis, using LCC methodology and actual operational data.
		Ercan *et al.* (2015)	United States	Compared diesel, hybrid, BE, B20, CNG and LNG buses, to find an optimal bus fleet combination for different driving conditions based on the total CO_2 emissions, life cycle costs and air-pollutant-related health damage cost impacts (measured in millions of dollars)
		Ercan and Tatari (2015)	United States	Evaluated the total air pollutant emissions and water withdrawal impacts of a transit bus with different fuel options (diesel, biodiesel, CNG, LNG, hybrid (diesel-electric), and battery electric.
		Ribau, Silva and Sousa (2014)	Portugal	Analysed FC-HEV and FC-PHEV city buses relative to diesel, highlighted the significance of the driving conditions and the conflict between objectives (minimisation of the cost and fuel, cost and LCA CO2eq, or fuel and LCA CO_2eq) with multi-objective genetic algorithms.
		McKenzie and Durango-Cohen (2012)	United States	Analysed the life cycle costs and GHG emissions associated with the manufacturing and operating phases of four types transit buses: diesel, CNG, diesel-electric hybrid and HFC.

3	Taxis *(4 articles)*	Y. Cai *et al.* (2017)	Beijing, China	Assessed the life cycle environmental effects and economic costs of multiple vehicles (i.e., conventional, hybrid, PHEV, and EVs) in multiple scenarios based on current and future policies.
		Deyang, Dan and Minmin (2016)	Shanghai, China	Performed a comparative analysis between electric taxis and petrol taxis, from the viewpoint of lifecycle cost and WTW emissions.
		Castel-Branco, Ribau and Silva (2015)	Lisbon, Portugal	Analysed the best theoretical hybrid powertrain based on maximum in-use efficiency, minimum life cycle GHG emissions, and minimum taxi owner's cost, using multi-objective genetic algorithm to achieve optimal trade-off solutions for different driving patterns.
		Vedrenne *et al.* (2014)	Madrid, Spain	Evaluated the substitution of diesel taxis with hybrid, CNG and LPG alternatives in four different scenarios, in terms of impacts closely related to the air quality situation: acidification, climate change, particulate matter, photochemical ozone formation and terrestrial eutrophication.
4	Freight/medium/ heavy-duty trucks *(6 articles)*	Figliozzi, Saenz and Faulin (2018)	United States	Analysed the life cycle carbon footprint of urban deliveries in a real-world case study of Portland, Oregon, using a lifecycle emissions minimisation model.
		Mareev, Becker and Sauer (2018)	German	Compared the life cycle costs of BE trucks and conventional diesel trucks in different transportation scenarios, including the charging infrastructure.
		Lee and Thomas (2017)	United States	Evaluated the economic and environmental life cycle trade-offs of medium-duty electric trucks compared to 9 non-electric technologies (e.g., diesel, biodiesel, CNG, etc.) based on cost, energy efficiency, fresh water consumption, and air emissions impacts (i.e., global warming, acidification, eutrophication, smog formation, monetised human health and ecological damage).

		Sen, Ercan and Tatari, (2017)	United States	Analysed and compared the life cycle emissions and costs, and air pollution externality costs of different types of alternative fuel-powered heavy-duty trucks (B20, CNG, hybrid, and BE).
		Song *et al.* (2017)	China	Performed a comparative LCA of the energy consumption and GHG emissions of diesel-and LNG-powered trucks or heavy-duty vehicles (HDVs) using actual, reliable data.
		Zhou *et al.* (2017)	Toronto, Canada	Compared a Class 6 medium-duty BE with a diesel truck in terms of life cycle GHG emissions and lifetime TCO, based on different drive cycles, operating temperatures and payloads.
5	Government/municipal fleets *(4 articles)*	Emery, Mbonimpa and Thal (2017)	United States	Examined the life cycle emissions and economic externalities due to climate change and health-related air pollutant impacts from operation of the non-tactical vehicle fleet at military installation.
		Sengupta and Cohan (2017)	Houston, Texas	Calculated the fuel cycle emissions and life cycle costs associated with petrol and alternative fuel vehicles (HEVs, PHEVs, BEVs, and CNGV) in the City's municipal fleet.
		Shahraeeni *et al.* (2015)	British Columbia, Canada	Conducted a comparative LCA of light duty commercial vehicles or pickup trucks powered by CNG and diesel in terms of GHG and CAP emissions, energy use, and cost effectiveness, for vehicle deployment in the municipal fleet.
		Rose *et al.* (2013)	British Columbia, Canada	Compared the LCA of diesel and CNG- powered heavy duty refuse collection vehicles, to inform the selection by decision makers based on realistic estimations of life cycle emissions, cost, and energy use.

When making comparisons between AFV technology options, one must require a comprehensive, quantitative assessment on a life cycle basis which goes beyond the fuel "well-to-wheel" (WTW) analysis (MacLean and Lave, 2003). From the initial review, it is discovered that the fuel WTW approach is commonly applied for quantifying/estimating the energy consumption and its associated GHG or CAPs emissions. This approach is a subclass of LCA, which can be used as a tool to evaluate and compare the energy consumption, economic cost, and environmental impacts when studying automotive fuels production and use (Orsi *et al.*, 2016). Nevertheless, given that the WTW analysis does not consider energy and emissions involved in building facilities and the vehicles, or end-of-life (EoL) aspects ((Roosen, Marneffe and Vereeck, 2015), they do not qualify as being a true LCA (since it does not cover the full life cycle inventory of the vehicle-fuel system). Out of the 400 articles initially considered, more than 50% of the studies were found inadequate to represent a true "LCA" of vehicle technology options. This justification is in agreement with the findings of the literature review survey by Hawkins, Gausen and Strømman (2012), which discovered that very few full life cycle inventory studies exist, despite an abundance of studies evaluating AFV technologies.

The system boundary of vehicle LCA is comprised of the fuel cycle and the vehicle materials life cycle. To illustrate example and for easier understanding, Fig. 7 illustrates a full inventory of a taxi vehicle-fuel system life cycle, drawing the interconnections between the vehicle and fuel cycles.

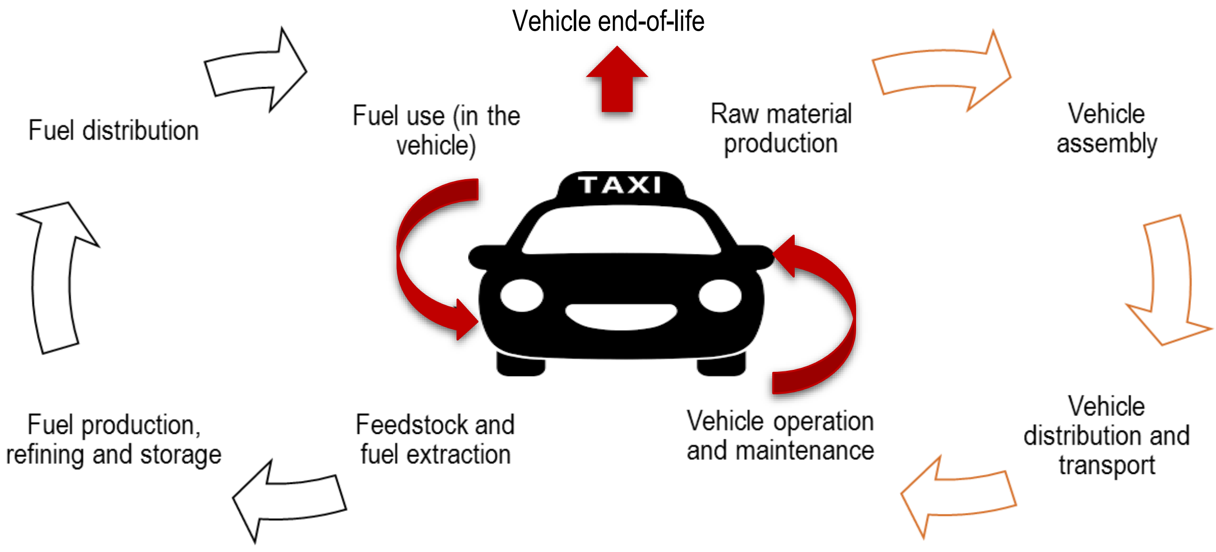


Fig. 7: Schematic overview of a taxi vehicle-fuel system life cycle (adapted from MacLean and Lave, 2003, p.39)

As illustrated in the above diagram, the LCA inventory of vehicle cycles primarily covers the material production, e.g., steel, plastics, non-ferrous metals such as aluminium; glass, rubber and composites such as fibreglass; and vehicle assembly, until the distribution and transport of the vehicle to the dealerships (Perera, Hewage and Sadiq, 2017). Then, vehicle operation includes the maintenance and repair over its lifetime, and finally, the EoL stage includes transportation of the vehicle to a dismantling facility, dismantling, shredding and disposal of the shredder residue, with some materials recycled for further use (Lave *et al.*, 2000; Gao and Winfield, 2012). Meanwhile, the fuel cycle is connected to the vehicle cycle through the fuel consumption in the vehicle during operation. This stage is often referred as the tank-to-wheel stage (TTW).

Besides the TTW stage. the fuel cycle covers the processes from feedstock recovery ("well"), raw materials extraction, transportation, production of the desired fuel, up until distribution of the fuel to consumers, known as the well-to-tank, WTT (Bicer and Dincer, 2017). The aggregation of the energy consumption, direct and indirect emissions caused by fuel consumed in the vehicle makes up for the complete inventory. Direct emissions are those emitted directly when the fuel is being used in the vehicle (or in the case of BEV, at the point of electricity generation). Meanwhile, the indirect emissions comprise those generated from energy used for manufacturing the vehicle (from materials extraction until assembly) and "upstream'' operations, from fuel extraction, production, refining, storage, distribution and dispensing (Ogden, Williams and Larson, 2004).

Considering the indirect impacts from upstream process as shown in the literature, the assessment of AFV technologies must not focus solely on the fuel use or vehicle operation phase. First and foremost, the fuel consumption and CO_2 emissions during the in-use stage only account for over 70% of the life cycle (Ma *et al.*, 2017). When evaluating new vehicle technologies, it is recommended that LCA is performed for the complete inventory of vehicle and fuel cycle, covering vehicle production, manufacturing and recycling, and the complete fuel cycle of fuel production, transport and the driving phase where fuel is consumed (Sharma and Strezov, 2017). By way of example, the justification for including vehicle manufacturing impacts has been demonstrated in Hawkins *et al.* (2013), which found the GWP of EV production to be twice that of conventional vehicles. Assessments relying solely on fuel and powertrain efficiencies are claimed to be missing key differences with regard to the production of vehicles with different types of powertrain-technologies, thus could lead to misguided comparisons, biased conclusions and suboptimal results of evaluated options.

Although many studies have covered the inventory quite well, the end-of-life (EoL) treatment of the vehicle (plus battery for BEV) is sometimes disregarded, such as in (Noshadravan *et al.*, 2015). The EoL stage requires extensive data collection, although proper data have not been available for many of the researchers. Furthermore, existing studies have shown that the impacts during EoL are small, immaterial and somewhat negligible (see for instance Hawkins *et al.*, 2013; Ally and Pryor, 2016, de Souza *et al.*, 2018).

2.6 Dealing with Uncertainty in AFV technologies LCA

From the review of past studies, it can be concluded that AFV technologies are evolving constantly and projections about the future are extremely uncertain. Within the context of AFV technologies, the comparative assessments in the existing studies are also subject to significant variations - not only in the scope and contextual settings, but in the underlying assumptions, due to inherent uncertainty factors (Abdul-Manan, 2015). Previous studies have demonstrated that the AFVs might not be realised everywhere and in every condition. The benefits of advanced AFV technologies are subject to the market, where they are sold and used, as the electricity sources, taxation and incentive schemes (Hawkins *et al.*, 2013), purchase price, sales tax, tariff, registration costs, government subsides, insurance cost etc. vary from one place to another (Al-alawi and Coker, 2018). Added to that are the unpredictable political and economic factors affecting global energy prices, customers' behaviour toward new technologies, the performance and cost of future technologies, and future governmental actions, which are amongst the uncertain factors mostly cited in the literature (Noori, Gardner and Tatari, 2015).

Uncertainty refers to an incompleteness of knowledge or lack of understanding, whereas variability (aleatory uncertainty) is described as "the inherent variations and randomness of the quantity, process or system of interest" (Dong *et al.*, 2018). According to these authors, uncertainty can affect the decision process, while variability cannot be eliminated. Amongst the categories of variability that are often examined in the literature are: temporal (time), spatial (location) or inter-object variations. Meanwhile, two types of uncertainty are commonly studied: model uncertainty and parameter uncertainty. The former captures the "imperfect representability of the true processes and systems", whereas the latter refers to "the lack of knowledge of the exact parameter value in a model" (Dong *et al.*, 2018).

Since the cost/benefits of AFV technology options cannot be determined with exact certainty, some alternatives can be riskier. To enable decision makers to find a balance between the high risk-benefit situation, and better assess AFV technologies with robust conclusions, uncertain and unknown factors need to be sufficiently accommodated (Noshadravan *et al.*, 2015). The capability of life cycle methods to estimate environmental burdens and health-related impacts in financial values, for instance, by integrating economic and environmental information of physical evidence, has been largely demonstrated. However, some doubts and uncertainties remain to form another challenge in yielding robust (i.e., tolerant to uncertainty) and reliable results that can be used to inform decision making. As a result, a model based on fixed, deterministic values is not robust enough to handle the uncertainty and variability factors reflected by the current market environment. Not only that it does not identify the factors, drivers of variation and parameter values that are critical, a deterministic model does not assess the magnitude of impact these uncertain and variability factors have on the analysis results.

Using a life cycle model as decision-support requires the assessment and communication of uncertainties problems to be done in a proper manner (Di Giuseppe, Massi and D'Orazio, 2017). As briefly summarised in Ling-Chin, Heidrich and Roskilly (2016), the use of scientific approaches by more research will directly reduce uncertainties; scenario comparison and graphical approaches will show the effects of inputs (e.g., parameters and choice) on the results; stochastic modelling will deal with uncertainties while analytical methods, such as fuzzy number, Bayesian and hybrid LCI, by nature propagate uncertainties. The analytical methods could be computationally intensive for systems with an extensive dataset of input variables, such as those included in this study, and thus the stochastic simulation methods are usually preferred (Venkatesh *et al.*, 2011). Thus, there is a growing interest in the integration of stochastic modelling and probabilistic methods for handling uncertainty in LCA to inform more robust decision making.

It has been largely acknowledged that uncertainty and variability need to be properly managed in LCA and communicated in the decision process. Evidence from past studies has demonstrated the capability of a stochastic model to deliver a more reliable conclusion (Zhu, Tao and Rayegan, 2012) that will make it easier for decision makers to work with greater objectivity (Cartelle Barros *et al.*, 2016). This was achieved by providing decision makers with a more complete picture of what the consequences of their decisions are considering the associated risks (Bastani, Heywood and Hope, 2012), through analysing and quantifying the impacts of real-world uncertainties.

Dong *et al.* (2018) claim that parameter uncertainty is addressed by the practitioners, as opposed to model uncertainty and impact assessment, which are rarely considered in current LCA practice except in academic application. Despite the critical need to address uncertainties when conducting life cycle-based analyses, a literature searches on the topic of life cycle sustainability assessment of AFV technologies conducted by the researcher revealed that the number of peer-reviewed articles dropped to more than 90% when the keyword of “uncertainty” was added as an inclusion criterion. Although it might not be the only reason, this example shows that the subject of uncertainty is still not widely covered in the existing studies.

Based on the literature review, studies on AFV technologies assessment based on a probabilistic approach are relatively rare, as all the 45 reviewed models are deterministic. Several studies (such as in Tong *et al.*, 2017; Y. Cai *et al.*, 2017; Zhou *et al.*, 2017) may be able to convey some uncertainties to decision makers in sensitivity analysis (by varying each input value individually while keeping all other parameters the same), and/or by using a different set of parameters in different scenarios (Song *et al.*, 2017; Wolfram and Wiedmann, 2017). Nevertheless, these types of models do not account for the correlation and joint effects between multiple parameters and the final output values, hence they are arguably to be less informative.

As discovered through the literature review presented in this section, the existing literature is fairly unanimous and conclusive in its assessment that uncertain factors have an impact on LCA results, thus affecting its accuracy and credibility, especially if the model is to be used as a decision-support tool. Despite its importance, many studies did not address uncertainty as an explicit area of investigation within the context of AFV technologies assessment, which may lead to inappropriate decisions. It is therefore important to take these uncertainties into consideration within the decision-support framework, to be properly managed in LCA and communicated in the decision process. This finding emphasised the need to undertake a stochastic/probabilistic approach as part of the decision-support tool functionality.

2.7 Summary

Informed by the literature review, developing a life cycle model that responds to the TBL complexities and conflicting priorities of decision makers, uncertainty and variability factors is not an easy and straightforward task. A probabilistic approach has been claimed to provide a solution for handling uncertainty and factor variations; however, to the researcher’s best knowledge, none of the currently available models/tools have incorporated stochastic modelling when evaluating AFV technology choices. This creates an opportunity to add to the growing body of research concerning a stochastic life cycle model that reveals enough knowledge to support decisions by providing a range of potential outcomes and the predicted chance of their occurrence.

Whilst some research has been carried out on LCA of AFV technology covering TBL sustainability aspects, an alternative option that performs the best and optimises (or maximises) all criteria simultaneously is almost non-existent and difficult to achieve in practice. The concept of optimising/maximising is therefore less practical in this circumstance. Therefore, it is valuable to explore an alternative decision strategy, as a mechanism for making satisfactory trade-off which would be useful to aid collaborative decision making.

The summary presented in Table 2 shows that the LCA of fuel technology options for taxi fleet is the least studied in the literature. This gap provides evidence justifying the need for developing a framework/tool to inform the decision making of stakeholders in the taxi industry, such as fleet operators, regulators, policy makers and vehicle manufacturers. Finally, an examination of studies on AFV technologies evaluation also reveals that the life cycle models for sustainability or TBL assessments are mostly established for European or North American contexts. This has left a gap for a model that is specifically developed for application in developing nations, especially in the Asian region.

Overall, the findings from literature review are beneficial to identify the gap and need for research, and useful to provide information for the development of a framework as proposed in this study. This thesis can therefore lay the groundwork for future research into a more holistic and practical tool for supporting decision making in a multi-stakeholder context. The literature review has identified various studies to assist the researcher in focusing on the aspects that are relevant considering the different scope and context, to reflect the perspectives of stakeholders and decision makers. The review of past studies also provides useful information and theoretical understanding of how the life cycle methods and model(s) are applied for evaluating the performance of AFV technologies from a sustainability and/or TBL perspective. Informed by the literature review, the comparative LCA of AFV technologies also provides an insight to facilitate in developing the integrated framework using the approach and methods as discussed next.

CHAPTER 3: FRAMEWORK OF THE DECISION-SUPPORT TOOL

3.1 Introduction

To fulfil the second objective of this research, the methodology for the decision-support tool is elaborated in this chapter. Firstly, a conceptual framework is presented. Then, the operational procedures of the framework are described, to illustrate how it can be implemented in practice. The chapter concludes with architecture of the integrated tool, with a graphical layout of the life cycle model showing the input, process and output.

3.2 Conceptual framework

The proposed framework is designed to be a shared platform for knowledge-based decision making towards sustainable fleet operations, considering uncertainties and differing objectives of decision makers. The conceptual framework is presented in Figure 8. The integrated circles inside the triangle represent the multi-dimensionality aspects to inform transport decision making. The square boxes at the tips of the triangle represent the fundamental method of the stochastic and life cycle sustainability-oriented assessment with the strategy of satisficing from the bounded rationality theory.

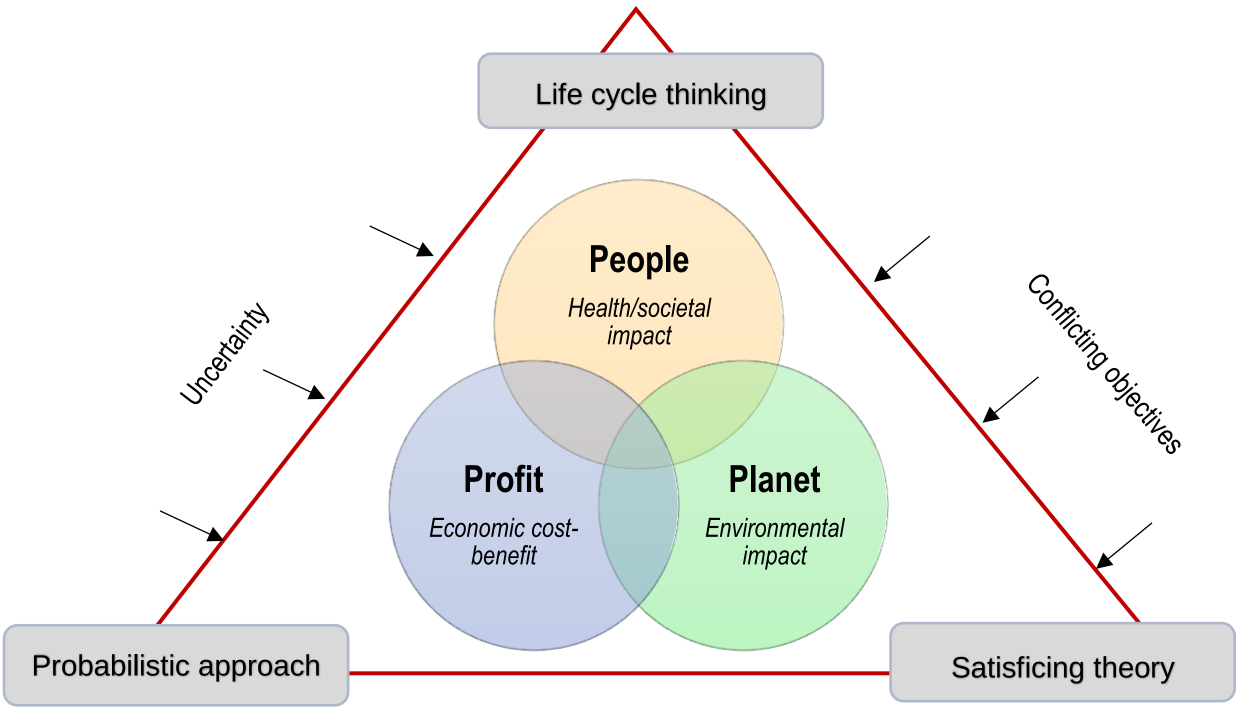


Fig. 8: Conceptual framework (source: author)

3.2.1 Triple-bottom-line oriented LCCA

In order to implement the proposed framework, a valid operational model is required that yield robust outputs of the life cycle sustainability, costs and benefits. A TBL-oriented analysis requires a multi-dimensional perspective for evaluating the attributes of AFV technologies, using appropriate criteria and indicators. Following ISO 14040 of the LCA framework, the inventory and impact indicators must be related to a common functional unit of the assessed product (United Nations Environmental Program (UNEP), 2011).

According to Finkbeiner *et al.* (2010), understandable and effective ways in presenting LCSA results are prerequisite to communicating them to the non-expert audience of real-world decision makers in public and private organisations. Ally and Pryor (2016) argued that the use of costs is the most relevant for comparing technology options for fleet selection and planning purposes. Meanwhile, Tarne, Traverso and Finkbeiner (2017) revealed that decision makers strongly emphasise the need to express sustainability impacts in monetary terms, in order to facilitate the interpretation and inclusion of sustainability criteria in management decisions. A major advantage of valuing the multi-dimensional TBL impacts in monetary terms is that it can provide greater clarity and aid non-expert users to understand the complex results. This approach is particularly useful for addressing the lack of a common and easy-to-communicate indicator. This defines the rationale for adopting the extended version of LCC, covering environmental and societal life cycle externalities, as described earlier in Section 2.5.

In the definition provided by Woodward (Woodward, 1997), "*LCC seeks to optimise the cost of acquiring, owning and operating physical assets over their useful lives by attempting to identify and quantify all the significant costs involved in that life, using the present value technique"*. The methodology is appropriate for the context of this study because it allows a huge amount of information to be processed and simplified, as the economic, social and environmental aspects can be evaluated in a common context, to represent the total life cycle sustainability impacts. It is worth reiterating that LCC has evolved to become a very flexible appraisal tool in incorporating SD aspects (Testa *et al.*, 2011) hence it is particularly relevant for this study.

The computation of LCCs typically involves the use of net present value (NPV) as the metric. NPV, or present discounted value (present worth), is widely applied in financial or economic analysis to compare net cash flows at different time periods where the future value of money has been discounted (Nurhadi, Borén and Ny, 2014). This metric reflects the future worth, which typically is less or equal than today's value. Equation 1 and 2 provide a basic understanding of how the future value of LCC can be written in the form of discounted PV and NPV.

Equation 1:

$$PV = \left(\frac{A_t}{(1+i)^t}\right)$$

Equation 2:

$$NPV_{LCC} = \sum_{t=0}^{T}\left(\frac{A_t}{(1+i)^t}\right)$$

Where;

A_t: Amount of costs (future value) at year *t*
i : Discount rate
t : Time of the cash flow, in year
T: Life cycle (analysis) period

3.2.2 Probabilistic simulation for dealing with uncertainties

Based on the problem statement described in Section 1.3, a limiting yet important consideration is that the model outputs (based on the quantified impacts of each criteria measure) are not always known with absolute certainty. To ensure robustness of analysis with confidence in the accuracy of input parameters and completeness of assumptions, uncertainty should be explicitly considered as much as possible. Examining and quantifying the uncertainty of an LCA can significantly enhance the usefulness of the findings, allowing decision makers to better understand the consequences of their decisions in the light of associated risks (Bastani, Heywood and Hope, 2012) and as a reference for future researchers (Ally and Pryor, 2016). Recognising this need, the proposed framework incorporates a systematic mechanism for evaluating technology options under uncertainties.

Before introducing the approach for dealing with uncertainties, the nomenclature of these factors is provided, as per Table 3, by classifying them according to the sources and when they occur (according to the 4-step phase of LCA). According to Huijbregts (1998), a classification is important in order to determine which are the appropriate methods to deal with them.

Table 3: The classifications of uncertainty and variability factors (adapted from Huijbregts, 1998)

Type of factors	LCA phase	Sources
Parameter uncertainty	LCI	• Inaccurate emission measurements
	LCIA	• Uncertainty in lifetimes of substances • Inaccurate normalisation data
Model uncertainty	LCI	• Linear instead of non-linear modelling
	LCIA	• Impact categories are not known • Contribution to impact category is not known • Characterisation factors are not known • Weighting criteria are not operational
Uncertainty due to choices[1]	Goal & Scope	• Functional unit
	LCI	• Use of several allocation methods
	LCIA	• Leaving out known impact categories • Using several characterisation methods within one category • Using several weighting methods
Spatial variability	LCI	• Regional differences in emission inventories
	LCIA	• Regional differences in environmental sensitivity • Regional differences in distance to (political) targets
Temporal variability	LCI	• Differences in yearly emission inventories
	LCIA	• Change of temperature over time • Change of social preferences over time
Variability between sources and objects	LCI	• Differences in emissions between factories which produce the same products
	LCIA	• Differences in human characteristics • Differences in individual preferences when using the panel method

In order to provide example on how the above factors can be addressed, the proposed framework will focus on Parameter Uncertainty, based on how likely this factor would exist within the context of this study due to inaccurate data when it is measured or collected. This examination is adequate for the scope of this thesis, as studies have shown that uncertainty in parameters and data affects the results most directly, producing invalid outputs that can ultimately impact upon management practices and decisions (Yu and Tao, 2009). In addition, Dong *et al.* (2018) claim that practitioners within the transport sector often give more attention to parameter uncertainty in both LCA and decision analysis. Therefore, at this juncture, other categories of uncertainty and variability factors are not dealt with by the proposed framework/tool.

The available tools for addressing uncertainties are shown in Fig. 9, which are adapted from Huijbregts (1998). Based on this classification, parameter uncertainty (inputs that are truly uncertain) can be addressed in 4 ways: probabilistic simulation; correlation and regression analysis, additional measurements; and expert judgement/peer review (as marked with + symbol within the red circle). Amongst these 4 techniques, probabilistic simulation (or sometimes known as stochastic modelling) is an especially promising technique for making uncertainty in model output operational (Huijbregts, 1998) hence applied for treating parameter uncertainty within the scope of this framework.

Types / **Tools**	Parameter uncertainty	Model uncertainty	Uncertainty due to choices	Spatial variability	Temporal variability	Variability in objects/sources
Probabilistic simulation	+					+
Correlation and regression analysis	+					+
Additional measurements	+					+
Scenario modelling			+		+	
Standardisation			+			
Expert judgement/peer review	+		+			+
Non-linear modelling		+				
Multi-media modelling		+		+		

Fig. 9: Approach for addressing uncertainty and the selected method (adapted from Huijbregts, 1998, p.277)

[1] Also known as scenario/assumption uncertainty in Zhang and Wang (2017)

Probabilistic simulation, which can be performed by Monte-Carlo or Latin Hypercube simulations, has advantage over the other methods when dealing with parameter uncertainties because the model can uses parameters that are randomly and independently varied in accordance with Probability Distribution Function (PDF) such as uniform, triangular, normal, or lognormal distributions, instead of being treated as fixed values (Huijbregts, 1998; Yu and Tao, 2009; Macián, Tormos and Riechi, 2017). In other words, analysts are no longer restricted to use single-point estimates, but instead it allows them to incorporate everything that is known about the parameter (Abdul-Manan, 2015). Plus, it is technically easy to deal with if the correlations between parameters can be estimated (Huijbregts,1998). This technique enables the stochastic model to generate random variables over a given range according to their respective PDF, to perform model simulations and yield desired predictions (Yu and Tao, 2009). The working principles of a probabilistic model with MCS are illustrated in Fig. 10, taken from Yu and Tao (2009).

Fig. 10: The principles of probabilistic model with Monte-Carlo simulation (Yu and Tao, 2009, p.183)

Emblemsvåg (2003), as cited in Macián, Tormos and Riechi (2017), claimed that MCS is particularly useful for cost management purposes, thus is an ideal method for quantifying parameter uncertainty in LCC studies. Whilst uncertainty analysis deals with “unknown” parameters by quantifying how uncertain they are, a probabilistic/stochastic model produces results in a range of possible outcomes, with their probabilities. The distribution of results can be very valuable and informative, since several values (e.g., min/max, standard deviation) are provided instead of just a single value (Mennenga, Thiede and Herrmann, 2013). With this approach, the life cycle model has the capability to better depict the results and provide more realistic understanding of results uncertainty, enabling decision makers to evaluate choices on the basis of their risk profiles.

3.2.3 Application of Satisficing Theory

Considering the limited information, time and computer programs to provide knowledge for decision making, the most rational way to proceed is through heuristic or search mechanism (Schwartz, 2002). A choice heuristic describes how one alternative is selected from a choice set., which begins with an analysis how the choice set is faced by decision makers and ends by them choosing an alternative (González-Valdés and Ortúzar, 2018). Furthermore, in many decision problems, oftentimes alternatives are not all available to the decision makers simultaneously or rather presented to them randomly and sequentially over time (Chun, 2015). The complexity in fleet decision making involving industry stakeholders and multiple decision makers with different objectives calls for the theory of satisficing to facilitate collaborative decision making. Consequently, the usability of the probabilistic simulation-based LCCA model is extended into a Satisficing choice model. To describe this development, Satisficing behaviour and principles are first described. Then, simplifications are adapted to the framework and working procedures are established.

More than half a century ago, Herbert Simon (Simon, 1955) proposed a theory of bounded rationality based on human behaviours in decision making, which provides the basis for the Satisficing choice heuristic. Simon argues that any choice model requiring the inspection of all attributes and a comparison (or consideration) of all the alternatives would be highly implausible in many practical applications, information gathering is costly due to cognitive and processing effort, and thirdly the difficulty combining attributes of a different nature (González-Valdés and Ortúzar, 2018).

The concept of “Satisficing” is defined in Miller and Shelton (2010) as “a decision-making procedure that attempts to meet criteria for adequacy, rather than identify an optimal solution”. Schwartz (2014) claims that a satisficing decision maker is willing to choose the best alternative when one is obviously at hand, however he may be willing to settle for less too, with a good enough alternative. In his work (Schwartz, 2014), a formulation of satisficing was presented for some u and all X:

Equation 3

If $x \in X$ and $u(x) \geq u(y)$ for every y in X then $x \in C(X)$.

Fig. 11 summarises the main characteristics and behaviour of satisficing decision makers in comparison with the maximisers. According to Luan and Li (2017), satisficers place similar importance on desirability; however, they value feasibility differently compared to maximisers. Satisficers are willing to choose the best alternative when one is obviously available, but they may be willing to settle for less too, with a “not the best” but a “good enough” option (Schwartz, 2014). Luan and Li (2017) argued that satisficers’ preference to go for a less valued option is not because they view the value as not important. But rather, they care about the level of effort in order to accomplish their choice hence the less valued and effortless option (which is not necessarily the very best outcome in all aspects) is preferred.

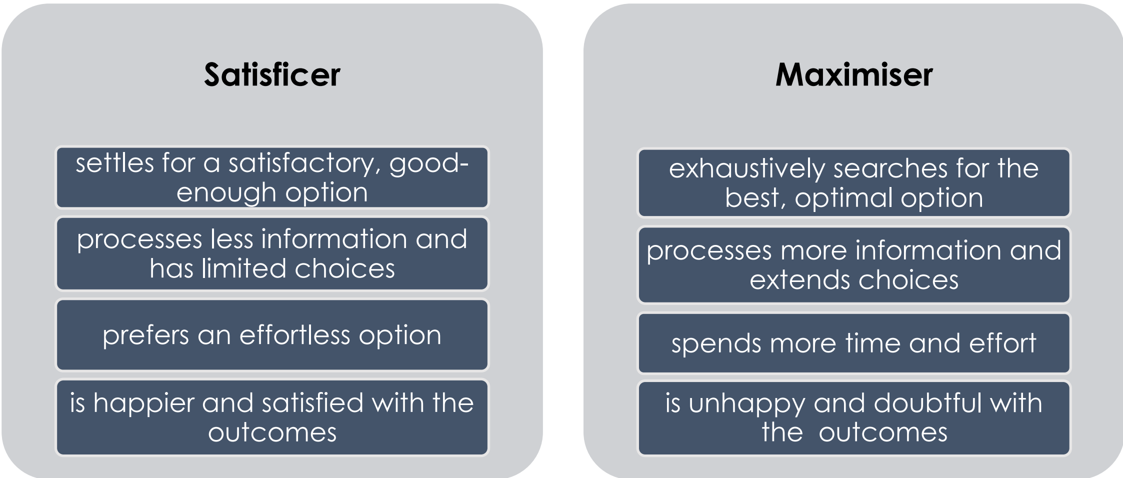


Fig. 11: The main characteristics of satisficers as compared to maximisers (adapted from Misuraca and Teuscher, 2013; Schwartz, 2014; Luan and Li, 2017)

As suggested by Simon (1955) and Schwartz (2002), people have the tendency to spend enough effort to make a satisfactory decision rather than one that optimises or maximises benefits from the decision. Therefore, Simon's work on Satisficing Theory (Simon, 1955) has advocated several simplifications that make the behavioural process more plausible for the human mind. He recommended the use of simpler heuristics to cope with a high cognitive burden in circumstances where the choice is too complex (González-Valdés and Ortúzar, 2018), or due to incomplete knowledge and information by the time a decision has to be made (Schwartz, 2002). His ideas are designed to accommodate the cost of searching and comparing alternatives, by simplifying the assumption and assessment procedures. The simplification was suggested through simple pay-off functions (e.g. distinguishing between acceptable and unacceptable alternatives), using a reservation value or acceptance threshold, and partial ordering pay-off functions (Simon, 1955).

Based on Simon's Satisficing Theory, decision maker discovers and analyses alternatives consecutively, following a simple procedure where they would stop and choose the best alternative they found if they are satisfied, or else they will keep searching (Simon, 1955). The process essentially involves examining alternatives until a practical (most obvious, attainable, and reasonable) solution with a sufficient level of acceptability is found, then stopping at that point instead of continuing to look for the best-possible (optimum) solution. Rather than processing a higher amount of information and engage in an exhaustive search and examination of each and every available option, satisficers tend to process less information and consider a more limited range of choices (Misuraca and Teuscher, 2013). They usually set an aspiration level and simply try to find any choice that reaches or exceeds that level, instead of attempting to select the best among all feasible choices (Chun, 2015). At any point where optimisation is simply not possible or too exhaustive, the good-enough option is adequate because to a certain extent it reflects a compromise between desirability and feasibility, as shown in Luan and Li (2017). This can potentially help decision makers to compromise and reach a consensus in a collaborative decision-making process, towards meeting sustainability goals.

Following Simon's Satisficing Theory, the model is therefore designed to induce two principles as follows:

- an alternative can be either "acceptable" or "non-acceptable" (using a reservation value of acceptance threshold);
- to accept the first "good enough" alternative (amongst the available options)

The working procedures will elaborate on how the above simplifications are adapted into the model.

3.3 Working procedures of the decision-support tool

The process flow and working procedure of the decision-support tool are broken down into three (3) stages, as shown in Fig. 12.

- Goal and Scope Definition
- Assessment and Quantification
- Results Interpretation

The above steps makes reference to the general decision-making process that was introduced 37 years ago by Keeney (1982), as discussed in Dong *et al.* (2018). As a life cycle-based tool, the framework upholds the principle of LCA (as in the ISO 14040-44), with the proposed improvement as per the scope and expected outcomes of this thesis (Section 1.6). It is worth mentioning that the tool is designed as a common justification platform to aid collaborative decision making, by providing statistical knowledge to help inform decision makers in selecting the best possible choice. However, examination on what selection or decisions are eventually made is beyond the scope of this study.

The first stage of the process is goal and scope definition. At this stage, alternatives and attributes are defined, then criteria are established which can be linked to the objectives of decision makers. The second stage involves the assessment and quantification of impacts based on known and uncertain parameters. The final stage is for interpreting the results; this is where alternatives are compared, trade-offs are explored; and satisficing choice is determined when the optimal option is not attainable. The process is elaborated next.

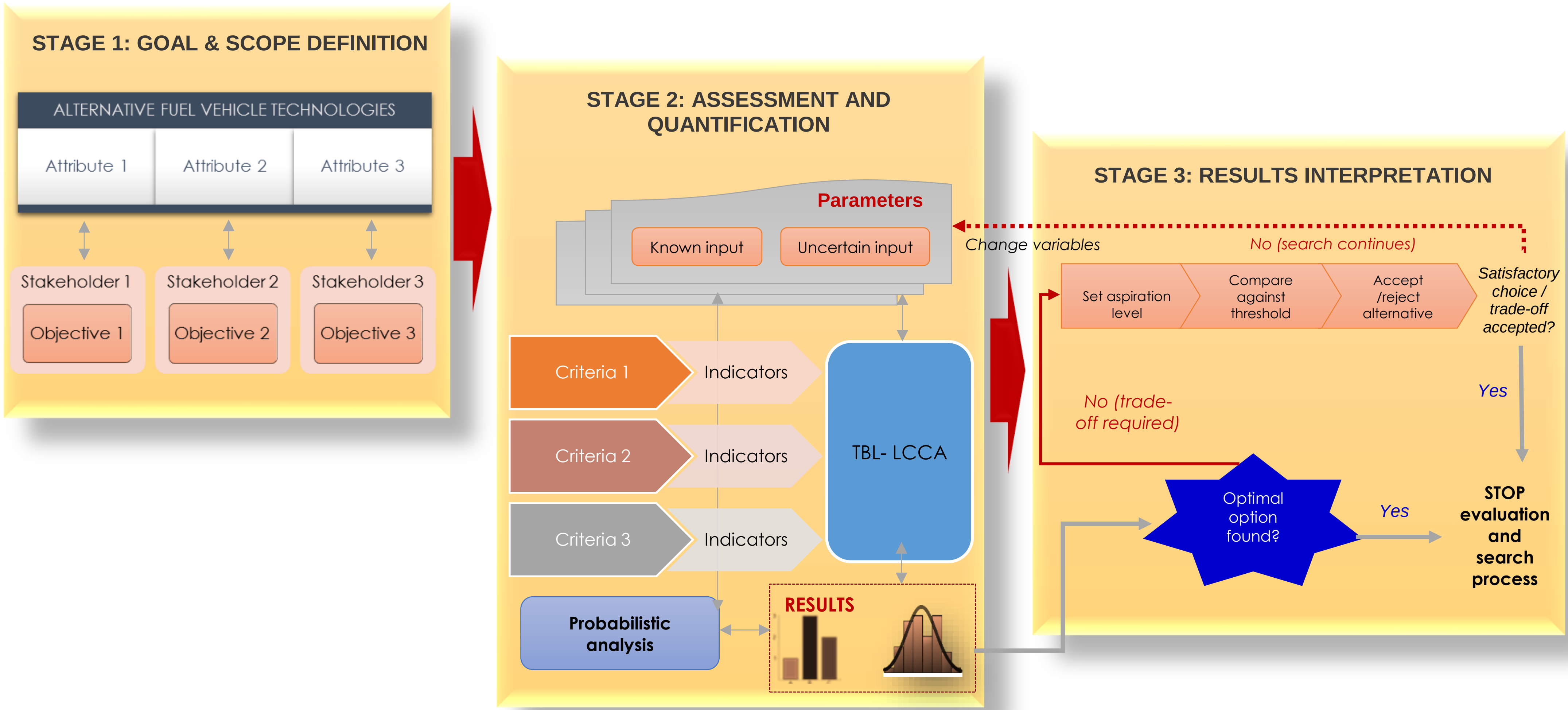


Fig. 12: Process flowchart and working procedures of the decision-support tool (source: author)

3.3.1 Goal and Scope Definition

First, it is important to identify clearly the various attributes of AFV technologies in order to determine the selection and decision making of the most appropriate choice for sustainable fleet operations. The use of multiple criteria enables the evaluation process to be conducted in a way that incorporates different interests and objectives of decision makers. When selecting the criteria, it is important that they enable comparison between alternatives, using appropriate indicators that measure how well each alternative performs with respect to the decision criteria.

Despite the extensive research on the topic of sustainability and AFV technologies, the findings from the literature review, as discussed in Chapter 2, suggest that there is no ‘’universally’’ accepted and standard set of criteria (and indicators) for evaluating AFV technology choices, because each study varies in scope and context. The most referenced and commonly used in similar studies can be considered as the most relevant, considering the goal and scope of study. In the context of sustainability assessment, the use of appropriate indicators is crucial, as it will determine how effective the tool will be in aiding decision making. The use of indicators, as recognised by the UN, would enable policy makers to perform a comprehensive assessment, which would lead to a better and informed decision toward SD (United Nations, 2007). Some of the criteria for selecting indicators are as follows:

- Indicators should be simpler, more comprehensive, easy to calculate, with available data, and the ability to reflect the three pillars of sustainability in depth (Feleki, Vlachokostas and Moussiopoulos, 2018).
- Indicators should not be more than five to six, in order to facilitate the interpretation of results (Belchí Lorente *et al.*, 2015) .

To provide an example for implementing the framework, 4 quantitative criteria are selected for the context of this study, based on their importance for evaluating AFV technologies and relevance in the context of taxis operating in a typical example of a rapidly growing city, which are regulated by government bodies and established under taxi associations. Fig. 13 shows the criteria and selected indicators, which can be used as an example to assess the consequences to the economy (Profit), society (People) and the environment (Planet). The linkage between these multi-dimensional impacts is important in getting the stakeholders to broaden their thinking and, consequently, expand their contributions towards the issues that may promote or hinder SD within a community (Thabrew, Wiek and Ries, 2009).

It is important to mention that the selection of criteria discussed in this section is not exclusive, but rather to get the framework operational and for testing its functionality. Given that the proposed tool is intended to support knowledge-based decision making, instead of making a specific choice, the involvement of stakeholders, their attitudes and perceptions toward the criteria are not examined. Furthermore, what kind of decisions and choice made by decision makers are deliberately excluded from the scope of this thesis.

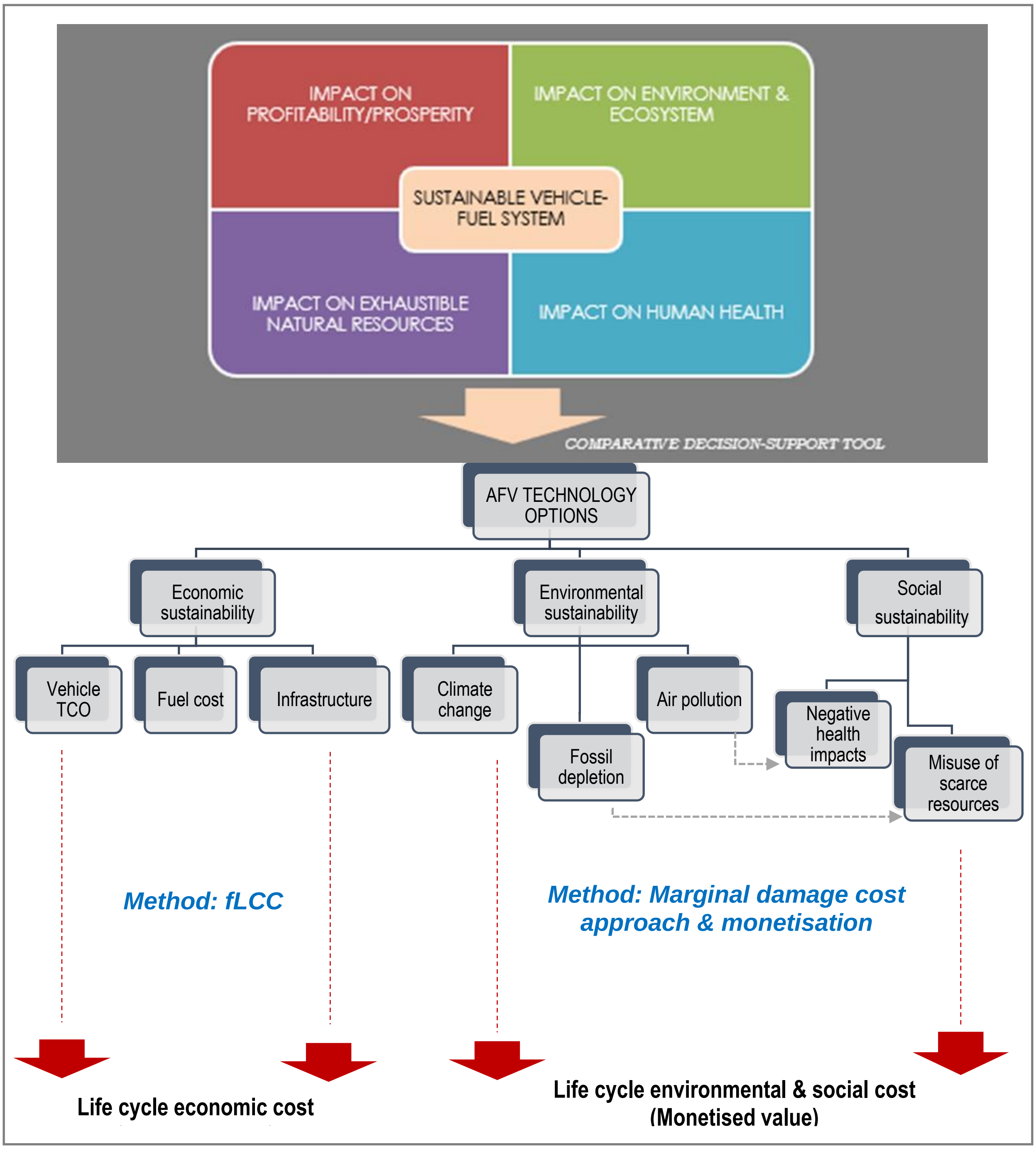


Fig. 13: Example of criteria and indicators for evaluating choices (source: author)

3.3.2 Assessment and Quantifying Stage

When conducting sustainability assessment, the quantification process is an important step that needs to be conducted in an efficient and effective manner (Tarne, Traverso and Finkbeiner, 2017). This requires an assessment of the performance of the vehicle-fuel system based on the selected TBL criteria, using a functional unit and under a clearly-defined system boundary. A comprehensive LCA of AFV technologies should cover all the impacts over the full life cycle, as described in Chapter 2.

Based on the example of criteria and indicators selected in the earlier section (Fig. 13), the life cycle sustainability costs/benefits can be quantified. Transforming the impacts of emission or any other relevant indicators into their monetary equivalents is referred to as "monetisation". With monetisation, the environmental and societal impacts from emissions and fossil energy resources can be quantified respectively as the life cycle external costs. Following Lipman and Delucchi (2006),

$$Life\ cycle\ private\ cost\ +\ external\ cost\ =\ social/societal\ LCC$$

where the external costs of GHGs and CAPs damages are estimated based on:

(i) estimated emissions (grams/km) both from vehicle operations (TTW) and upstream (WTT), and
(ii) estimated damage cost values ($/g) of emitted GHGs and CAPs

The monetisation method is not uncommon for bringing different indicators with different measurement units to the same dimension or scale (Bai, Labi and Li, 2008). It is one of the more practical ways to establish a common baseline for cross-sectoral stakeholders with different expertise, to ease collaboration and reach a decision. Although the damage cost values used for valuing the impacts in monetary basis are highly uncertain, the cost estimates can support decision making in the energy sector (Streimikiene, 2010). The approach for monetising non-economic aspects has been widely applied by governments and is relatively easy to use (as many references are available). A similar approach has been adopted in previous studies, such as Ogden, Williams and Larson (2004); Goedecke, Therdthianwong and Gheewala (2007); Wong, Lu and Wang (2010); Mitropoulos and Prevedouros (2015).

3.3.2.1 Life cycle economic costs

Given that the model seeks to compare alternatives, the life cycle economic cost/benefit aspects that must be included are the attributes associated with the use of specific powertrains or fuel types. Within the context of AFV technologies evaluation, the economic performance is typically conducted by calculating the vehicle TCO and fuel (or energy costs).

- **Vehicle total cost of ownership (TCO)**

Vehicle ownership costs are important aspects in fuel-vehicle adoption choices for both individual and business purchases (Palmer *et al.*, 2018), and TCO has been regularly used as an indicator to account for all these costs. TCO reveals the total cost incurred by the fleet owners and/or operators directly (also referred to as private LCC throughout this thesis). Various TCO calculations have been published for the economic performance valuation of AFV technologies, mainly in terms of their cost effectiveness, such as in Ally and Pryor (2016); Stempien and Chan (2017); Palmer *et al.* (2018).

Across scientific literature, the definition of TCO can be summarised as "an estimate of all direct and indirect (hidden) costs associated with an asset or product, throughout its life cycle", which is said to resemble the WTW (Roosen, Marneffe and Vereeck, 2015). TCO is often adopted in sustainable procurement exercises as it considers the time horizon that reflects the entire life cycle (and the economic costs associated with each phase of the cycle), unlike the conventional purchasing evaluations that only focus on the acquisition cost. The term life cycle in this definition can be referred to as the vehicle's lifetime (from production to disposal); however, TCO can also be calculated over a given length of time in which the vehicle still has a residual value at the end of this period (Camilleri and Dablanc, 2017). TCO is used as an economic indicator because it takes a life cycle perspective, thus is aligned with the scope of study. However, in this example, TCO will be applied to analyse only direct costs incurred by taxi operators and/or owners. Other intangible aspects or indirect monetary costs can be included in future work.

The vehicle TCO of an evaluated AFV can be determined based on Equation 4 below.

Equation 4:

$$Vehicle\ TCO = Initial\ acquisition\ cost + Lifetime\ operating\ costs - residual\ value$$

where:

Initial acquisition cost involves: vehicle and battery purchase, licensing and registration fee, financing cost;

Lifetime ownership and operating costs (non-fuel) comprise of: vehicle insurance, road tax, vehicle maintenance and repair costs (engine oil costs; battery replacement, inspection, cleaning, towing; tyre costs and accessories);

Residual value includes: any remnant or salvage value at the end of the vehicle life. This could be the result of a component having a remaining life, which could be used or sold. It is calculated as resale value minus any disposal cost.

- **Running cost of fuel**

The second element of life cycle private costs examined in this study defines the costs resulting from the day-to-day running of an operation. The vehicle fuel consumption varies by the type and category, and the literature has shown its decreasing trend each year as a result of improved engine performance, reduced air resistance and weight of the vehicle (Romejko and Nakano, 2017). The computation of variable costs of fuel consumption follows the common practice adopted in previous studies, by using the electricity/fuel consumption data according to the type of drive cycle (urban, extra-urban or combined). It has conclusively been shown that the official manufacturers' data for fuel consumption are far from accurate, hence studies that seek accurate estimation of the fuel costs need to be corrected with a real-world adjustment factor. As an example, Wolfram and Wiedmann (2017) multiplied the official fuel consumption values with respective on-road adjustment factor (1.37 and 1.51) to account for the discrepancy between the drive-cycle fuel consumption and actual real-world values of around 37% for ICEVs and 51% for HEVs on the NEDC, when analysing the emissions and fuel consumption of different powertrains. These correction factors were taken based on a comprehensive statistical analysis of on-road fuel consumption of about 1 million vehicles from seven NEDC-employing countries.

To ensure comparability between different fuel types, the analysis of fuel cost should be based on refinery gate cost or retail price (MacLean and Lave, 2003), which has the tax element in it (or not, in the case of some fuels which are exempted). It is misleading and inaccurate to exclude the tax exemption or reduction, as these are some of the benefits enjoyed by AFVs.

- **Infrastructure cost**

Meanwhile, the importance of an efficient fuelling or charging infrastructure in order to support the implementation of AFVs, as discussed in many studies, is acknowledged. The capital cost of infrastructure development and operational costs is important and needs to be included, particularly when evaluating newly developed or future technologies such as EVs and FCEVs prior to implementation as the high value can offset the benefits of AFVs. However, when evaluating currently available technologies, alternatives are often already have established infrastructures, thus this factor can be omitted in this scenario by assuming no additional cost is incurred by the operators (or other stakeholders within the transport sector).

3.3.2.2 Life cycle environmental and social costs/benefits

Besides cost, the literature has shown that most AFV technologies have different attributes in terms of emissions. Within the scope and context of this thesis, the quantification of life cycle emissions has been conducted for the following substances: volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM2.5 and PM10) and SOx, with full inventory emissions that cover the upstream and tailpipe emissions. These pollutants have been included in most referenced studies, thus are viewed as being representative of a vehicle's life cycle.

This section will describe the approach for quantifying the life cycle environmental and societal impacts of emissions and fossil energy use from monetary cost/benefit perspective.

- **Emissions**

As pointed out earlier, vehicle emissions pose significant environmental, health, and economic risks for all communities and citizens (Rose *et al.*, 2013). To quantify climate/global warming impacts from GHGs emissions, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission values are expressed in terms of grams of CO_2-equivalent emissions (CO_2e). The conversion into CO_2e can be computed by using the 100-year global warming potential (GWP) by the Intergovernmental Panel on Climate Change (IPCC), as adopted in most existing studies. The IPCC measurement of GWP represents the amount of heat each gas contributes to climate change, relative to the standard CO_2 (Rose *et al.*, 2013).

When evaluating emissions, GHGs and climate change cannot be the sole criteria for estimating the impacts of AFV emissions. Since taxis operate typically in urban areas where the local air quality is important, it is imperative that the impacts of pollutants emissions are included when evaluating AFV technology's sustainability performance. Tong *et al.* (2017) argue that technology assessments that ignore environmental and public health effects from pollutant emissions are incomplete, because these are consequences borne by society and not just the emitter. They are often labelled as external effects of emissions. Recently, it has become standard practice to internalise them by making such effects part of the decision-making process of transport users, particularly in Europe. Based on the mandate from EU legislators, the European Commission has presented a state-of-the-art and best practice guide on external cost estimation (Maibach *et al.*, 2008).

Before quantifying the external costs associated with emissions, the life cycle inventory (LCI) data need to be collected. LCI deals with the accumulation of system inputs and outputs data, which is crucial when undertaking LCA (Islam, Ponnambalam and Lam, 2016). In this phase, the exchanges between unit processes and organisations of the product system and the external environment (which lead to environmental, economic and social impacts) are compiled (United Nations Environmental Program (UNEP), 2011). Meanwhile, CAPs emissions include carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOC), sulphur oxides (SOx), and particulate matter (PM).

Based on the system boundary specified in the earlier section, the life cycle emissions comprise GHGs and pollutants produced at the point of use (direct emissions) and those generated during other stages in the vehicle and fuel life cycles. Accordingly, the life cycle emissions of the overall system can be described as the equation 5 below (refer to Perera, Hewage and Sadiq, 2017):

Equation 5:

$$LCE_S = LCE_V + LCEwtw$$

where

LCE_S = life cycle emissions of the system (vehicle and fuel life cycle)

LCE_v = life cycle emissions of the vehicle CTG

LCE_{fwtw} = life cycle emissions of the fuel WTW

The vehicle life cycle emissions, LCE_v comprise of the indirect emissions generated from energy used for manufacturing the vehicle (from materials extraction until vehicle assembly) until its EoL (when the vehicle is being disposed or recycled).

Meanwhile, the fuel life cycle emissions, LCE_{fwtw} covers the "upstream" emissions from fuel extraction, production, refining, storage, until distribution and dispensing, as well as direct emissions, following equation 6 as follows,

Equation 6:

$$LCE_{fwtw} = E_{wtt} + E_{vop}$$

where:

E_{wtt} = Indirect upstream emissions during WTT

E_{vop} = Direct emissions during the vehicle operation, TTW (when the fuel is being used in the vehicle, or in the case of EV, at the point of electricity generation).

A typical taxi operation may include idling and customer waiting times, which could increase the level of emissions from conventional fuel-based vehicles, as examined in the urban freight study of Figliozzi, Saenz and Faulin (2018). However, this factor is not taken into consideration in this model, as it is assumed that idling may decrease over time as the newer vehicles can automatically shut off when they are not moving. Nevertheless, the age of vehicle is accounted for in the assessment by applying the emission elasticity based on an estimated annual increase of pollutants emissions by 20% (or a factor of 1.2).

To account for the externality damage of emissions, the emissions inventories provided in LCI are monetised using a damage cost approach, which takes into account the impacts on human health, building materials, and crops that are caused by a range of pollutants. The monetisation approach is a convenient method for measuring impacts with different physical units, using a single damage estimate or indicator (Spadaro and Rabl, 2001). It offers a reliable cost comparison, given that the impact of different polluting factors can vary substantially (Roosen, Marneffe and Vereeck, 2015). The damage cost approach is well established and internationally accepted, and is also often cited in bibliographies (Bortolazzo, Cavallazzi and Valente, 2018), although there are limitations to this method, as outlined by these authors, such as poor accuracy of the results and difficult data collection in developing countries. However, the model developed in this research seeks to compare the expectation value of the damage, rather than to measure the actual impact. Henceforth, the damage cost approach is adequate for the scope and objective of this study.

The monetisation of emissions is carried out in accordance with the UK DECC (Department of Energy and Climate Change) and DEFRA's (Department for Environment, Food and Rural Affairs) damage cost methodology (DEFRA, 2011, 2019; DECC, 2015), given that it has been established widely across government departments and agencies. Following this approach, the GHGs and CAPs emissions are assumed to be marginal. Therefore, the resulting externalities can be estimated by multiplying the amount of emissions (by species and by location) by the marginal damage cost per unit of emission (of the same species emitted in the same location), as shown in Fig. 14. A similar approach has also been adopted in previous studies; see, for instance, Tessum, Hill and Marshall (2014); Noori, Gardner and Tatari (2015); Tong *et al.* (2017)).

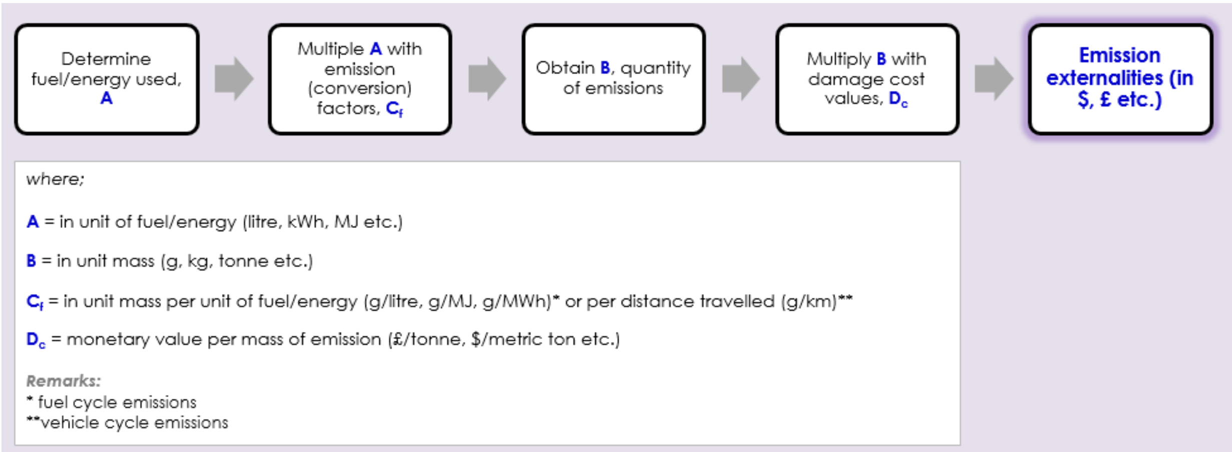


Fig. 14: Procedural steps for monetising the impacts of emissions (source: author)

Based on the steps presented above, the formula to calculate climate change and air pollution damages is shown in Equation 7.

Equation 7:

$$Amount\ of\ emissions\ (in\ mass, e.g., tonnes, kgs)\ x\ marginal\ damage\ cost\ per\ unit\ mass\ of\ emission$$

The approach for calculating the external cost of GHGs and CAPs is different, considering that GHGs are globally mixed, thus their marginal damages are the same in any locations (Tong *et al.*, 2017). On the contrary, CAPs are locally mixed, hence their marginal damages vary by locations. Taking into account this difference, the formula specifically for climate damages is written as:

Climate change damages = $$C_{\text{GHG}} = \sum_j p_j \times e_j$$

where C_{GHG} = the climate or global warming external cost in monetary value

Pj = the emitted amount of GHGs substances j (CO_2, CH_4 and N_2O) in grams, in CO_2 equivalent

ej = the marginal damage cost of CO2 emissions in $ per gram.

As CO_2 contributes largely to climate change or global warming, the marginal damage cost is often referred to as the cost of carbon. The social cost of carbon (SCC) has been widely used in the past, whilst the non-traded cost of carbon has been used recently in the UK (DECC, 2015).

Meanwhile, the external damage of air pollution can be computed based on Equation 8.

Equation 8:

Air pollution damages = $\sum life\ cycle\ CAP_{missionsspecies,location}\ \ x\ marginal\ damage\ cost$

When valuing emissions in monetary terms, it is important to note that such analysis can be complex, due to the wide range of marginal damage cost or carbon cost values that have been reported and adopted in the literature. In view of this, the damage cost values used in this model are based on the damage resulting from emissions and not the costs of policies aimed at reducing emissions. The total impact or external LCC of emissions is then calculated by summing the climate and air pollution damage costs associated with GHGs and CAPs emissions.

The key for presenting the comparative results determined by the proposed method is that it can be understood by all stakeholders and decision makers, i.e., using a common language, to facilitate ease of communication and negotiation towards consensus decisions. Accordingly, the external LCC of emissions can be used as an indicator to present climate, health and mortality effects in a common basis with economic or financial impacts quantified by the traditional fLCC.

- **Fossil energy resources**

As presented in Chapter 2, most life cycle studies evaluating AFV technologies have examined energy consumption at inventory level. In this research, the amount of fossil resources (petroleum, coal and natural gas) for generating such amounts of energy is the primary concern. Rather than just examining the life cycle fossil energy consumption, social instability related to oil supply (being the primary fossil energy resource) is another aspect that needs to be factored in when evaluating options, as it is not only affecting the economy but the social needs of future generations. When the production of these fossil fuels is scarce, new, so-called unconventional sources will need to be produced to ensure sufficient supply and satisfy fuel demand (Goedkoop *et al.*, 2009). Therefore, externality costs for oil supply security is also quantified in this model, as part of the societal LCC.

Like the emissions inventory, the energy consumption factor (in Unit Energy per KM) is compiled from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, which supported the accurate estimation with proper comparison between various types of fuel and powertrain technologies. The total energy consumed over the whole life cycle can be estimated by multiplying it by the lifetime operating distance. Then, the ReCiPe method is used to value the fossil energy used as the monetised damage to resource cost, to account for the social/externality costs of fossil fuel depletion. This reference it is practically the most established, well known, and has been adopted in many other LCA studies (see, for instance, Sharma and Strezov, 2017; Schulte and Ny, 2018). This indicator reflects an increase of costs and energy because future generations will have to switch from conventional resources to unconventional resources, which are generally more energy-intensive and more costly to produce (Goedkoop *et al.*, 2009).

Following the ReCiPe method, the use of fossil resources is expressed in kilograms of crude oil equivalent, by multiplying the total life cycle of energy from petroleum, coal and natural gas with a mid-point characterisation factor. Although there is no clear evidence of possible shortages in natural gas, the exploitation of natural gas fields is often associated with the exploitation of oil, since both resources are often found in the same location (Goedkoop *et al.*, 2009). Meanwhile, for coal, the marginal increase is not strongly related to scarcity, but to the cost of the workforce and for environmental protection.

3.3.3 Results Interpretation

At this stage, results are interpreted to reveal the performance of evaluated technology choices. Following Simon's Satisficing Theory, decision makers do not seek the "ideal" solution to problems, which can be defined as the solution that yields minimum (or maximum) values for all criteria. With the proposed framework, the procedures performed at this stage represents the simplified Satisficing behaviour, where the model randomly evaluates alternatives against aspiration levels and seeks a satisfactory or acceptable solution. The acceptability is determined when all attributes are satisfactory by adequately meeting the aspiration levels, thus is assumed to have reached a level of compromise or consensus. Therefore, the first step (refer Fig. 12) is to set the aspiration levels (or minimum threshold of acceptance). Then, results related to each attribute is compared against the threshold; alternatives are filtered as "acceptable" or "not acceptable", and finally revealing the satisfactory trade-off solutions. At this juncture, the evaluation process can be stopped if such solution is accepted by all decision makers.

The simplification describes above is adapted to reduce the complexity and demanding work for exploring the possible trade-offs, particularly if one attribute is undesirable to decision makers hence difficulty to compensate any of the other attributes. Another benefit of this model is it provides knowledge regarding the compensation value. With the use of a common metric, the model informs how much needs to be traded-off when selecting any of the possible solutions. Although Simon's Satisficing Theory suggests that the first acceptable alternative is selected by decision makers, let's assume that alternatives are evaluated and compared simultaneously. In this process, an alternative that achieves the best trade-off between the attributes or objectives of decision makers is the satisficing choice. Decision makers are then left to select the alternative, given all the information and evidence provided by the model.

3.4 Structure of the decision-support tool

Using the example of attributes and criteria as described in earlier sections, the probabilistic simulation-based LCCA is designed to encompass three inter-connected sub-models: energy resource, emissions and cost. As a probabilistic simulation-based model, uncertain inputs are characterised with PDF, in order to produce the model outputs as a range of probable outcomes (with their probability of occurrences) instead of static, single-point estimates. Fig. 15 presents the model overview, showing the inputs and outputs, as well as components of the tool.

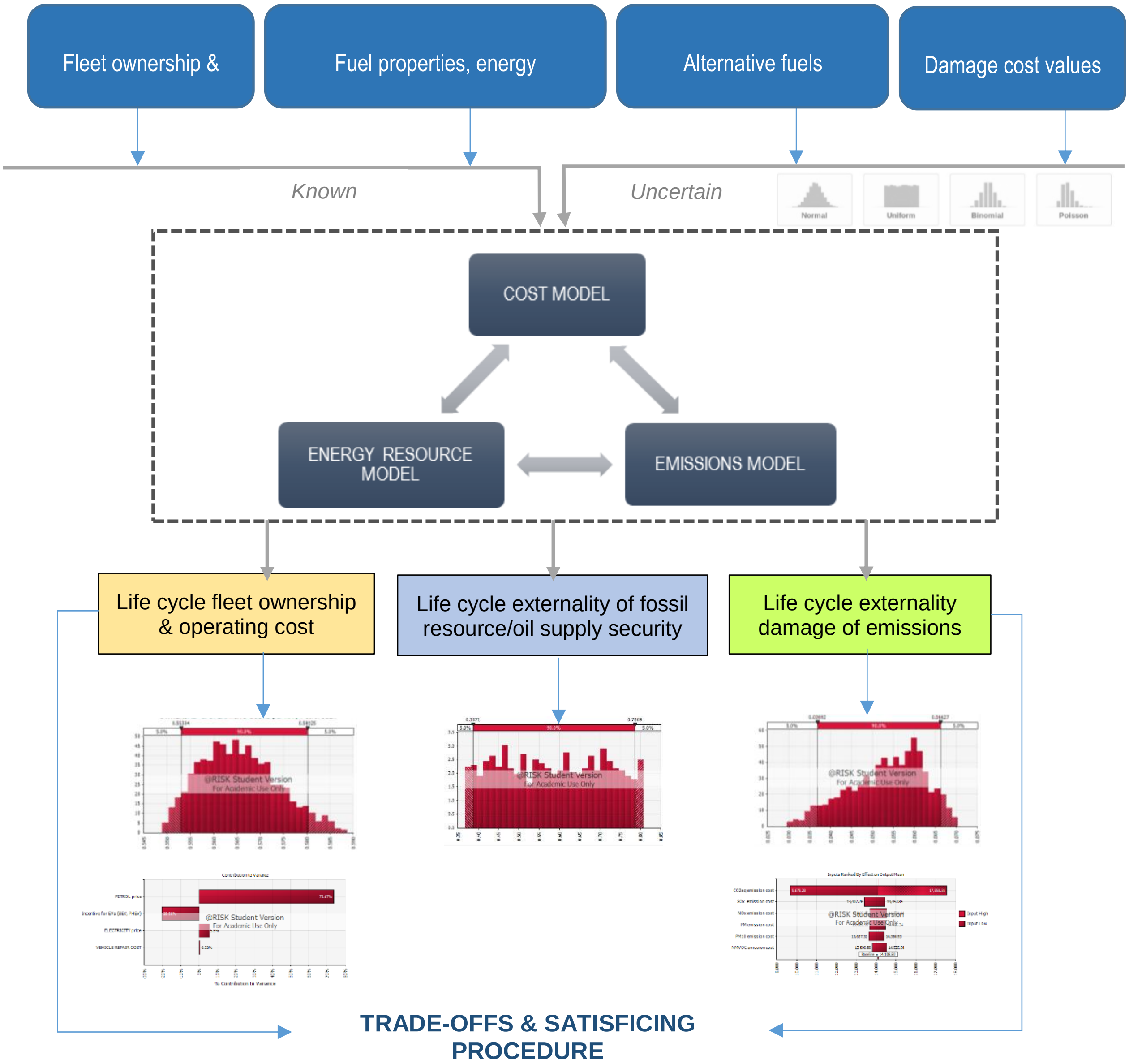


Fig. 15: Model structure and components of the decision-support tool (source: author)

To encourage wider adoption of the framework, it is important that the tool is simple to develop and easy to be used. Therefore, it is specifically designed and implemented as a spreadsheet-based model for it to be user-friendly without requiring much computing knowledge and expertise from the end-user. This implementation enables the model to be readily applicable and easy to develop, without the use of complex computer programming or algorithms to determine alternative solution, unlike the optimisation models that have been developed in the past.

Based on the formula derivations presented in the earlier sections, calculations are performed using formulas that were coded into the spreadsheet to enable scenario planning and to incorporate changing input parameters. The functionality of probabilistic simulation is delivered by @Risk, which is part of the Decision Tools Suite developed by Palisade. This software application fulfils the needs for the tool in accordance with the aim and objectives of this research, but most importantly it can deliver the functionality as a probabilistic simulation-based model with reasonable effort and resources.

In the spreadsheet, the user interface (dashboard) uses the input data to perform the computations at the back end. The dashboard contains boxes to key-in (or select) the input parameters, whilst calculated outputs are presented in tables and charts. Besides the main dashboard, the model consists of worksheets organised as follows:

- An LCI for compiling the data inventory;
- The LCC calculator;
- A database storing general assumptions and multipliers.

The snapshots of dashboard and main worksheets are presented in Appendix 1.

3.5 Summary

This chapter describes the overarching fundamental elements of the framework. Drawing upon the LCT approach, the probabilistic analysis and Simon's Satisficing Theory, an integrated framework has been designed to inform multi-stakeholder decision making. The working procedures has been described, and the structural layout for implementing the framework has been presented. Accordingly, the type of data required for the model input parameters, LCI, as well as baseline assumptions for building the model database have been identified, which the methodology for gathering such data is described in the next chapter.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 Introduction

Following the design and operational procedures of the decision-support tool presented in Chapter 3, data required for implementing the framework is identified, which can be gathered from a research method. Henceforth, the purpose of this chapter is to describe the approach and procedures of inquiry (called research designs) based on the philosophical views, before the specific data collection and analysis methods are explained. The chapter will also clarify issues of validity and reliability to be considered. Finally, the ethical issues will also be discussed.

4.2 Research Strategy and Design

When designing a piece of research to address a problem, researchers begin by working out what data are needed and then focus how they will obtain these data. The strategies adopted by researchers depends on their understandings and associated decisions, which provide the context and boundaries of the selected data collection techniques and analysis procedures (Saunders and Tosey, 2013). These elements were described by Saunders (2009) through the concept of research onion (see Fig. 16).

According to Cresswell (2014), researchers need to consider the philosophical worldview (or paradigms) that they bring to the study, as this information will help explain whether qualitative, quantitative, or mixed methods approach is appropriate for the study. The research design that is related to this worldview (also known as procedures of inquiry) and the approach are translated into practice through the specific data collection methods and analysis procedures, for the derivation of the input data required for the integrated decision-support framework. In this section, the philosophical views, the research design and methodological choices that are adopted for the study (as denoted in red boxes) are described.

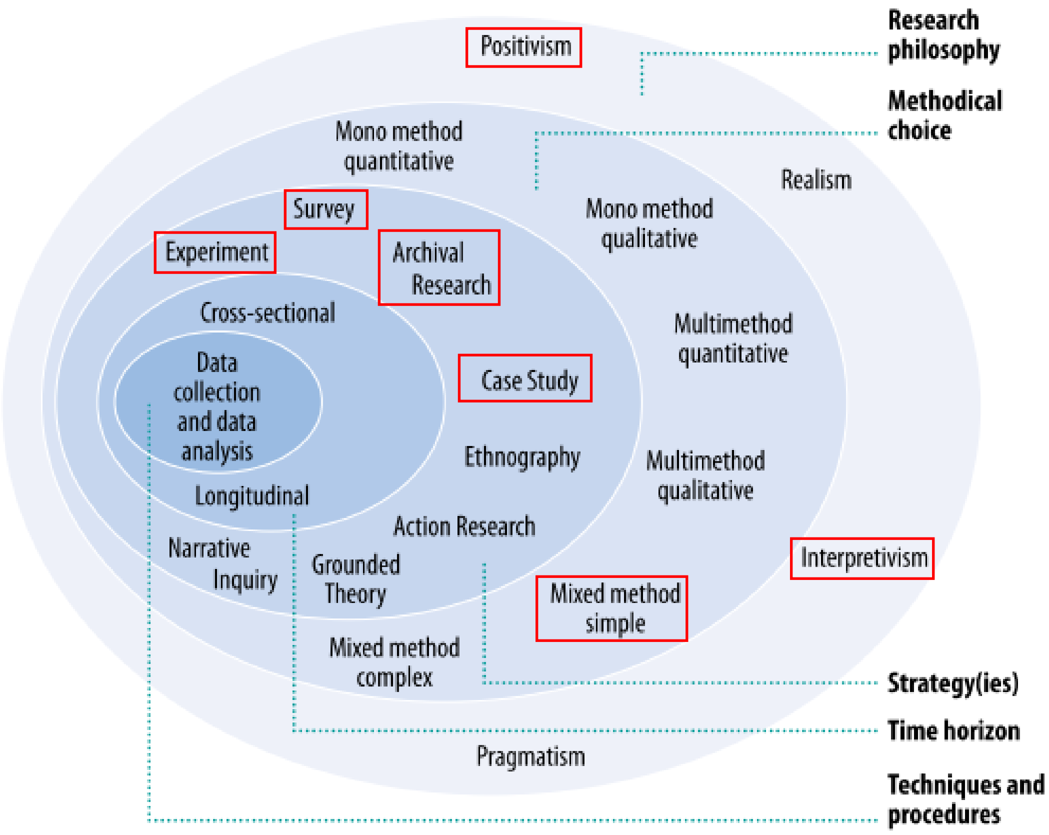


Fig. 16: The research onion and approach of the study (adapted from Saunders and Tosey, 2013, p.59)

4.2.1 Philosophical views

The selection of research methods is guided by the basic belief systems or worldviews called paradigms (Guba & Lincoln, 1994), or philosophical views of the world (Davies and Hughes, 2014). Punch (2014) defines paradigms in more simplistic terms, as a way of looking at the world and a view of how inquiries should be done (hence the term inquiry paradigm), which is sometimes used in the literature. In essence, paradigms influence the beliefs and perspectives of researchers in understanding the social world, which shapes opinions about the appropriateness of methods adopted for carrying out the study (Kumar, 2014).

Although the terminology of this research philosophy is not the central understanding for a research project (Davies and Hughes, 2014), it still influences the practice of research and thus needs to be identified regardless (Creswell, 2003). The philosophical perspectives of researcher can help to justify the approach and mode of enquiry, which subsequently determine the structural aspects of a study design (Kumar, 2014).

According to Saunders' research onion, as shown in Fig. 16, the most significant philosophies are: *Positivism, Realism, Interpretivism,* and *Pragmatism*. The first philosophy is *Positivism*, which is an approach to social science developed from the traditions of the natural sciences (Davies & Hughes, 2014). It is based on an epistemological assumption that apprehendable reality exists (Guba & Lincoln, 1994) and that the world is governed by a series of rules and laws that can be tested and understood through experiments (Creswell, 2013). In another definition, *Positivism* is an epistemological position whereby knowledge should be based on what can be observed and measured (Davies & Hughes, 2014). It is based on a belief that scientific action produces concepts that are useful, thus *Positivism* is sometimes called "scientific method, positivist research or empirical science" (Jonker and Pennick, 2010). Therefore, *Positivism* as an approach has been acknowledged in many literatures to be more appropriate and likely to be associated with quantitative research (Punch, 2014). It asserts the belief that there are objective accounts of the world, thus the function of science is to describe and explain it in the form of universal laws, through careful observation and measurement of objective reality.

In contrast, an interpretivist researcher is more concerned with gathering rich insights into subjective meanings than providing law-like generalisations. According to Saunders and Tosey (2013), the *Interpretivism* philosophy relates to the study of social phenomena in their natural environment, focusing on people rather than objects. Contrary to *Positivism*, data collection and analysis of an interpretivist nature are likely to involve qualitative data from in-depth investigations.

Similar to Positivism, Realism is a philosophical position associated with scientific enquiry (Saunders and Tosey, 2013). It is a prominent approach which validates and supports key aspects of both qualitative and quantitative approaches while identifying some specific limitations of each (Maxwell, 2016). This philosophy is an integration of a realist ontology (there is a real world that exists independently of our perceptions, theories, and constructions) with a constructivist epistemology (our understanding of this world is inevitably a construction from our own perspectives and standpoint). Realism states that reality exists independent of the mind and that what a researcher's senses show her or him is the truth, although the researcher is influenced by world views and their own experiences.

As a result, the collection techniques and analysis procedures can be varied, utilising either or both quantitative and qualitative data.

Another philosophy is *Pragmatism*, which focuses the research importance on the findings' practical consequences. Pragmatist researchers believe that no single viewpoint can ever provide the entire picture, and that there may be multiple realities (Saunders and Tosey, 2013). However, this does not necessarily mean that they would always use a mixture of data collection techniques and analysis procedures. Instead, the research design should enable credible, reliable and relevant data to be collected for supporting the next course of actions.

This research is aimed at developing an integrated justification platform for evaluating technology choices, that can be used to support collaborative decision making towards sustainable fleet implementation. The proposed framework has been designed by integrating existing theories and methods, then it is implemented and tested by making the tool operational following a structured and measurable procedures *(Positivism)*. In addition, the assessment of AFV technologies has been predominantly influenced by quantitative approaches. However, the researcher's ontology and epistemology of this study is also based on *Interpretivism*. The results produced in the applicability testing cannot be generalised and explained in the form of universal laws, as they are limited to a particular set of assumptions, circumstances and individuals at a specific time.

4.2.2 Methodological choices

Peeling away the philosophical views reveals the next layer of the research onion, methodical choices, which essentially highlights a basic yet important choice all researchers face when designing their research: whether to use a quantitative method or methods, a qualitative method or methods, or a mixture of both. Based on the philosophical views or *Positivism* and *Interpretivism* as described earlier, a mixed method approach is appropriate for implementing the framework and developing the tool with a real data. There are many definitions and varied interpretations of quantitative and qualitative approaches in existing literatures; however, they can be summarised in Table 4.

As shown in Table 4, quantitative researchers use numbers and large samples for testing theories, whilst qualitative researchers utilise words and meanings in smaller samples to build theories. In quantitative studies, the study designs are specific, well-structured, have been tested for validity and reliability, and can be defined and recognised in an explicit way.

On the contrary, qualitative study designs are less specific and not well-defined, besides not having structural depth (Kumar, 2014). There are several different types of study designs that can be used in quantitative researches. Amongst the most commonly used are online surveys, cross-over comparative designs, trend studies and cohort studies (Kumar, 2014), experiments and non/quasi experiments (Creswell, 2013). In contrast, case study design, oral history, participant observation and reflective journal logs are some of the most common designs used in qualitative research. The research strategies and design adopted in this research (see Fig. 17) are elaborated next.

Table 4: Features of Quantitative and Qualitative Approaches (adapted from (Kumar, 2014)

	Quantitative	Qualitative
Underpinning philosophy	• Rationalism: 'That human beings achieve knowledge because of their capacity to reason' • Traditional, positivist, experimental	• Empiricism: 'The only knowledge that human beings acquire is from sensory experiences' • Constructivist, naturalist
Underlying principles	• Empirical research data **IS** in the form of numbers • Social facts have an objective reality • Variables can be measured • Substantiation is based on large sample size • Emphasis is on validity & reliability of findings, valuing objectivity • Draws conclusions that can be Generalised	• Empirical research data **IS NOT** in the form of numbers (mostly words) • Reality is socially constructed • Emphasis is on the description of variables • Uses fewer cases • Values authenticity • Places no or less emphasis on generalisations
Purpose	• To quantify the extent of variation in a problem, issue or phenomenon • *Example*: To explain prevalence, discover regularities, formulate theories	• To describe variation or diversity in a problem, issue or phenomenon • *Example*: To explore experiences, meanings, perceptions and feelings

4.2.3 Strategies and design

The next layer of the research onion is strategies, which emphasises that one or more strategies can be used within the research design. Research design is defined by Kumar (2014) as "the roadmap that a researcher decides to follow throughout the research journey in order to find answers to research questions, as validly, objectively, accurately and economically as possible." Accordingly, the mixed methods simple design is selected to study the topic, which combines both qualitative and quantitative data collection techniques and analysis procedures. These methods depend largely on the nature of the research questions, aims and objectives and particular situations (Jonker and Pennick, 2010; Davies and Hughes, 2014; Kumar, 2014). Meanwhile, Yin (2014) outlines three basic conditions that can be used to guide the selection (see Table 5):

- The type of research question
- The extent of control a researcher has over actual behavioural events
- The degree of focus on contemporary as opposed to historical events

Table 5: Relevant Situations for Different Research Methods (Yin, 2014)

Method	Form of research question	Requires control of behavioural events?	Focuses on contemporary events?
Action research	Who, what, why, how many, how much?	Yes/No	Yes
Experiment	How, why?	Yes	Yes
Survey	Who, what, where, how many, how much?	No	Yes
Archival analysis	Who, what, where, how many, how much?	No	Yes/No
History	How, why?	No	No
Case study	How, why?	No	Yes

In order to explain the strategies taken in this research, as illustrated in Fig. 17, it is important first to recall the aims and objectives. The objectives and strategies are mapped out accordingly in Table 6. The justifications for selecting the strategies are described next.

Table 6: Strategies mapped out against the research objectives (source: author)

Objectives	Strategies
Develop a theoretical understanding of the methodologies for evaluating AFV technologies from a TBL perspective, and a new framework suitable for integration into the life cycle model.	ARCHIVAL ANALYSIS
Implement the computer-aided framework using test simulation models	EXPERIMENT
Apply the model for evaluating currently available fuel/powertrain technologies in a taxi context, to support multi-stakeholder decision making.	SURVEY, CASE STUDY

- **Archival analysis**

Based on Table 6, it is shown that archival analysis is suitable for research that focuses on "what" questions; it has no control over actual behavioural events and focuses on contemporary events. Following the key steps and process of this study, archival analysis is the first method used in this research. In this research, the framework and life cycle cost model has been developed using archival data from various sources, both published and non-published materials. This include vehicle manufacturer's documents, industrial and academic publications as well as government agencies' databases, reports and archived documents, hence will not necessarily require focus on contemporary events. Additionally, the research has no control over behavioural events.

- **Experiment (via computer simulation and modelling)**

Considering the nature of the investigation, the implementation of the framework can be made possible through the experiment method, which can be performed with computer simulation and modelling. This approach is appropriate for research that focuses on "how" questions, which reflects the procedures for making the framework operational. Accordingly, an experimental model is developed using computer-aided software; thus, requires control over behavioural events.

- **Survey**

Like archival analysis, surveys are appropriate to answer "what" questions, rather than how or why; they have no control over actual behavioural events and focus on contemporary events (see Table 5). These three conditions can be applied to this research as follows:

- First, the evaluation of the proposed tool is performed by gathering feedback from potential users ("what" questions), and research has no control over behavioural events
- Secondly, the specific task of gathering primary data is intended for developing the cost estimates for the model inputs, hence the question of "what" rather than "why" or "how".
- Finally, the applicability of the framework is tested for and within the studied context, i.e., taxi fleets in Kuala Lumpur, hence it requires a real-life situation and focuses on contemporary events.

The survey is one of the most widely used methods in social sciences, with the purpose of producing statistics in the form of quantitative and numerical descriptions about some aspects of the study population (Fowler, 2013). This method is almost always carried out for a specific purpose, which makes an implicit assumption that the result produced will be an accurate reflection of reality (Davies and Hughes, 2014). In quantitative research, the information is typically collected from a representative sample of the study population, by asking questions through a questionnaire or a structured interview, with the aim of generalizing from a sample to a population (Creswell, 2003). In this research, the survey method is used to collect information for the model inputs which are quantitative in nature, thus requires straightforward facts rather than opinions. Subsequently, the data is suitable to be gathered using questionnaires.

Although the survey questionnaires have limitations, such as low response rates and the risk of bias (Kumar, 2014), this method offers the opportunity to explore a broad range of issues and produce a statistical outcome that is crucial to the success of this study. For the context of this study, the adoption of survey study design is to fulfil the requirement for real data that are essentially collected from primary sources, following the recommendation of Ozbay *et al.*, (2004) in order to improve the credibility of LCCA results.

- **Case study**

In view of the unique and complex nature of the research, the researcher has included a case study as part of the study design. Although a case study is predominantly a qualitative study design, it is also prevalent in quantitative research (Kumar, 2014). While the research primarily follows the usual route of quantitative approach, it involves some qualitative processing to a certain extent. The results produced from the experimental model are limited to certain input parameters and assumptions hence the conclusions cannot be generalised for a different scope or contextual setting. Henceforth, case study is the third approach adopted in this study. Theoretically, case study is applied because it allows the researcher to explore areas where little is known and to have a holistic and in-depth understanding (Kumar, 2014), which helps in producing a rounded portrayal of an identified subject (Davies & Hughes, 2014). Within the context of this research, the case study method allows exploration of the model applicability in a real world, which help the researcher to improve the framework further.

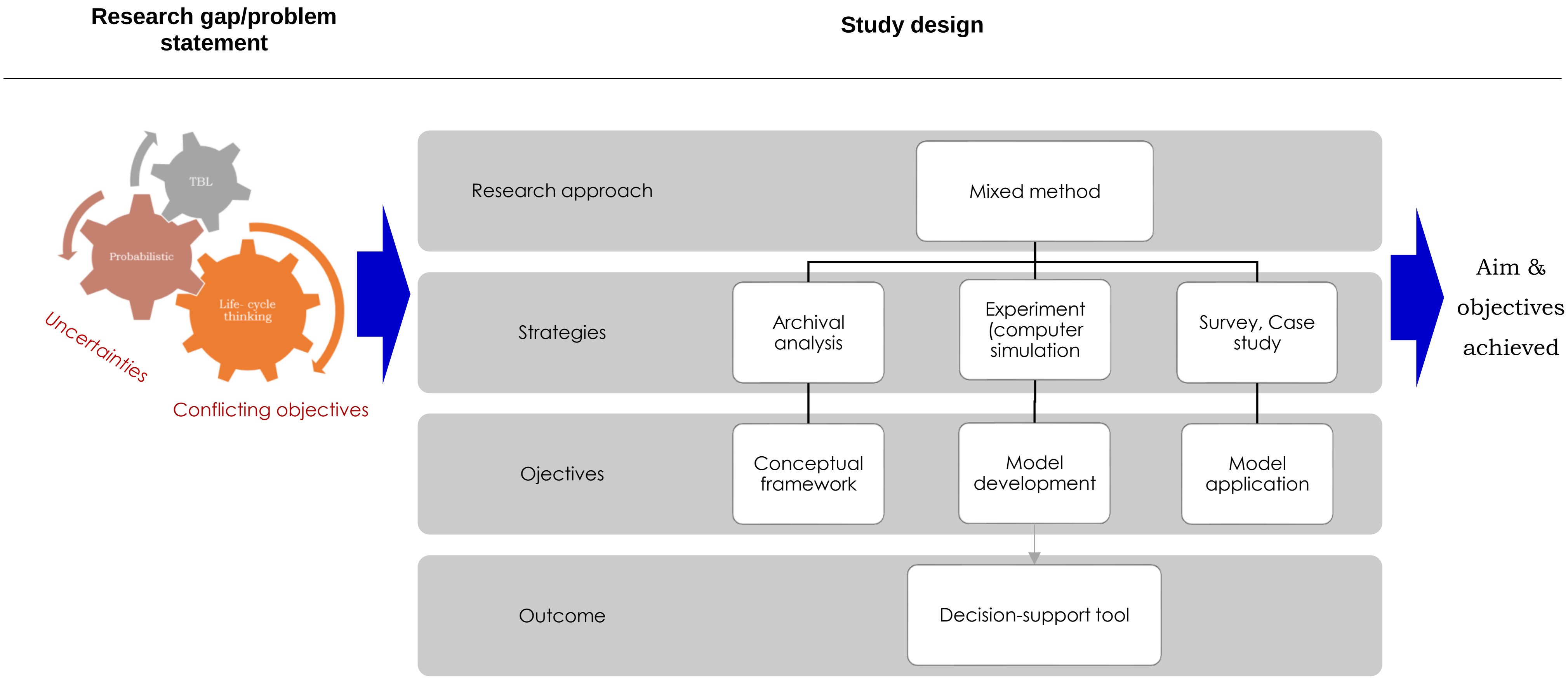


Fig. 17: Research design and the connection between strategies and objectives (source: author)

Following the study design, the next section discusses the specific data collection methods and analysis procedures used in the study and justify the reasons for their adoption.

4.3 Methods of data collection and analysis

Research methods indicate specific sequential steps or actions, which include data collection and analysis (Jonker and Pennick, 2010). Nearly all previous studies have concluded that the framework of LCA is data driven, with extensive data requirements (Korpi and Ala-Risku, 2008). As claimed by (Ozbay *et al.*, 2004), the credibility of LCA results is highly dependent on the source of data used, which in this case indicates the requirement for a reliable data collection method. A notable part of the LCA is the collection of reliable data (Bicer and Dincer, 2017), as the data quality has a profound impact on the quality of the results predicted or estimated by an LCA tool (Rose *et al.*, 2013). Obviously, the more thorough the data collection process, the better the decision-support model is, hence selecting the right methods for gathering data is crucial in this research to ensure credible results. Data from primary and secondary sources were collected, to estimate the probability distribution of the input parameters for generating the model outputs. This approach can reduce bias and overcome the issues of validity and reliability.

Primary data refers to information gathered using the first approach, or first-hand information found out by the researcher, while secondary data or second-hand information are information extracted from existing sources (Kumar, 2014). The quantitative research method was adopted for data collection because the processes of the tool for which the data was required are quantitative. In quantitative research, the most frequent method used for data collection is the questionnaire, followed by the collection of secondary data material such as company documents, annual reports, financial reports and so forth (Jonker and Pennick, 2010). As a result, data collection in this study is carried out by means of:

- Survey questionnaire (primary data)
- Document analysis (secondary data) including government reports, vehicle manufacturer's website, fuel and emissions database etc.

The next subsections discuss the procedure for collecting data from both primary and secondary sources, using the method above.

4.3.1 Survey questionnaire

Given that none of the other notable studies on vehicle-fuel transportation carried out in the context of Malaysian cities have studied taxis specifically, there is in fact not much taxi data in Malaysia that can be gathered from the literature. Nor has there been any publicly available data from reports or any publication that can be used in this research to model the comparative evaluation using the proposed tool. Such parameters include taxi fleet operations and cost profiles.

A questionnaire refers to a list of written information which requires answers that are recorded by the respondents (Kumar, 2014). It is intended to facilitate communication, driven by the researcher's own agenda and typically in a brief way (Davies & Hughes, 2014). In this research, a typical taxi cost and operating profile is estimated for building the assumptions and inputs for the model, which are quantitative in nature. This requires straightforward factual questions rather than opinions. The use of a questionnaire is therefore selected due to the following reasons:

a) It is less expensive, faster and convenient (Gillham, 2000; Kumar, 2014)

- It allows for a wide range of inputs from geographically dispersed respondents that are representative of the sampling region (in this case, Kuala Lumpur, hence facilitates ease of response and maximises the response rate.

- Besides this, it is easier and faster (shorter turnaround) for the researcher to obtain information from a large sample, especially if the questionnaire is administered collectively such as in captive groups.

- Using a questionnaire is also more convenient for respondents, as they can complete it whenever and wherever it suits them, in their own time and space. It is suitable and ideal in this research, as respondents may need to refer to previous documents and/or check with other sources when providing answers.

b) It offers great anonymity (Gillham, 2000; Kumar, 2014)

- Due to the nature of the investigation, some respondents may be cautious about committing themselves and disclosing certain information, hence the use of a questionnaire allows anonymity, which will reduce respondent bias and potentially increase the likelihood of obtaining honest information. A good example to illustrate this is that taxi operators may want to protect their profitability and business interests; thus, they are reluctant to disclose any information that may affect their positions. By making the

c) It is easy to generate quantitative data and easy to analyse

Another disadvantage of questionnaires such as the inability to probe or clarify responses are managed by structuring the questions to be as straightforward, clear and specific as possible. Whilst the questionnaires are designed to be “responsive” and respondent-friendly by taking into account the background, education level, etc., of the respondents, they were administered in two ways. The copies of paper-based questionnaires were distributed either in person or were dropped in directly to the taxi operators and drivers across the targeted area. For those unable to be reached in person, the researcher sent the documents via email to the taxi companies. Each set of questionnaires was accompanied with a formal invitation letter, an information leaflet and a participant consent form. This set of documents is provided in Appendix 2.

Considering the nature of the investigation, both open and closed-ended questions have been adopted, as there is a need for a variety of rich information that is easy for the investigator to analyse (Kumar, 2014). The questionnaire begins with a few closed-ended questions that are aimed at gaining knowledge about the respondents’ service background so as to subsequently present them with the category of questions that is best suited and tailored to them. The next questions are mostly open-ended, with the aim of gathering information about the costs of owning and maintaining taxi fleets, in addition to the operating profile. A copy of the questionnaires is provided in Appendix 3.

4.3.1.1 Sampling approach

In quantitative research, a sample is selected to draw inferences pertaining to the focus of enquiry. This approach saves time, money and human resources (Kumar, 2014), as it is not practical or possible to collect data from each and every individual within the study population. Within the context of this research, the primary data collected were provided by the sample of respondents, who could be the representative of either the taxi companies, the taxi drivers or individual operators (who are not necessarily the owners) of the vehicles.

Sampling was done using a non-probability approach. The techniques adopted are convenience sampling and quota sampling, for the following reasons:

- *Convenience sampling*:
  - This approach was selected because it provides ease of accessibility, has geographical proximity and uses the known contacts of the researcher (Kumar, 2014).
- *Quota sampling*:
  - Considering the operating pattern of taxis in the study area, this technique was selected because it guarantees the inclusion of the type of respondents needed (Kumar, 2014).
  - Individual taxi operators/drivers roam from one destination to another, resulting in difficultly to be approached on-site; however, they have dedicated taxi stands or terminals where they operate from.
  - To ensure that the selected sample is representative of the entire study population, focus is given to the main/major terminal located within the geographic area.

The sampling strategy for collecting primary data is intended to estimate the sample size and the representativeness of the sample population. The size of the representative sample was calculated and pre-determined based on the size of the targeted population, using standard variables and formulas as shown in Table 7.

Table 7: Variables for estimating the sample size (source: author)

Confidence level	95%
Margin of error	5%
Sample size required	
Estimated response rate (based on mean overall (individuals and organisations), as per Baruch and Holtom (2008)	45%
Respondents to invite:	$\frac{Number\ of\ respondents\ needed}{Estimated\ \%\ response\ rate}$

4.3.1.2 Pilot study

In order to evaluate the suitability and feasibility of the research as a whole, and to test the development of the framework, an exploratory pilot study was initially conducted. As argued by several researchers, such as Frazer and Lawley (2000), a pre-test is necessary to identify and eliminate potential problems. In other words, piloting allows the researcher to improve the research design and make the necessary adjustments prior to conducting the main study. Essentially, the pilot study conducted in this research comprised several key phases, as follows:

- Developmental stage, which covered questionnaire design
- Ethics approval
- Distribution of questionnaire to targeted sample
- Analysis of data from pilot survey
- Preliminary modelling of TBL-LCCA

In this pilot study, the questionnaire was pre-tested, using a sample of around 20-30 respondents, as recommended by Frazer and Lawley (2000). The purpose of this questionnaire was to collect information regarding the taxi fleet operating profiles, as well as the costs incurred by fleet owners and operators over the service life. A small sample of taxi fleet operators/drivers who attended a half-day training session organised by the Land Public Transport Commission was invited to pilot the survey questionnaire. Paper copies of the questionnaire were personally distributed to the sample, with the help of the event organiser. A total of 23 participants were given the questionnaire in the pilot survey during a taxi operator training course held on 22nd October 2015, whereby 22 responses were collected, representing a response rate of 96%. This group of respondents was, however, was not specifically invited for the main survey, as some of their identities were kept anonymous, and contact details were not provided by the event organiser.

Based on feedback from the administrator, the average time taken to complete the questionnaire was approximately 30 minutes. It was, therefore, necessary to simplify and reduce the number of questions in order to shorten the time needed to complete the questionnaire. Some of the questions were rephrased, and the format and structure of the questionnaire were refined, as the administrator claimed that participants preferred close-ended questions (with option of answers). Feedback seemed to suggest that the respondents found the questions ambiguous and difficult to answer. Therefore, a revised questionnaire was prepared for another round of distribution. The second phase of pilot study resulted in 10 responses, out of the 30 forms randomly distributed at the taxi waiting area in KL Sentral, the main public transport terminal in the city. Feedback and data supplied by the respondents in both phases of the pilot survey were subsequently used to refine the questionnaire further to make it more suitable for the main survey. The survey results were analysed with descriptive statistics, then the figures were compared to a report by an unnamed Malaysian transport agency (confidential) of which both were found to be comparable, hence data is assumed to be valid and representative.

4.3.2 Secondary documents

In addition to primary data, secondary source materials are useful for developing and testing the tool using real data. Thus, document analysis is the second method that was adopted for building the baseline assumptions and input parameters of the model. These include government-published statistical reports, vehicle technical specifications documents obtained from manufacturers, published energy prices, data from the most recent peer-reviewed studies, and the like. This method is adopted because secondary sources typically have large databases (Davies and Hughes, 2014) that can be accessed effectively.

According to Yaduma, Kortelainen and Wossink (2013), more environmental analysts have been using the benefit transfer method, especially when dealing with non-market valuations. Such a technique is heavily reliant on secondary data, as the required information is not available in the studied context. A good example is the damage cost values for emissions and fossil fuel resources, which have been used by governments in countries such as the UK (DEFRA. This is not the case in Malaysia, therefore the transfer of benefit method was applied for estimating the damage cost values that are valid for the study context. An appropriate adjustment of the estimates was made to account for differences in currency purchasing power, demographic, income etc., between the two countries.

4.3.3 Existing database

According to Rose *et al.* (2013), the LCA of AFV technology can be relatively laborious, time- and data-intensive, particularly in gathering the inventory data. Henceforth, it is advantageous to access the necessary data from established and valid database that are well known and have been extensively used by other industry practitioners and/or researchers.

In this research, the LCI data and baseline assumptions related to energy consumption and associated emissions are collected from GREET which comprises fuel WTW and the vehicle cycle, rather than performing a complete eLCA and reinventing the wheel. The use of GREET is practical, as it provides a great access for accurate estimates and valid information that has been acknowledged by experts, given that the tool has been used by more than 140 companies, government agencies, universities, and hundreds of other organisations in the U.S. and several other countries (Elgowainy *et al.*, 2013). Furthermore, this research does not aim to determine the absolute/actual values but rather to develop a framework and tool for decision support, which requires testing using sample dataset.

4.4 Issues of validity and reliability

In any type of research, the concept of validity relates to the question of whether the analysis produces the end result that is an accurate representation of the psychosocial or textual reality that the researcher claims them to be (Davies & Hughes, 2014). In terms of measurement procedures, Kumar (2014) defines the concept of validity as *'the ability of an instrument to measure what it is designed to measure',* which is pertinent only to a specific instrument and is an ideal state that the researcher aims to achieve. Kumar (2014) grouped validity in quantitative research into three categories:

a. *Face and content validity* – based upon the logical link between the research question, or an item on the research instrument, with an objective.
b. *Concurrent and predictive validity* – judged by how effective an instrument is, in comparison with a second assessment done concurrently (*concurrent validity*) and by the degree to which an instrument can forecast outcome (*predictive validity*).

c. *Construct validity* – based on statistical procedures and is an indication of the quality of research instrument in measuring what it is supposed to measure.

The concept of reliability, on the other hand, is viewed by Kumar (2014) from two sides: how reliable and how unreliable a research instrument is. The first question mainly focuses on the ability of an instrument to produce consistent measurements, whereas the second focuses on the degree of inconsistencies and error in measurements. Thus, reliability is defined as "*the degree of accuracy or precision in the measurement made by a research instrument"* (Kumar, 2014) or in simpler terms, the ability to produce consistent measurements each time. As a consequence, the research tool to be used in this study has to be consistent and stable, as well as accurate with a low degree of error.

Triangulation refers to the use of different methods in a project, with a view to explore research questions from different angles (Davies & Hughes, 2014), which involves combining multiple sources to collect data, in order to check the validity of findings and the reliability of such methods in producing similar results (Jonker and Pennick, 2010). It can be achieved by using different types of data or different ways of asking similar questions (hence different methods). Within the context of this study, mixed methods approach was adopted to gather similar data for implementing the framework/developing the tool (as discussed earlier). Application of these methods will help to overcome issues of validity and reliability.

4.5 Research ethics

The concept of ethics in social science research encompasses the research stakeholders, the research participants or subjects, the researcher, and the funding body (Kumar, 2014). Some ethical issues need to be considered when collecting data from primary and secondary sources. The ethical issues to be examined in this research relate to the following areas, adapted from Kumar (2014):

- ***Research participants***: collecting data, seeking consent, providing incentives, seeking sensitive information, the possibility of causing harm to participants and maintaining confidentiality
    - Voluntary informed consent will be sought from every participant. Each participant will be provided with a letter introducing the researcher, explaining the research and purpose of the survey, and guaranteeing anonymity in reporting and confidentiality with respect to their responses.

- The researcher will clearly emphasise that participation in the survey is on a voluntary basis, and thus the participants have the right to pull out at any time during the study.
- The letter will also indicate that any data to be collected will be stored securely and will be destroyed (if requested) at the end of the project.
- The consent forms will need to be signed and dated by both parties (researcher and participant), with a copy provided to the participant upon request. If the participants do not want to print their name on the form, a signature and date will be sufficient.

- ***Researcher:*** introducing bias, inaccuracy in reporting and inappropriate use of information
  - All data collected in this research will be kept strictly confidential by the researcher. None of the reports or publications from this study will include any information that makes a participant recognisable as an individual.
  - All completed responses will be stored securely in accordance with the Data Protection Act and will be kept for a maximum of five years. Electronic copies of the completed questionnaire will be stored securely and confidentially (password protected) and will only be accessible to the researcher and doctoral supervisors.

- ***Secondary data***: misuse of data (in representation or interpretation)
  - For secondary data, a non-disclosure agreement (NDA) between the researcher and an undisclosed government agency was signed to enable analysed results from a taxi driver survey to be used for this research. The NDA specified several conditions for using and presenting the data, including a requirement to destroy the information at the end of the study.
  - The researcher will inform the undisclosed party about any issues or changes that might affect the NDA.
  - Other secondary sources, documents and databases of information, either obtained directly from the owner or downloadable from the public domain, will be used and presented appropriately.

4.6 Summary

In this chapter, the research approach and study design have been established to provide methods for developing and testing the tool with a sample dataset. Considering the quantitative nature of the study, the research design has been predominantly based on a mixed method approach. The implementation of the framework and the applicability testing through an experimental model (in a taxi case study) are the focus of the next three chapters.

CHAPTER 5: THIRD PARTY USER TESTING AND EVALUATION

5.1 Introduction

Having designed the fundamental elements of the computer-aided framework and prior to applying the model in a real case study, the next stage is to get the initial model tested and evaluated by third party users (someone other than the researcher). Firstly, this chapter provides some background information on the terminology of validation and the various techniques that have been used to validate a decision-support model. Then, the framework/model is tested and evaluated through face validation. Finally, the results from survey questionnaires are analysed and presented.

5.2 Background of model validation

According to Sargent (2013), the users of the models are all rightly concerned with whether the model and its outputs are "correct" for its use. This includes decision makers who use information gained from the model to make decisions, and the individuals affected by such decisions. This concern is addressed through model verification and validation, which is part of the model development process. From a modelling standpoint, Sargent (2013) defines validation as the "substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". In contrast, verification is defined as "ensuring that the computer program of the computerised model and its implementation are correct". In other words, verification enables us to check if "we are building the product right", while validation ensures that "we are building the right product". Given that this research is aimed at developing a decision-support tool based on a new integrated methodology, the model is tested to ensure that it meets user expectations (in terms of what it is intended to do, in accordance with its specific purpose).

The next section describes the process for testing the model and presents the subsequent results from the evaluation exercise.

5.3 Face validity by third-party users

There are several methods that have been used for validating a model, such as: animation (displaying the model's operational behaviour graphically); comparison to other models (results are compared to the results of other valid models); face validity (taking expert opinions on whether the model and/or its behaviour are reasonable); parameter variability–sensitivity analysis (changing the input values and internal parameters of a model to determine the effect upon the model's behaviour and its output); and historical data validation (using historical data to determine and test whether the model behaves as the system does). Considering the scope, aims and objectives of this research, the framework/tool is firstly tested and evaluated through face validity.

The approach of face validity involves third parties (someone other than the researcher), preferably experts and prospective end-users. This ‘‘independent" type of testing is beneficial in assessing the credibility of a simulation model (Sargent, 2013). In other words, when the external validation procedure is conducted by an independent or third party and the simulation model is concluded as valid, there is higher probability that the model can be accepted by the others as valid and that the results might be considered as "correct".

In this study, the main objective of gathering feedback from the independent third parties is to assess the model adequacy, practicability and acceptability to potential users. Henceforth, the testing and evaluation process is limited to the involvement of relevant stakeholders and industry participants within the context of the case study. Moreover, the sample or prototype tool was constructed specifically for the case study (using relevant inputs which are tailored for this context, e.g., local currency, damage cost values adjusted to the local context using relevant exchange rate). Accordingly, the participants were targeted from the following stakeholder groups:

- Fleet operators (specifically from taxi companies rather than individuals, as they are most likely able to access and test the model).
- Government officers from transport agencies (regulators and policy makers).
- Experts from transport-related research institutions located in Kuala Lumpur (or nearby cities).

Participation in this survey was on a voluntary basis. Initially, more were contacted with an introductory invitation (without the evaluation package) to clarify if they would be interested to participate in the model testing. They were identified from the researcher's network, as it was important to select the right participants who had relevant experience or knowledge of the subject. Although this approach could have limited the number of potential samples, the feedback from these targeted groups would be more relevant for the purpose of this testing. The initial testing by industry participants was considered to be of value, but it was thought more important to gain feedback on the benefits and challenges from the use of the tool in order to improve it further.

Amongst the identified stakeholder groups, only 15 participants were initially keen to receive the testing and evaluation pack, of which only 6 participants returned the completed survey forms after the two months' timeframe (refer Table 8).

Table 8: Respondents of user testing and evaluation (source: author)

	Stakeholder groups	Number of respondents
1	Fleet operators	1
2	Government officers	3
3	Research/academic experts	2

The third parties received the evaluation pack (via email), consisting of an Excel spreadsheet (a sample or prototype model for testing), and the survey documents, including a formal invitation letter, a participant information leaflet, a consent form, and a feedback form (refer Appendix 4). The evaluators were given the opportunity to test the tool's functionality in producing outputs based on the input parameters they specified. Then, survey questionnaires were to be filled out by the participants, to gather their feedback after testing the model. The questionnaires had been designed to encompass a number of criteria, as follows:

- User-friendliness and ease of use
- Comprehensiveness
- Systematic and in-depth level of assessment
- Clarity of outputs with effective graphical displays for communicating results
- Holistic overview
- Robustness of method
- Readiness for use and applicability in real process
- Relevance and usefulness to multiple user groups (with different group functions)
- Practicality and helpfulness (in general) to aid decision making

As the original model developed by the researcher contained @Risk simulation, some of the analysis results may not have been able to function without the software, thus a supplementary document was provided to illustrate an example of how such simulation was performed. The theoretical framework was also provided, to help participants understand the fundamental concept and functionalities of the model.

Based on the feedback received from six evaluators, the results are shown to be representative. The results of the model testing and evaluation by external parties are organised in two parts: a) Closed-ended questions; and b) Open-ended questions, as presented next.

a) Closed-ended questions

Using closed-ended questions, the prototype model was evaluated in terms of the scale of importance the respondents would place on characteristics that the model needs to acquire, and the level of usability of the model (in the present condition). The term usability in this context refers to the ability to deliver relevant functions with respect to the characteristics indicated in the question. Figs. 18-26 show the analysed results for the two aspects appraised in each question.

In terms of the model usability (in the present condition), the feedback from third party testing and evaluation exercise revealed that the tool was:

- Comprehensive and robust, with the majority of the respondents (87%) scored it as high usability, whilst the remaining (13%) scored it as a very high usability;
- Able to provide clarity of outputs (with effective graphical displays to communicate results) and a holistic overview, with 67% of respondents rated it as being of “high” usability;
- Robust in its methodology, with the majority (50% and 33%) scoring it as “high” and “very high” usability, respectively;
- User-friendly and easy to use, with 17% of respondents scored as “very high”, 33% scored as “high”, whilst the remaining (50%) rated as “moderate” usability;
- Systematic and in-depth, with respondents equally divided, giving a score as “moderate”, “high” or “very high” usability;
- Practical and helpful to aid decision making, with half (50%) of the respondents rating it as of “high” usability;

- Quite relevant to be used by multiple user groups, as the responses were split equally between “moderate” and “high” usability.

In terms of the readiness of the tool to be used and its applicability in real practice, the evaluators’ feedback was not unanimous. However, 67% felt that the model was either moderately ready or highly ready. In summary, all the aspects and characteristics listed in the survey form were considered important by users, except for the readiness of the tool, which one evaluator felt to be not very important.

Q1: ***User-friendliness and simplicity (ease of use) for comparing various alternatives***

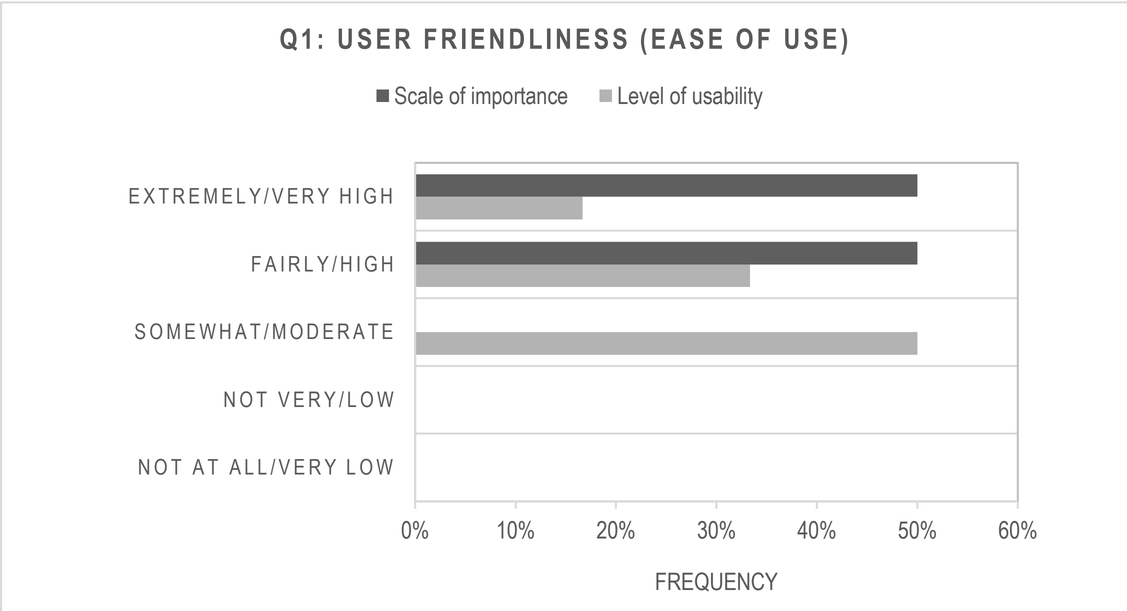


Fig. 18: Results of User Testing: User-friendliness and simplicity (source: author)

Q2: Comprehensiveness of analysis (based on criteria and factors included)

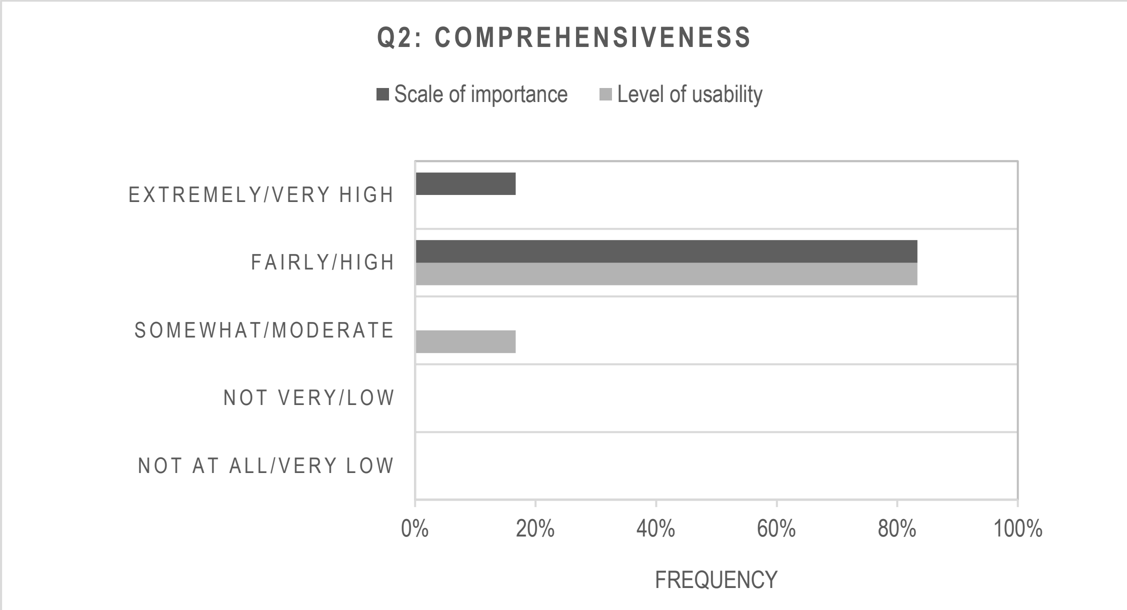


Fig. 19: Results of User Testing: Comprehensiveness (source: author)

Q3: Systematic and in-depth level of assessment

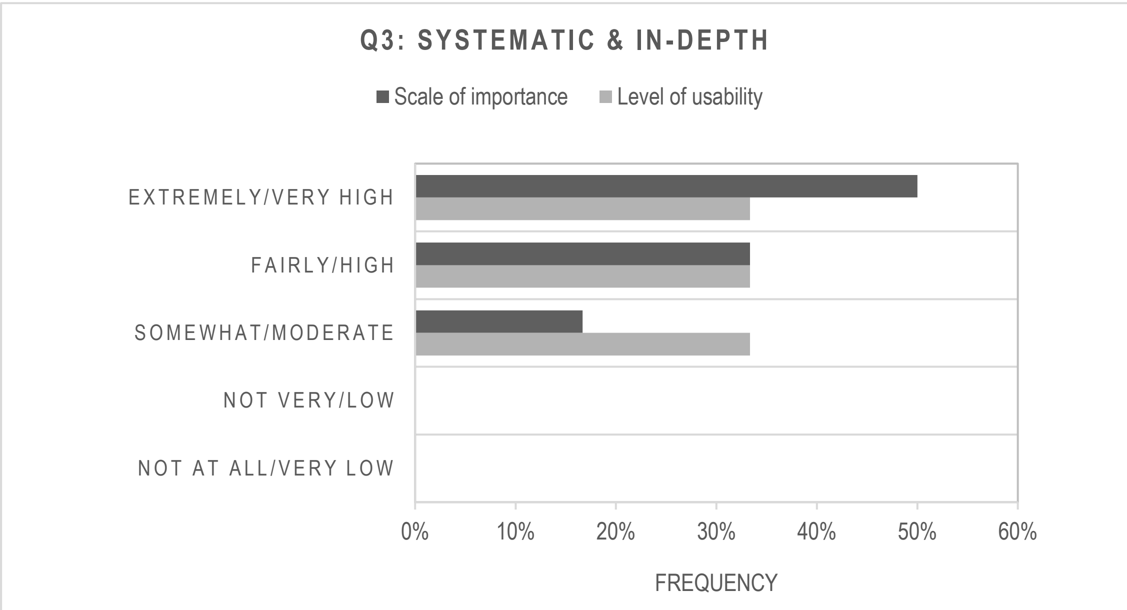


Fig. 20: Results of User Testing: Systematic and in-depth (source: author)

Q4: Clarity of outputs, with effective graphical displays for communicating results

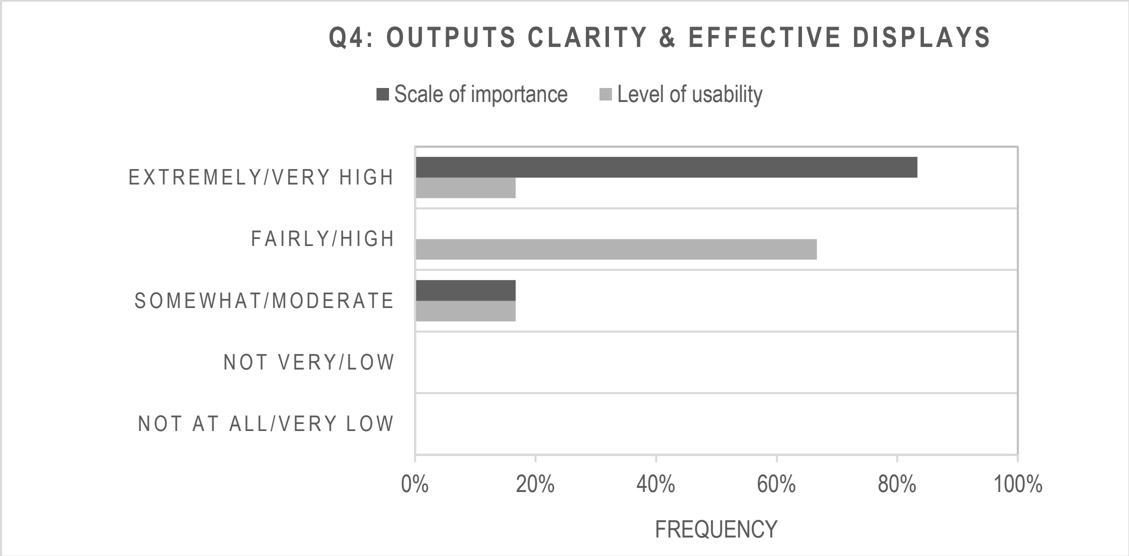


Fig. 21: Results of User Testing: Clarity of outputs and effective displays (source: author)

Q5: Holistic overview (covering multiple aspects or perspectives)

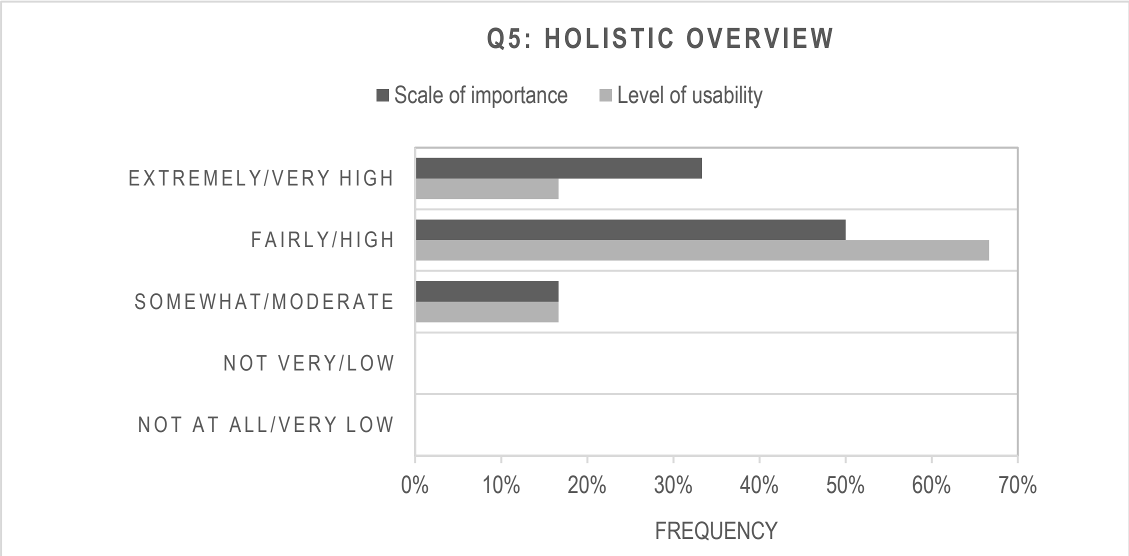


Fig. 22: Results of User Testing: Holistic overview (source: author)

Q6: The robustness of methodology

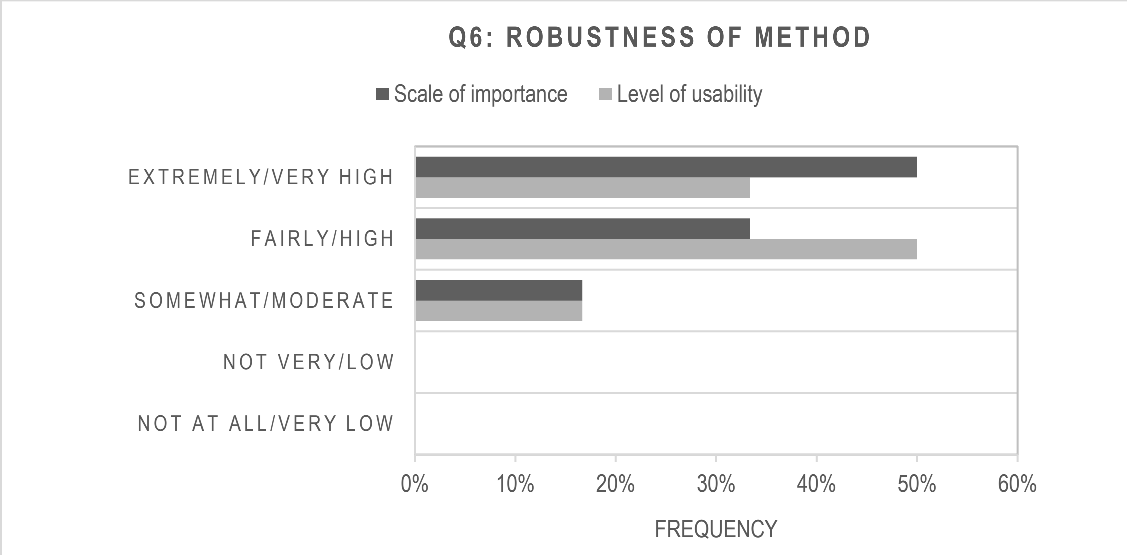


Fig. 23: Results of User Testing: Robustness of method (source: author)

Q7: Readiness for use and applicability in real process

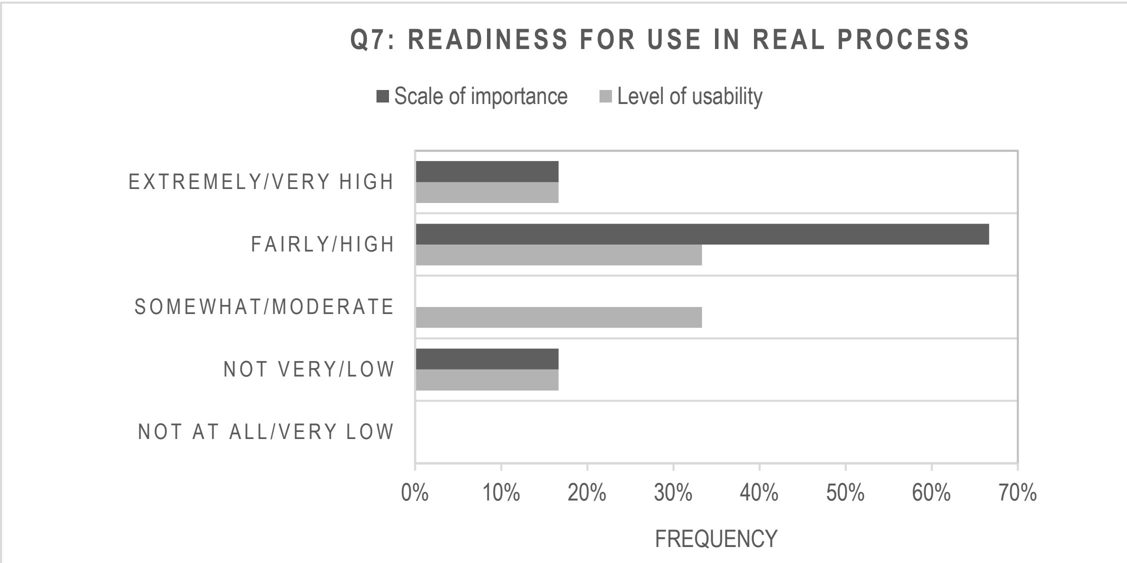


Fig. 24: Results of User Testing: Readiness and applicability in real process (source: author)

Q8: Relevance and usefulness to multiple user groups with different group functions

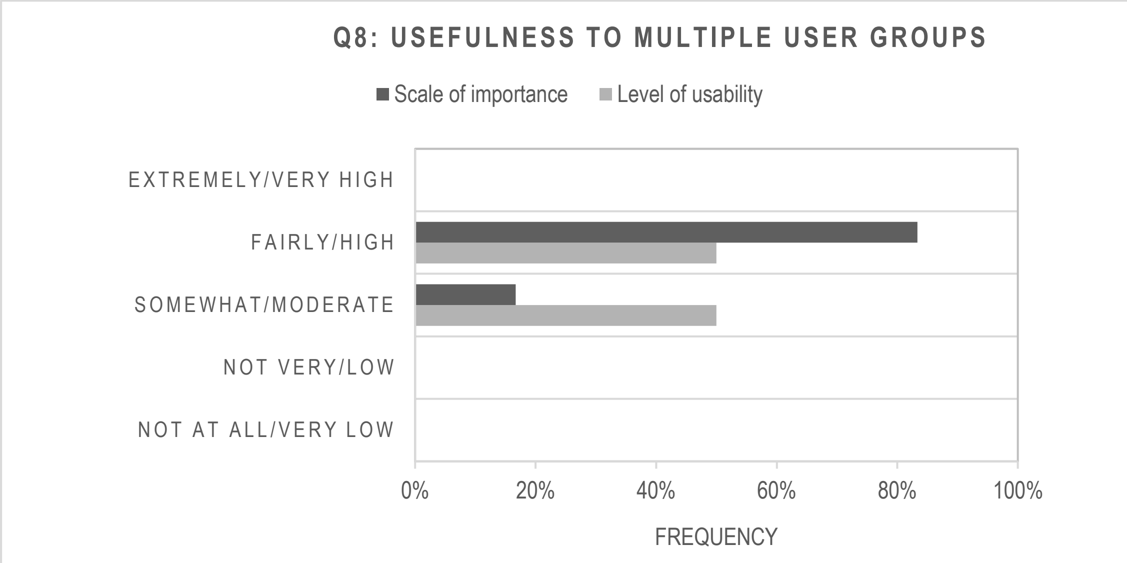


Fig. 25: Results of User Testing: Usefulness to Multiple User Groups (source: author)

Q9: Practicality and helpfulness (in general) to inform/aid decision making

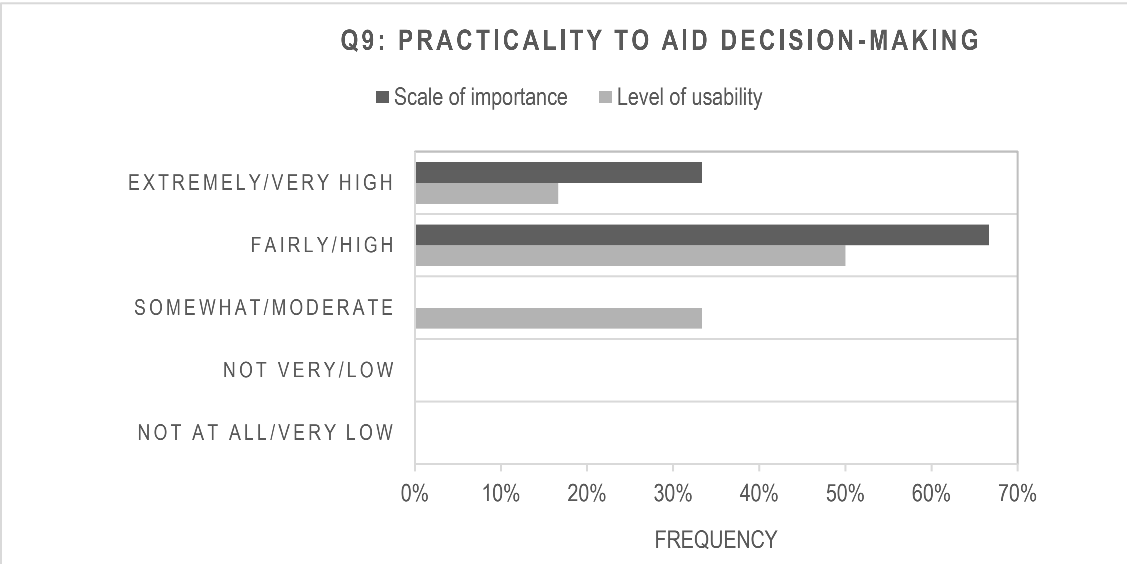


Fig. 26: Results of User Testing: Helpfulness to aid decision making (source: author)

Overall, the value and usability of the tool was generally accepted by the test population hence is assumed to be representative. The findings also provided useful insights that would help in making improvements to the present framework and model, as part of future work.

a) Open-ended questions

In addition to the closed-ended questions with the Likert Scale response, as presented above, the evaluators were asked open-ended questions (some can be considered as structured and semi-closed). The responses are summarised in Table 9.

As can be observed from the summary table, the lack of clarity, explanatory background information and instruction were considered as the most challenging and difficult by the evaluators. Consequently, three evaluators (fleet operator and government officers) suggested that the model needs to be made more user-friendly, with easier navigation and clear instruction (with a help button that can display information or explanation). Despite the challenges, only one evaluator felt that the tool did not make them aware of the possible trade-offs between multiple criteria. Meanwhile, 100% of the evaluators agreed that the tool provided them with more insights to help them to make better and more reliable decisions. Finally, amongst the motivating factors for applying the tool (such as the one proposed) prior to making choices and decisions are energy saving, road tax (already in place) and toll exemption. All the relevant improvements suggested by the evaluators will be taken into account in order to improve the tool further, as part of future work.

Table 9: Summary of responses from model evaluators (source: author)

Questions	**Evaluator 1** *(Experts)*	**Evaluator 2** *(Experts)*	**Evaluator 3** *(Government officer)*	**Evaluator 4** *(Government officer)*	**Evaluator 5** *(Government officer)*	**Evaluator 6** *(Fleet Operator)*
Road block or difficulty when using the tool, if any	Scenario analysis	No clear instruction for inflation rate	No issue	No indication of a follow-through action.	Boxes for input are confusing	Lack of clarity in general and financial information
Additional features for model improvement, if any	Model is good for the objective	More details for the baseline calculation	NA	Ease of use and interpretations, easier fonts and better icons/ graphics	To include next and help button	Well explained
Provide awareness on possible trade-offs between multiple criteria?	Yes	Yes	Yes	Yes	No	Yes
Provide more insight to aid better and more reliable decision-making?	Yes	Yes	Yes	Yes	Yes	Yes
Other motivating factors for making choices, if any	Energy saving	-	-	-	-	Road tax or toll exemption
Other suggestions or comments	No	No	No	No	More interactive and user friendly	No

5.4 Summary

This chapter has been concerned with the initial testing and evaluation of the proposed framework/model developed in this thesis, through face validity involving third-party users. The feedback from respondents is generally positive, hence is assumed to be representative as the usability value of the tool was accepted and understood. Having tested and evaluated by third parties, the model is then applied in a case study, as described in the next chapter.

CHAPTER 6: MODEL APPLICATION IN A CASE STUDY

6.1 Introduction

Based on the third objective of this research (Section 1.4), the primary aim of this chapter is to apply the proposed model in a case study, using real data as much as possible. The context of the case study is firstly described, which represents a typical case example of taxi fleets operating in a rapidly growing city (hence the importance of implementing sustainable practices). Subsequently, assumptions and input parameters are defined, and the 3-step procedure of the model is elaborated.

6.2 Contextual settings and case study background

Kuala Lumpur is the central, most prosperous urban area in Malaysia. The justification for selecting this city (to be representative of a case example of taxi fleets) is outlined below:

1. It is located in Malaysia, a developing Southeast Asian country which faces many challenges affecting SD due to rapidly growing urban areas.
2. SD practices in the urban transportation system are lacking; for instance, there are no established emission standards for vehicles in place. More stringent policies are then necessary to drive a substantial uptake of AFVs.
3. There is an absence of regulation-mandated policies and legislation for adopting AFV technology public transport fleets, including taxis.
4. Data required for life cycle-based analyses are limited, due to the lack of publicly available sources.

Based on the justifications above, Kuala Lumpur is a suitable example that would provide an avenue to apply the tool and for testing it with real data.

6.2.1 Urbanisation of Kuala Lumpur

Table 10 summarises the profile of Malaysia and its capital city of Kuala Lumpur in terms of land area, population and gross domestic product (GDP). The data were compiled from reports by the Department of Statistics, Malaysia (D. o. S. Malaysia, 2015) and the Ministry of Transport Malaysia (M.o. T. Malaysia, 2014).

Table 10: Profile summary of Malaysia and Kuala Lumpur (Department of Statistics Malaysia, Ministry of Transport Malaysia)

Country/urban area	Malaysia	Kuala Lumpur
Land area	330,803 km^2	243 km^2
Population	27.6 million	1.63 million
Population per km^2	83	6,696
Vehicles on the road (per km)	17.4 million	4.62 million
GDP	5%	-
Annual rate of urban population	3.8%	-

Like other developing countries in Asia, Malaysia has undergone massive urbanisation over the past decade. According to the statistics reported in World Urbanization Prospects 2018 by the United Nations Population Division, the urban population in Malaysia has increased steadily over the years, from 26.6% in 1960 to 75.45% in 2017 (The World Bank, 2018). In 2015, the rate of urban population growth (4.0% a year, on average) was among the fastest in the region, surpassed only by Lao PDR, Cambodia, and Vietnam (The World Bank, 2015). As of 2010, Kuala Lumpur was the eighth largest urban area in the region, larger than other megacities such as Jakarta, Manila, and Seoul. This urban area expanded from 1,500 to 1,700 km2 in the period between 2000 and 2010, representing an average of a 1.3% increase per year.

Urbanisation has clearly been influential in the development of Malaysia's economy. The continual economic growth and accelerating urbanisation has not only increased the number of inhabitants but has also brought in numerous challenges in urban transportation. The high number of motor vehicles on the road, particularly in Kuala Lumpur areas, not only causes traffic congestion but contributes to high GHG emissions and air pollution (Kamba, Rahmat and Ismail, 2007), particularly due to the use of older vehicle fleets, besides the lack of emissions regulation and enforcement. Consequently, a number of studies on urban transportation have emphasised the need for Malaysian citizens to shift from private vehicle usage to public transport (e.g., Nurdden, Rahmat and Ismail (2007); Shahid, Minhans and Che Puan (2014).

6.2.2 Alternative fuel vehicles in Malaysia and related studies

The use of CNG-powered vehicles, either the dedicated or bi-fuel versions, is not popular amongst private passenger vehicles, even though it has been widely deployed for taxi fleets. The 2017 Transport Statistics Malaysia showed that they account for 82% of the total of new taxis registered in the year 2013, increased from 78% in the previous year (source: Ministry of Transport Malaysia). From this statistic, one could say that the Malaysian taxi industry is already at the forefront of contributing towards sustainable transportation in Malaysia, although the motivation behind such adoption is primarily due to cheaper CNG, 65% and 57% lower than the price of petrol and diesel respectively (Idris and Abu Bakar, 2009).

Despite the importance of a life cycle approach for sustainability-TBL assessment of AFV technologies, a search of the literature revealed limited studies that have been conducted within a Malaysian context. Azmi and Tokai (2016) evaluated the "New Generation Vehicles" such as HEVs and BEVs, produced in Malaysia; however, this study was limited in scope to the environmental impacts of vehicle production process, or "cradle-to-gate" (from material extraction until the vehicle is ready for delivery). Meanwhile, Teoh *et al.* (2017) have examined the TCO of electric buses against conventional natural gas buses, although the analysis is simply conducted from a financial feasibility point-of-view.

6.2.3 The Malaysian taxi industry

As part of the country's urban public transport system, taxis in Kuala Lumpur are heavily regulated. Therefore, decision making related to taxis often involves cross-sectoral stakeholders. For instance, prior to introducing the increased taxi fare (which took an immediate effect from January 2015), the Land Public Transport Commission (previously known as S.P.A.D) has conducted a series of stakeholder engagement for the taxi fare review exercise in 2013, involving several government agencies, vehicle manufacturers, fleet operators, and even consumer groups. In the taxi fare review interaction paper, the SPAD Chairman stated that "the engagements with key stakeholders on matters of national interest, should be the norm moving forward, in order to upgrade and improve the public transport industry in a more holistic manner".

Taxi fleets in Kuala Lumpur are categorised into several classes. As a general rule, taxis in Malaysia can be owned either by private companies, associations, large corporations, or small family businesses and recently, ownership licenses have also been given to individuals (Land Public Transport Commission, 2017). Fig. 27 illustrates the taxi population in Kuala Lumpur according to the types of license ownership, which shows diversity in terms of the service classes. These 2014 statistics show that budget taxis hold the majority (80%) of the share, hence assumed to be representative of the whole taxi population.

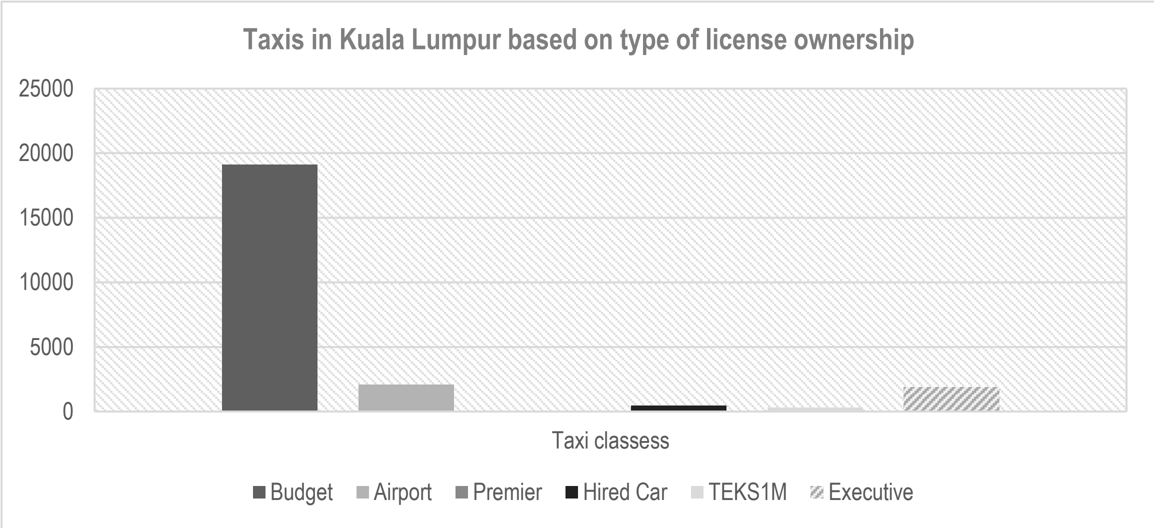


Fig. 27: Categories of taxis in Kuala Lumpur according to license ownership (Land Public Transport, Malaysia)

6.2.4 Representative sample of the taxi population in Kuala Lumpur

In this study, the population size is estimated based on the number of taxis that were registered based on their operator's license (refer Table 11). Whilst the actual size of taxi operators' population can be smaller (e.g., company can own and operate hundreds or thousands of fleet), the statistics is however not available.

Table 11: Representative sample size of population used in the study (source: author)

Distribution method: In person/drop in	
Taxi operators' population (as at 31st May 2016) *based on number of licenses for Kuala Lumpur area *(source: Land Public Transport Commission)*	6,322
Confidence level	95%
Margin of error	5%
Sample size required *(calculated using sample size calculator)*	**362**
Estimated response rate (based on mean overall (individuals and organisations), as per Baruch and Holtom (2008)	45%
Respondents to invite: $\frac{Number\ of\ respondents\ needed}{Estimated\ \%\ response\ rate}$	804

Despite the larger sample size targeted in Table 11, the paper-based questionnaires were only distributed to 30 companies and 200 individual taxi operators. The researcher was unable to invite more fleet operators due to time and resources constraint, as the individuals had to be reached in person, whilst the contact details of most companies are not publicly available. Out of the distributed sets of survey forms, a total of 116 were completed and returned (from six companies and 110 individuals), representing response rates of 20% and 58% respectively.

Based on the responses, the demographic of survey respondents has been broken down into two categories, according to the type of taxi fleet ownership, as follows:

- Categories of fleet operator's
  - Companies - which hold ownership of the taxi permit and license
  - Individuals - who own the taxi permit and license, and also self-drive the vehicle

Fig. 28 presents the breakdown of respondents according to the categories above.

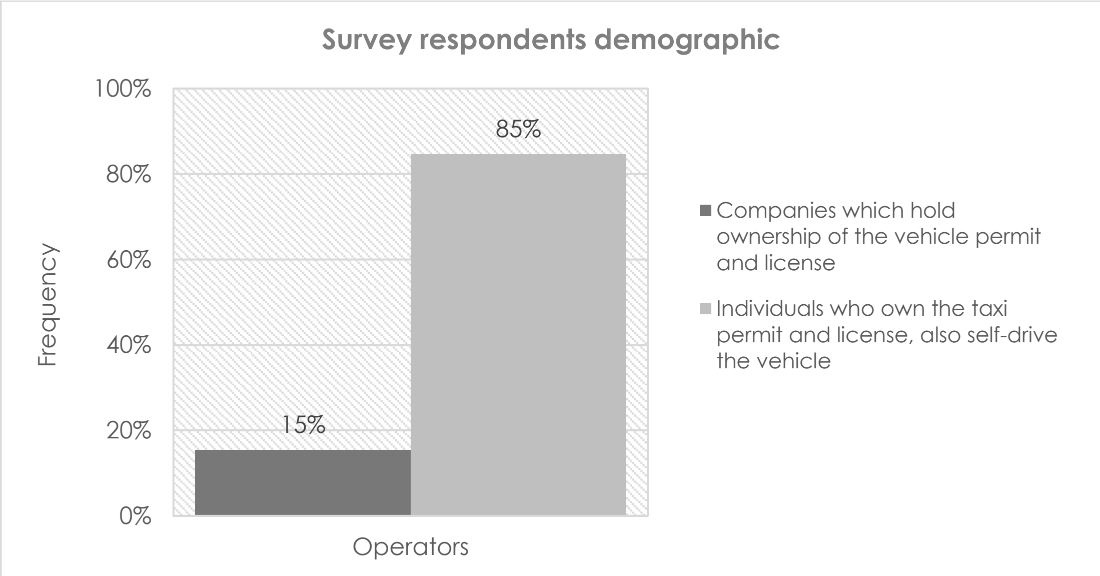


Fig. 28: Demographic of survey respondents based on taxi fleet ownership (source: author)

Information gathered from the survey participants has been analysed with descriptive statistics. The information was used to a certain extent to build the assumptions and reference values for the model parameters. The analysed results are presented in the next chapter.

6.3 Model application and procedure in detail

6.3.1 STAGE 1: Defining the goal and the scope of analysis

The primary goal of this research is to develop a tool that provides information regarding the performance and suitability of AFV technology choices, to facilitate stakeholders in the taxi industry to make informed decisions. The decision-making process on the selection of the AFV technology for taxi fleets is predominantly based on deterministic and probabilistic estimates multiple aspects. The primary focus of the case study modelling is to provide information about the TBL effects associated with the vehicle-fuel technology. To ensure a fair and level playing field comparison between various options, a consistent set of baseline assumptions was used in the evaluation. In this case, the baseline is referred to conventional petrol ICEV.

Meanwhile, the scope of the experimental case study was limited to the following:

- Taxi fleets operating within the Kuala Lumpur areas, thus other types of road transport vehicles were not considered.
- The time horizon of this study is up to 15 years, considering the maximum lifespan of vehicle. Taxi vehicles are to be retired after certain years of service, which can be varied according to the regulation.
- The AFV technologies evaluated are those currently available (at the time of this study) and in the next five years.
- As representative local data have not always been available, e.g., concerning health-related impacts and emission factors, the social costs of carbon etc., data for corresponding European cities have been used instead, following the transfer of benefit method described in section 4.3.2.
- The validity of the analysis results of the case study simulation is of secondary importance. The focus is on how to put the developed framework into practice.
- All fuels/technology options are assumed to have large-scale mass production and a fully developed infrastructure, hence no additional cost for construction is incurred in the scenario.

Alternatives and technology choices

To demonstrate the workability of the tool and its fundamental methodology, a comparative analysis is performed between a baseline (reference vehicle) and alternatives that are currently available in the market. Accordingly, this exercise has considered the following:

- Alternative power trains – namely hybrid electric & battery electric
- Alternative fuels – namely CNG and biofuels (B20 biodiesel from palm oil, E85 bioethanol from palm oil biomass)
- Retrofit options – referring to alterations to existing vehicles in the fleets (bi-fuel petrol NGV)

Diesel is another type of conventional petroleum-based fuel (like petrol), which is still widely used in some countries, such as the UK. However, diesel-fuelled passenger vehicles are not common in Malaysia, hence are excluded from the comparative analysis. The two types of biofuels (biodiesel and bioethanol) are considered in the analysis because they are currently the two most promising biofuels being projected to replace conventional fossil fuels in transportation (Lim and Lee, 2012).Taking advantage of being one of the largest producers of palm oil in the world (Tye *et al.*, 2011), there have been significant research and government policies supporting their development as energy alternatives in the country. By focusing on biofuels production from palm-based waste and by-products, the social issue of competition with food sources for human consumption is eliminated, plus there are abundant resources available throughout the year. As for BEV, it is assumed that such vehicles are able to travel 270 kilometres per full charge, based on currently available vehicles in the market, as modelled in Azmi and Tokai (2016). This version is assumed to be sufficient for taxi fleet travel distance on a daily basis, which has been validated by the findings from a survey of taxi operators conducted in this research. Fig. 29 illustrates the different fuel types/technologies evaluated in the experimental case study.

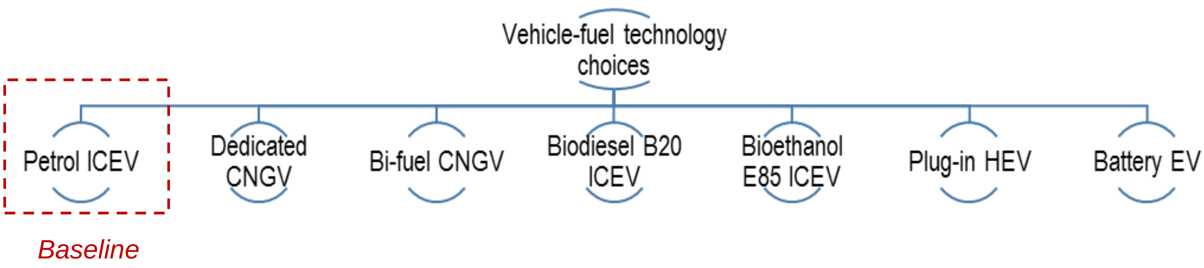


Fig. 29: Various vehicle-fuel technology choices considered in the case study (source: author)

- **System boundary**

An appropriate comparison between conventional ICEV and AFV technologies requires that the system boundary be set to include all relevant differences between them. Following the description of fuel WTWs and vehicle CTGs, as provided in Chapter 2, the system boundary of LCA performed in the case study covers the full life cycle. The life cycle refers to the period over which the costs and TBL impacts are assessed, which is not constrained to the vehicle lifespan (the duration over which it reaches a maximum level of permitted serviceability). Within the context of the case study, a taxi fleet vehicle has an operating age limit, which may be shorter than the usual vehicle life. For example, the average lifespan of a vehicle can be up to 10 years, as assumed in Macián, Tormos and Riechi (2017) and Sen, Ercan and Tatari (2017). However, the maximum age or operating limit for it to be used as a taxi can be seven years– depending on the taxi regulation (such as in the case of TEKS1M). In this scenario, the resale and/or salvage value is included in the analysis at the end of the taxi operating period, as it is assumed that the taxi fleet vehicle is then sold, to be used as a personal vehicle up to the end of its lifespan.

The different timelines described above are defined in the model accordingly. All technology options are compared over the same analysis period, based on input parameters specified in the following sections.

Data inventory: Input parameters

Given the illustrative case of AFV technologies evaluation for taxi fleets, many factors can be considered: for instance, the technology that is employed, vehicle fuel economy/efficiency, vehicle lifespan, characteristics of the fuel used, and emissions factors, among others. These are some of the parameters that may affect input values and the sustainability performance of each alternative, as shown in the literature.

The overall LCA performed in this thesis is subject to inherent uncertainty or uncertainty scenarios. Therefore, uncertainty is an essential element of LCA, which needs to be examined carefully before interpreting the results (de Souza *et al.*, 2018). Unlike other deterministic studies, where average fixed values are used (see, for example, Faria *et al.*, 2012; Tong *et al.*, 2017), some parameters like fuel/energy retail prices are treated as "uncertain", thus are specified as a range with probabilistic distribution. Whilst gathering inputs for the case study modelling, it is important to mention that not all parameters are considered as "known" and can be specified as deterministic, fixed single-values. In fact, some are unknown or difficult to be estimated, due to the lack (or non-existence) of consistent data: for instance, the marginal damage cost, given that there is little research and no established or official standard values for Malaysian context that can be used.

Due to the absence of local data for damage cost values, data published by DEFRA UK are used in the model. The values are adjusted and extrapolated to the Malaysian context by multiplying them with the purchasing power parity (PPP) exchange rate, per capita income and where necessary, the population size (for quantifying impacts of local pollutants). As for the GHG emissions or climate change cost, the shadow cost of carbon (SPC) is used instead of the social cost of carbon (SCC) provided on the United States Environmental Protection Agency official website, given the relevance of UK data as reference for estimating the representative local context. All these values are also adjusted to the present year, using the appropriate inflation rate based on historical data. These parameters are considered as "uncertain"; hence they are assigned with probabilistic distributions and therefore contain a range or set of values, e.g., minimum, most likely, maximum, low, central, high, etc.

Evidently, not all parameters are varied and defined with PDF. In the experimental case study, input parameters which are mostly related to the fleet, fuel and operation details, are categorised as "known" since they can be estimated from expert opinions, surveys or historical data. The input values are only varied in sensitivity analysis and have no probabilistic distribution. The categories of input parameters used in the model are shown in Table 12.

Table 12: Category of input parameters (source: author)

Known parameters	Unknown/uncertain parameters
Vehicle operating age limit (as taxi)	Fuel/electricity retail price
Vehicle lifespan	Fuel Tax exemption
Annual distance (mileage travelled)	Government subsidy (for fuel)
Working hours	Vehicle purchase incentive
Operating conditions (drive cycle and fuel consumption)	Vehicle repair cost (relative to the cost of service & maintenance per year)
Inflation rate	Marginal damage cost of emissions
Down payment for fleet purchase	Cost of damage to fossil resources
Discount rate	
Loan interest rate	
Loan term	
Alternative fuel use ratio (for bi-fuel or hybrid)	
Satisficing limits and criteria weights	

6.3.2 STAGE 2: Probabilistic simulation-based LCCA

Following the purpose of conducting LCC, which is for comparing a series of alternatives against a baseline, the outcomes are presented in a way that enables that comparison. As discussed in the earlier chapter, there are considerably large uncertainties associated with AFV technology adoptions and their consequences. As such, a probabilistic simulation approach is necessary to incorporate uncertainties within the analysis. Accordingly, the model outputs (monetised impacts) are appraised in a stochastic manner. Examples of questions that the model intends to answer are:

A. What is the probability that the estimated LCCs of alternative technologies are less than the baseline value?
B. What parameters have the largest influence on the uncertainty of the LCCs of AFV technologies?

To answer Question A, the results are compared based on two measures, as follows:

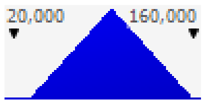
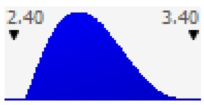
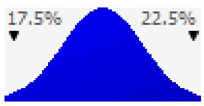
- The relative savings/reduction indicated from the mean difference, Δμ between AFV technologies and the baseline;
- The relative 90th percentile savings/reduction (α90) between AFV technologies and the baseline;

Overall, the above outputs represent the overall cost-effectiveness, savings reduction potentials from alternative-fuelled taxis over a defined period. The results of the relative difference function can be a positive or negative value. If the values of monetary savings are positive, they would mean that the alternative is relatively a better option (more energy-efficient, lower costs and emissions) than the conventional petrol taxis chosen as the reference vehicles in this study. Otherwise, the negative values indicate that there are no such benefits from AFVs implementation for taxi fleets, or that the baseline is relatively better.

Meanwhile, Question B is addressed through uncertainty analysis. Parameter uncertainty is managed by assigning a probability distribution to each input parameter, fitting the best to the data (Dong *et al.*, 2018). The probability distributions of input parameters represent a reasonable operating definition of the uncertain parameters (Yu and Tao, 2009). As long as the estimates for key parameters are reliable, these Authors argued that it is better to perform a simulation than to depend on deterministic models. It is recommended that only those variables with a high degree of uncertainty (herein categorised as unknown or uncertain) are established as a range, according to the type of PDF. As shown in Table 13, the uncertain input parameters are established as a range based on four types of PDF. Consequently, the contribution of uncertain parameters to the overall output variability is examined in order to identify the most influential factor for the change in the outputs and which uncertain parameters that are consistently the major sources of variations in every simulation.

While most recent data from reliable sources have been used to build energy consumption and emissions inventories, the external cost of marginal damage estimates of GHGs and CAPs emissions, as well as fossil resources, are highly uncertain. The so-called conversion factors for valuing the damage in monetary values are inherently inconsistent. Furthermore, the scientific understandings of health and environmental impacts of local CAPs emissions, for instance, are still heavily debated, as they vary by location and increase with increased population density (Mitropoulos and Prevedouros, 2015). Since the information is not yet established for the local Malaysian context, data for London was used to provide close representation of Kuala Lumpur context, due to some similarities in the size of the city, and its population.

Table 13: Probability distributions applied in the case study (source: author)

	Type of PDF	Description and justification	Parameters	Input distributions[2] example
1	Uniform	Parameters have an equal probability to get a value between a given range. Minimum and maximum values are used, which are "educated guesses" based on expert opinions, survey or secondary data.	Marginal damage cost of PM10 and NMVOC emissions, external damage cost of fossil resources	 (Fossil resources cost)
2	Triangular	Uses a minimum, a most likely value, and a maximum, which can be derived from the literature. Applied when there is a scarce/limited data of uncertain parameters (Yu and Tao, 2009)	Shadow price/social cost of carbon, PM, SOx and NOx damage cost	 (NOx marginal damage cost)
4	PERT	Uses an approximation for sampled data by specifying a minimum, a maximum and a most likely value derived from historical data and literature.	Retail prices of fuels**historical data is officially published*	 (Petrol retail price)
5	Normal	The most commonly used distribution	Incentive for vehicle purchase, repair cost	 (Incentive for EV/HEV)

6.3.3 STAGE 3: Trade-off and multi-attribute satisficing

Assuming that an optimal option is not achievable, trade-offs are explored between the multiple attributes of AFV technologies. To explore the trade-offs, parameters are varied in different scenarios (see Table 14). Besides using the actual, close-to-reality parameters based on data collected from the survey (Scenario A), a hypothetical example of a scenario (Scenario B) was also created in such a way that different alternatives were performing the best in each criteria aspect in order to illustrate a difficult, conflict decision problem. Scenario A is considered as the base case, closely reflecting the scenario today. In Scenario B, a low-intensive taxi operation is assumed (low daily mileage and operating days). Given that the taxi is not intensively driven, the vehicle service life and operating age limit can be extended.

The evaluation performed in Scenario B simply seeks to identify alternatives that perform better or comparable to the baseline, despite lack of support (financially) from the government (no incentive, subsidy or tax exemption). New conditions are then varied to show how and if the varying factors can affect the trade-off decisions toward achieving the best-compromised option. Varying these factors is important to enable stakeholders to align the conflicting priorities and find middle ground that would satisfy all parties. The use of a common aspiration level specified as the satisficing threshold of acceptance or “limits” enable such an outcome to be achieved.

Table 14: Example of varying parameters in different scenarios (source: author)

Parameters	Unit	Base Case:	Scenario B:
Daily distance travelled	KM	200	100
Operating days per month	days	26	22
Taxi fleet operating age limit	years	7	10
Vehicle lifespan	years	10	12
Operating condition (drive cycle)	-	Urban	Extra-urban
Use ratio (Petrol: Alternative fuel)[3]	-	50:50	70:30
- Discount rate[4]	%	3.0	1.5
- Inflation rate	%	2.5	1.5
- Loan term (financing)[5]	%	5	7

6.4 Summary

In this chapter, a model has been applied in a case study and tested experimentally using representative data collected from both primary and secondary sources. The context of case study and relevant background information have been described in this chapter. The procedural steps of the model have been carried out and elaborated. The model outputs and findings from the modelling and simulations are discussed in the next chapter.

[3] Fuel use ratio applicable for bi-fuel CNGV and PHEV
[4] Discount rate is assumed to be constant throughout the analysis period
[5] Loan term for financing the vehicle purchase

CHAPTER 7: DISCUSSION OF FINDINGS

7.1 Introduction

The aim of this chapter is to present the results from the experimental case study, which provides evidence on the applicability testing of the model in using real data. It is important to mention that the findings are limited to the scope and assumptions defined in Chapter 6, hence may not be representative and valid for evaluating AFV technologies in another context.

7.2 Findings & Discussion I: Survey results for collecting model parameters

It is important to note that the findings of this survey are assumed to be representative of the targeted population. The validity and reliability of the results are also subject to the accuracy of data provided by respondents in the survey. This research is not aimed at determining the absolute or “true” life cycle TBL impacts and sustainability performance of different technologies, but rather aims to provide a framework/methodology that enables such an evaluation to be conducted in a holistic context, for decision-support.

7.2.1 Vehicle fleet characteristics

Figs. 30-32 provide an overview of the types of vehicles (model, fuel use, transmission) being used as taxi fleet. Meanwhile, the results presented in Fig. 33-35 show the analysed data related to fleet acquisition and ownership. Although the mean or most dominated values obtained from descriptive analysis may not be directly used in the model, the findings presented in this section are useful in providing indicative estimates that are representative of the studied context, particularly when there are no other available sources of data that can be found in the literature.

a. Vehicle model

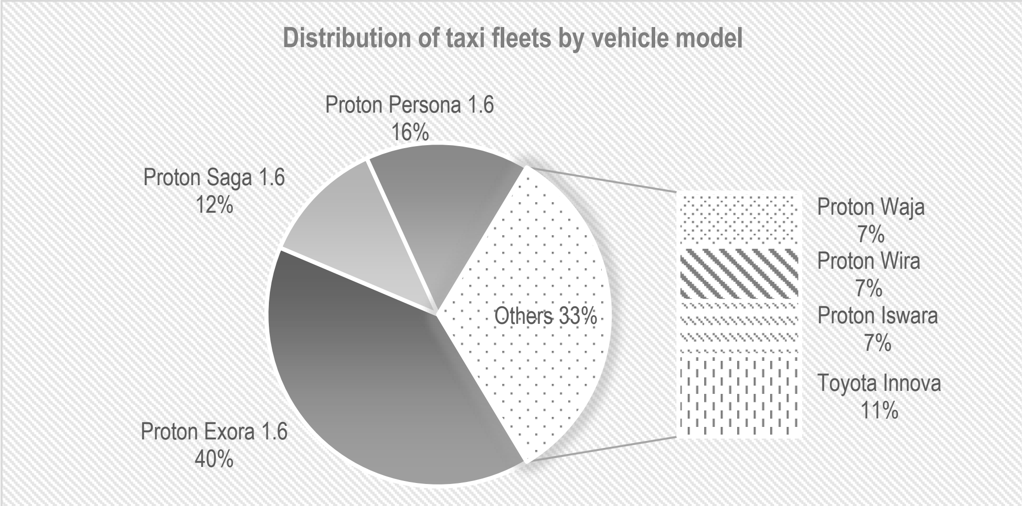


Fig. 30: Survey results of vehicle models (source: author)

b. Vehicle fuel use

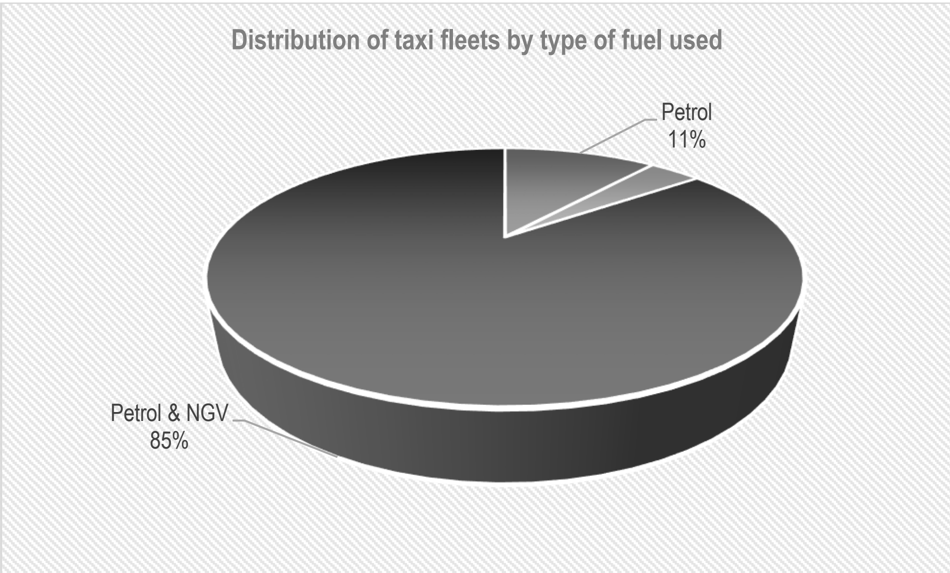


Fig. 31: Survey results of vehicle fuel use (source: author)

c. Vehicle transmission

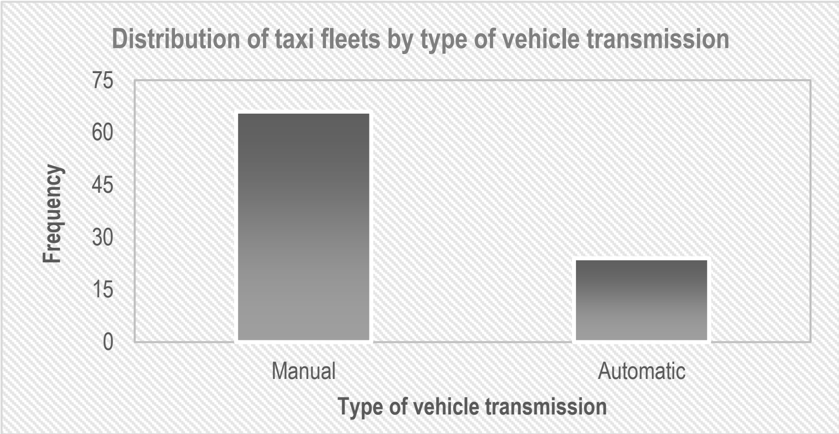


Fig. 32: Survey results of vehicle transmissions (source: author)

d. Vehicle age limit (by fleet ownership)

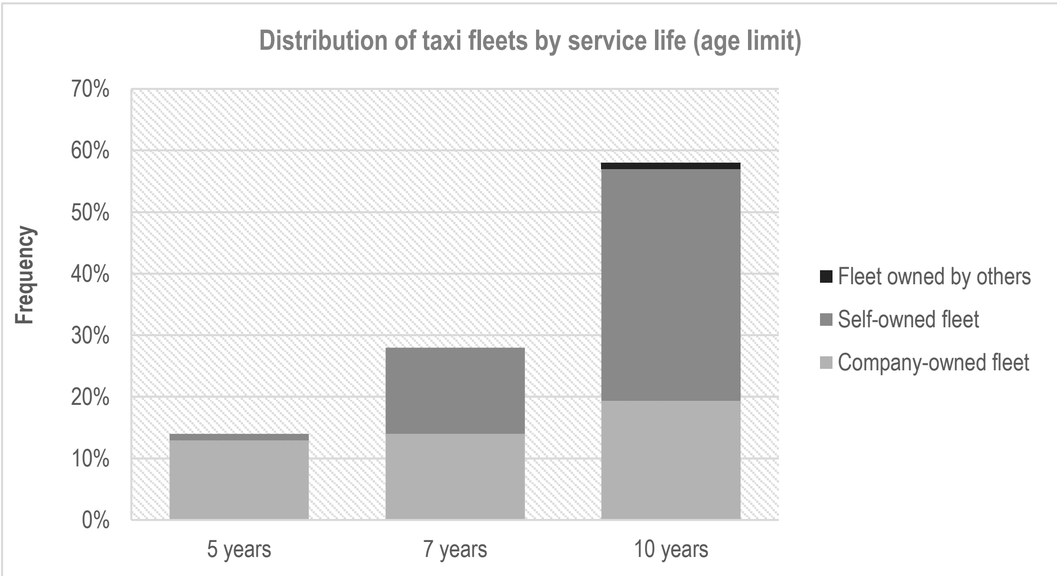


Fig. 33: Survey results of vehicle age limits (source: author)

e. Vehicle fleet acquisition method

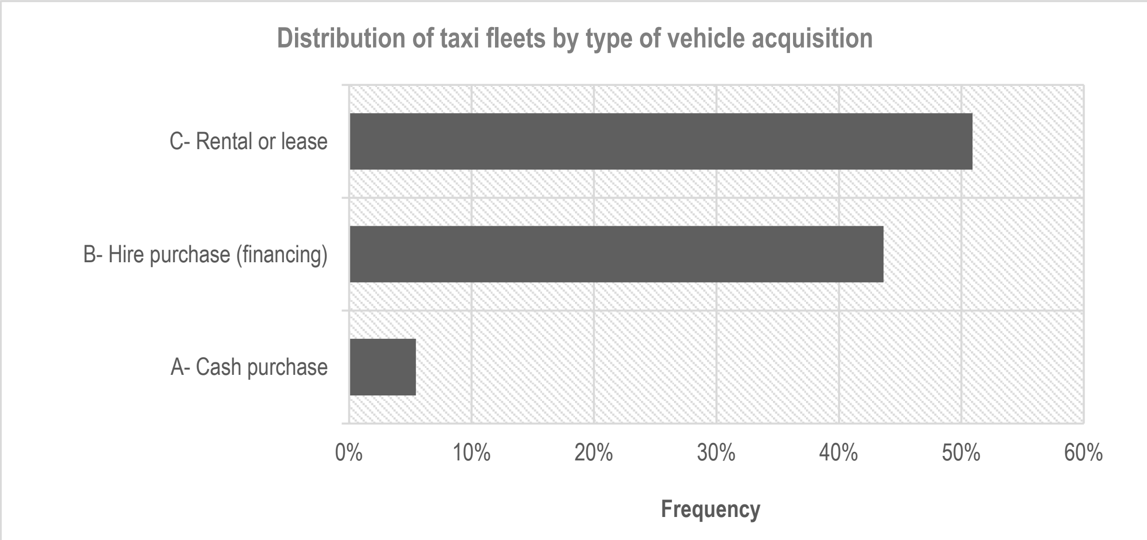


Fig. 34: Survey results of vehicle fleet acquisition methods (source: author)

f. Initial down payment for vehicle purchase via financing

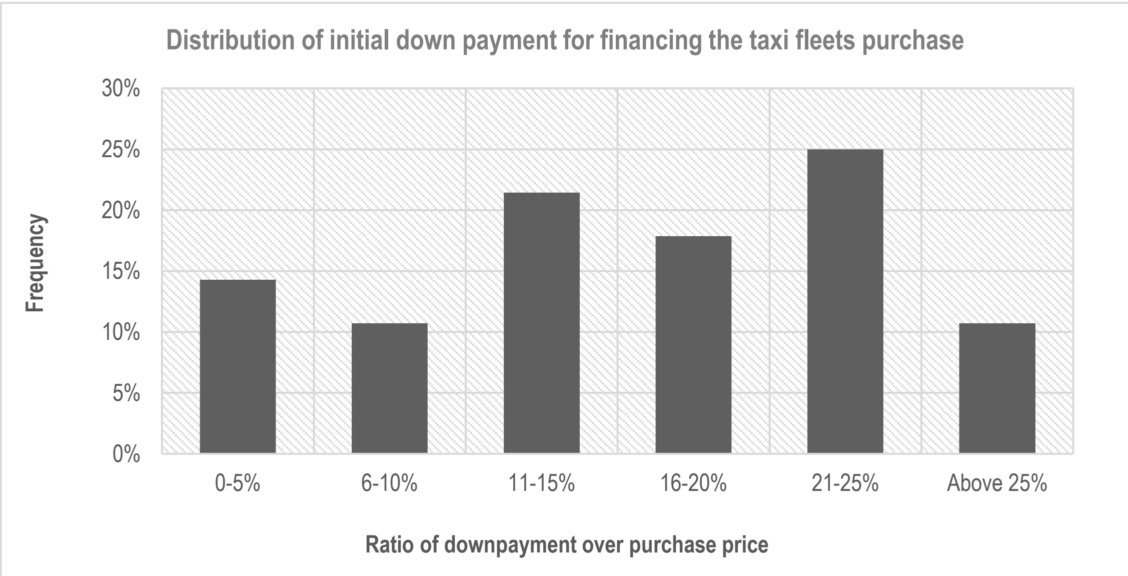


Fig. 35: Survey results of initial down payment for vehicle purchase (source: author)

7.2.2 Taxi operating profile

In this section, the results of descriptive analysis related to the taxi operating profile are presented (Figs. 36-37). The findings can be useful to build assumptions and illustrate the variation in life cycle impacts, due to the changes in input parameters that are established from empirical data.

a. Daily distance travelled

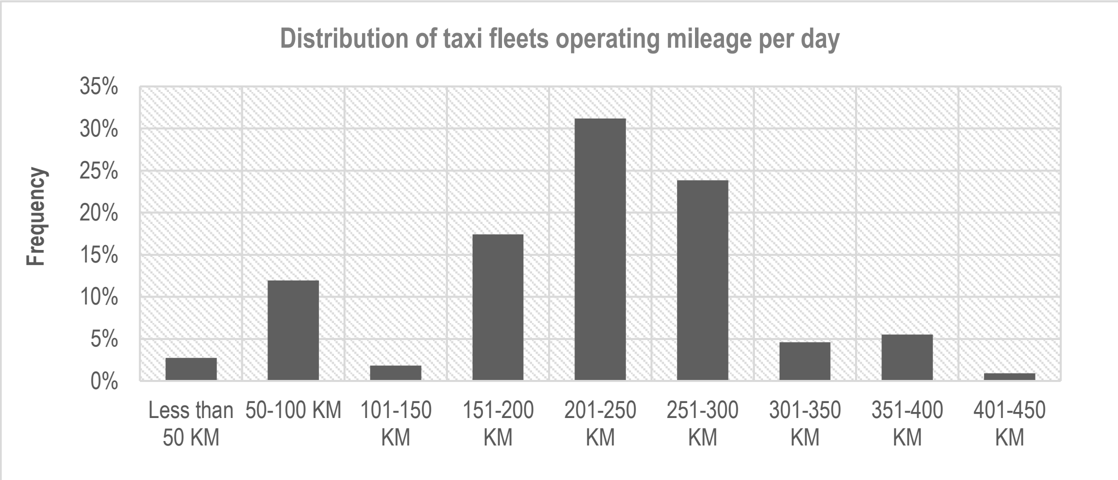


Fig. 36: Survey results of daily operating distances (source: author)

b. Operating days per month

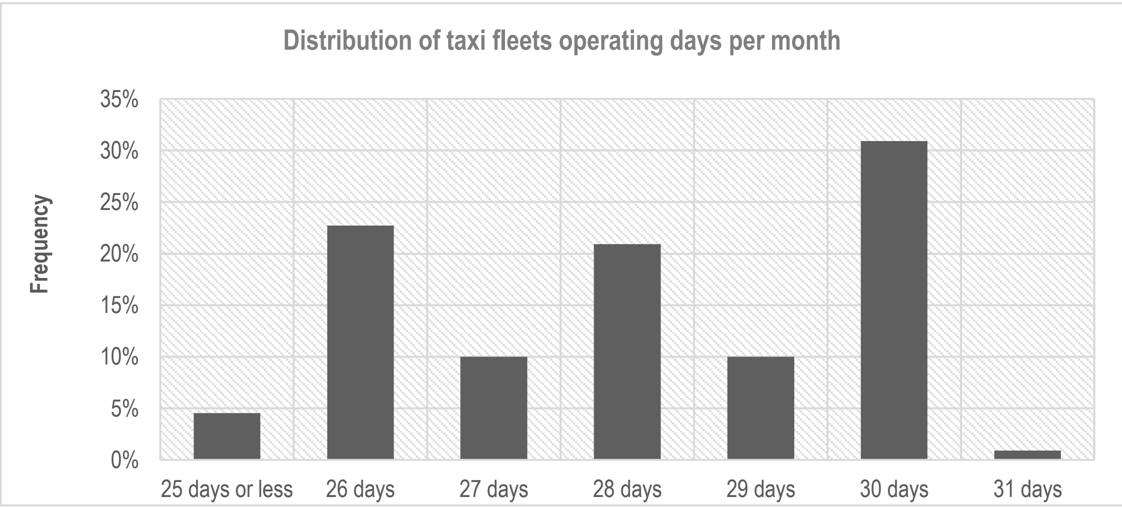


Fig. 37: Survey results of operating days per month (source: author)

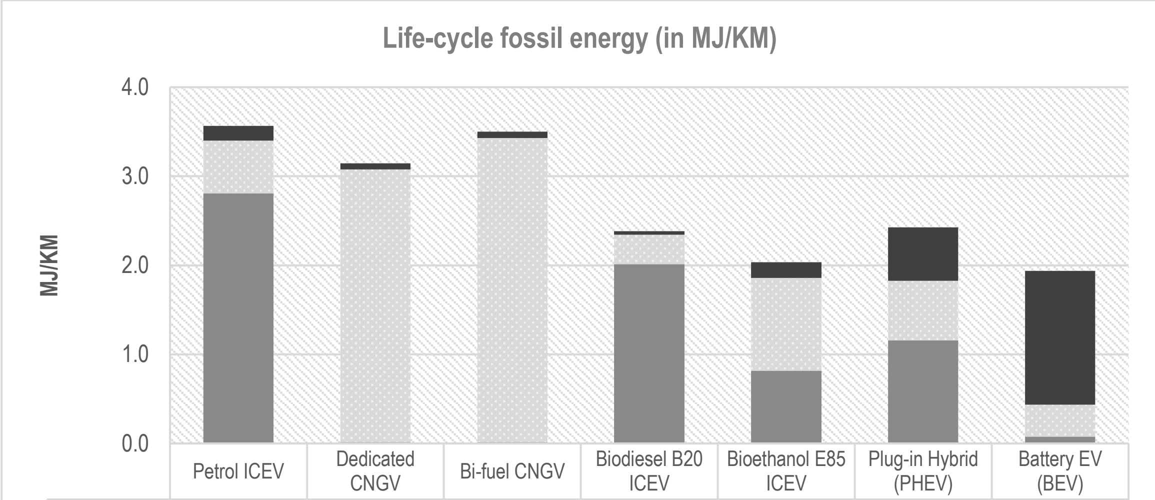
7.3 Findings & Discussion II: Inventory analysis

Based on the energy consumption and emission factors (per mile) taken from GREET, the total energy consumed and mass of emitted substances over the full life cycle for seven different types of taxi fleet are quantified. Table 15 outlines the total energy consumption factors calculated per kilometre distance travelled (functional unit), whilst the breakdown of fossil resources that make up the total consumption is illustrated in Fig. 38. Accordingly, the total energy consumed over the lifetime distance travelled by the taxi is estimated, based on assumptions specified in the base case scenario (see Fig. 39). When comparing fuel efficiencies, it is important to differentiate between the total energy and that which is produced from fossil resources. Depending on how and what aspects are considered for evaluating the options, these two factors need to be clearly distinguished in order to provide transparency to decision makers.

Based on the energy consumption factors, the use of fossil fuels resources (i.e., petroleum, coal and natural gas being the primary energy production) in kilogram crude oil equivalent (kg oil eq.) is estimated per kilometre (see Fig. 40).

Table 15: Life cycle factors of energy consumption in MJ per KM (source: GREET)

Vehicle-fuel types	Energy consumption (MJ) per 1 KM
Petrol ICEV	3.82
Dedicated CNGV	3.50
Bi-fuel CNGV	3.66
Biodiesel B20 ICEV	2.93
Bioethanol E85 ICEV	4.65
Plug-in Hybrid (PHEV)	2.72
Battery EV (BEV)	2.33



	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	Biodiesel B20 ICEV	Bioethanol E85 ICEV	Plug-in Hybrid (PHEV)	Battery EV (BEV)
Coal	0.16	0.07	0.07	0.04	0.18	0.60	1.50
Natural Gas	0.59	3.06	3.41	0.33	1.04	0.67	0.36
Petroleum	2.81	0.01	0.02	2.01	0.82	1.16	0.08

Fig. 38: LCI results of energy from fossil resources in MJ/KM (adapted from GREET)

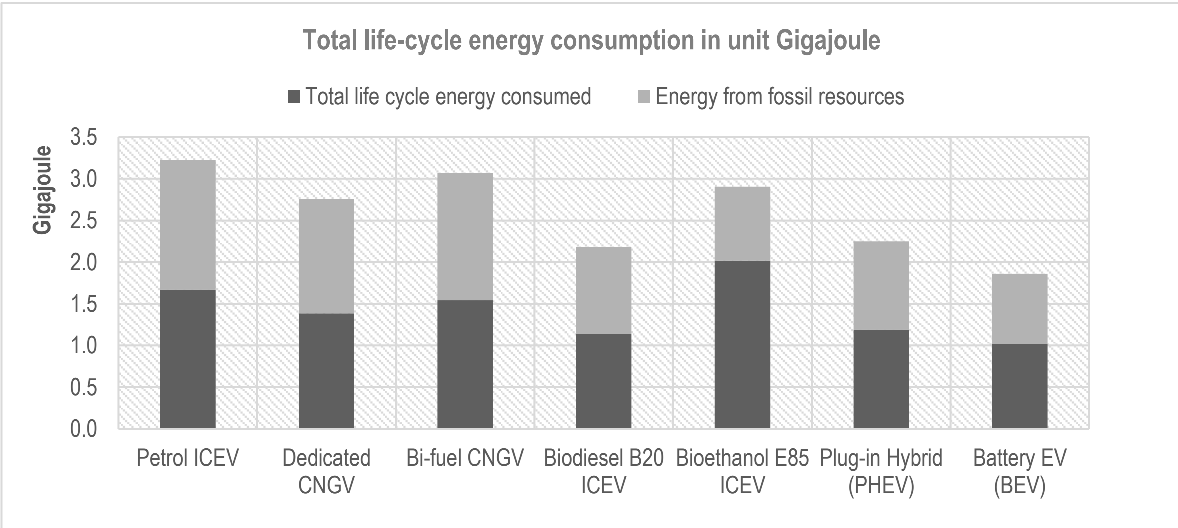


Fig. 39: LCI results of total energy consumption in unit Gigajoule (adapted from GREET)

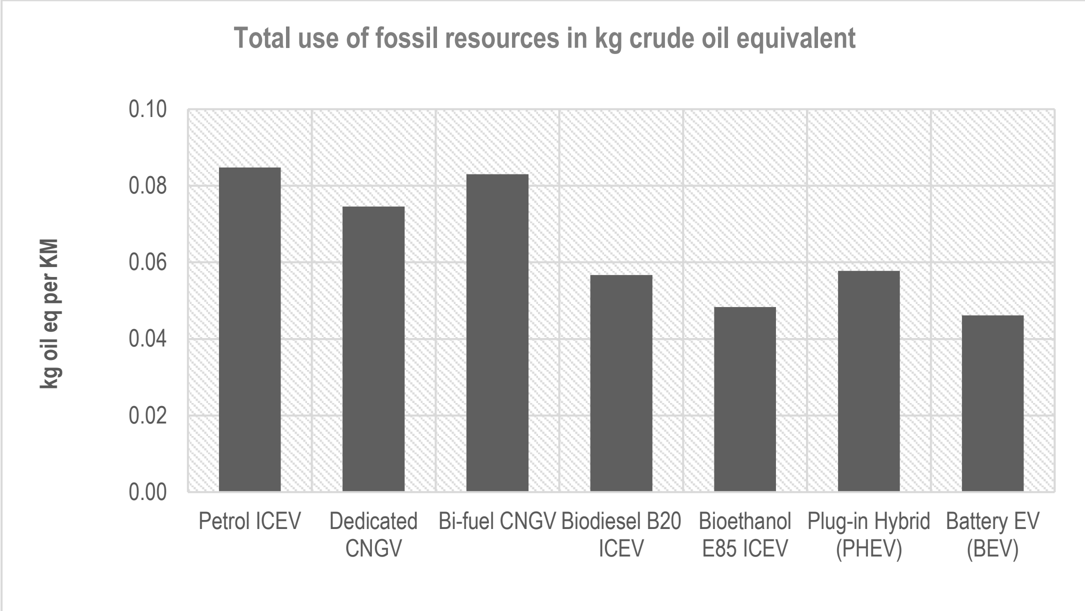


Fig. 40: LCI results of fossil energy resources use in crude oil equivalent (adapted from GREET)

In terms of GHGs emissions, Table 16 shows the inventory results in unit grams of CO_2e per kilometre driven. To provide illustrative results in terms of the total emitted substances over the full life cycle, the inventory data are then multiplied by the lifetime operating mileage. Figures are computed illustratively for the base case scenario, and Fig. 39 presents the outcome in tonnes of emissions.

As shown in Fig. 41, all the fossil fuel-based options produce high GHGs emissions, ranging from 100 (CNGV) to 120 tonnes (petrol ICEV). On the contrary, vehicle electrification and bio-ethanol E85 can significantly provide emissions benefits as far as carbon footprints or climate mitigation are concerned. As for CAPs, Fig. 42 presents the total inventory of NOX, PM10, PM2.5, CO, MVOC and SOx emissions in unit mass (tonnes), encompassing direct (tailpipe), indirect and upstream emissions during vehicle and fuel production. It is worth mentioning that the compiled LCI of emissions values are increased year by year (when estimating the marginal damage in monetary units) to account for the increase due to the mileage and age of the vehicle.

Table 16: Life cycle GHGs emissions factors in grams per KM (source: GREET)

Vehicle-fuel types	Grams of GHGs emissions (in CO_2e) per KM
Petrol ICEV	273.4
Dedicated CNGV	229.9
Bi-fuel CNGV	254.8
Biodiesel B20 ICEV	248.5
Bioethanol E85 ICEV	198.8
Plug-in Hybrid (PHEV)	192.6
Battery EV (BEV)	180.2

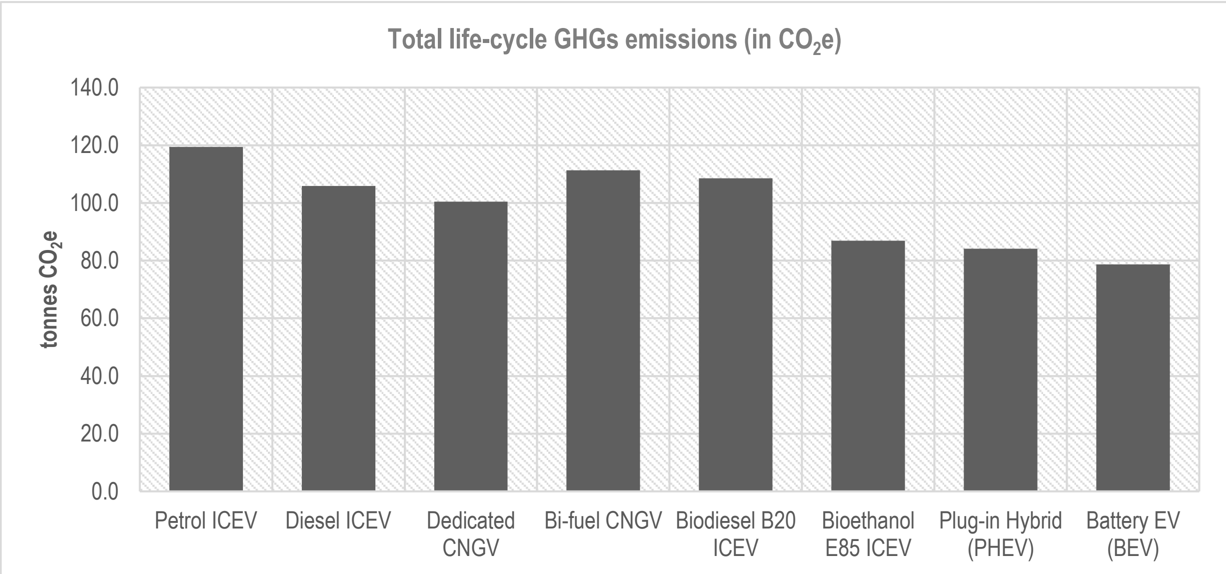
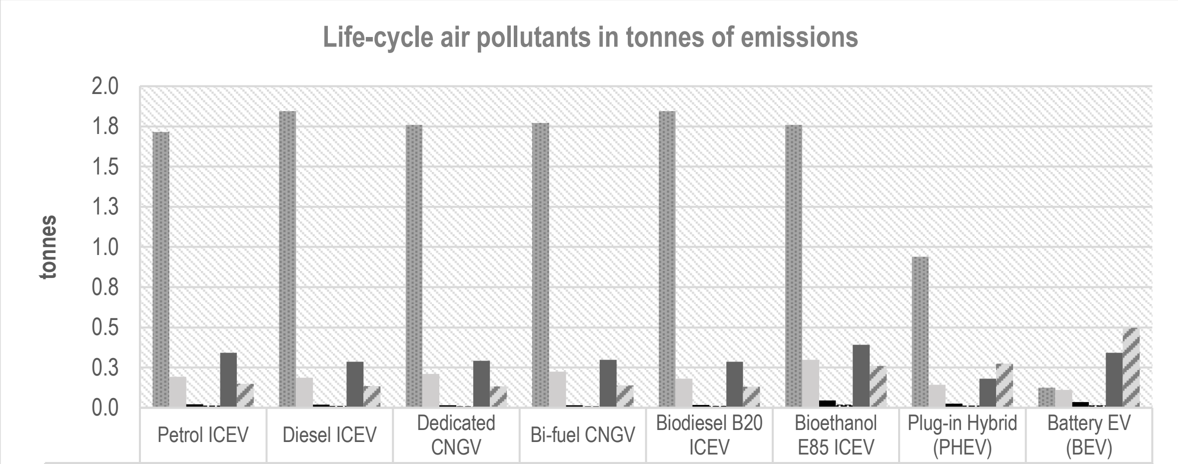


Fig. 41: LCI results of GHGs emissions in tonnes CO_2e (adapted from GREET)



	Petrol ICEV	Diesel ICEV	Dedicated CNGV	Bi-fuel CNGV	Biodiesel B20 ICEV	Bioethanol E85 ICEV	Plug-in Hybrid (PHEV)	Battery EV (BEV)
CO	1.7	1.8	1.8	1.8	1.8	1.8	0.9	0.1
NOx	0.2	0.2	0.2	0.2	0.2	0.3	0.1	0.1
PM10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PM2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NMVOC	0.3	0.3	0.3	0.3	0.3	0.4	0.2	0.3
SOx	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.5

Fig. 42: LCI results of air pollutants emissions in tonnes (adapted from GREET)

7.4 Findings & Discussion III: Probabilistic LCCA of AFV technologies

The outcomes of LCI analysis shown above are subsequently used to quantify the life cycle sustainability cost/benefits in terms of the monetised damage to human health and the ecosystem.

To compare between taxi fleets with different fuels or powertrain configurations, the results are presented for private and external LCCs. This assessment was performed stochastically, hence outputs are presented as a range (with statistical significance) rather than single deterministic values. To provide consistency in the way results are presented, the monetary values are compared per kilometre basis (see Figs. 43-45). The results are compiled from @Risk simulations outputs, based on the range and distributions as summarised in Table 17. In each analysis, MCS runs are applied with 1000 iterations (see Appendix 5 for details of outputs in each iteration).

Looking at the ownership and operating LCC of technologies in Fig.43, the variation seems to be lower than the externalities shown in Figs. 44 and 45. The variation in external LCC of the evaluated vehicle types might be due to large uncertainty in the damage cost values, as the variation is consistent across all vehicle types. However, the life cycle ownership and operating cost of E85 ICEV varies in a larger range compared to the others, which might be due to a variety of reasons. This factor can be investigated in Uncertainty Analysis, presented in the next section.

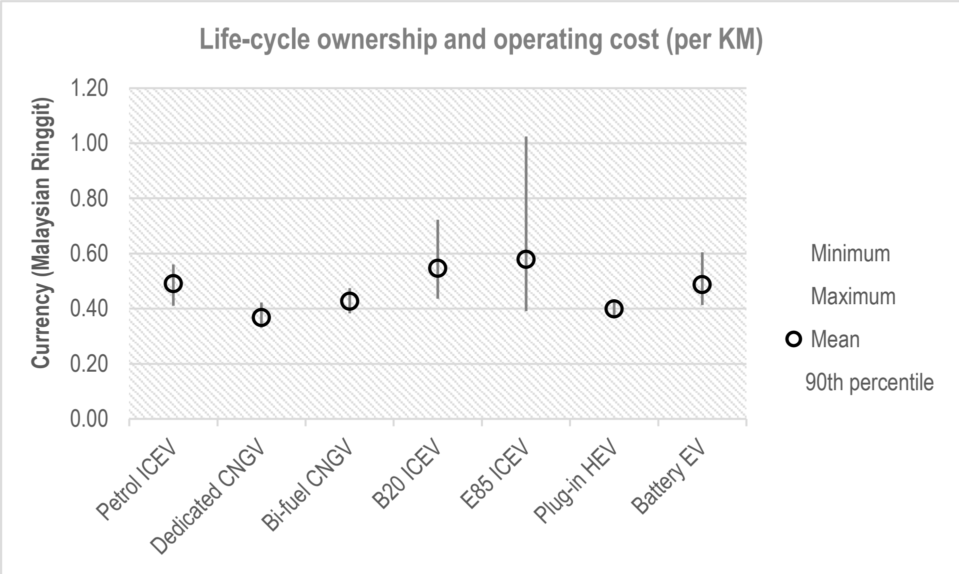


Fig. 43: Results of life cycle ownership and operating cost (source: author)

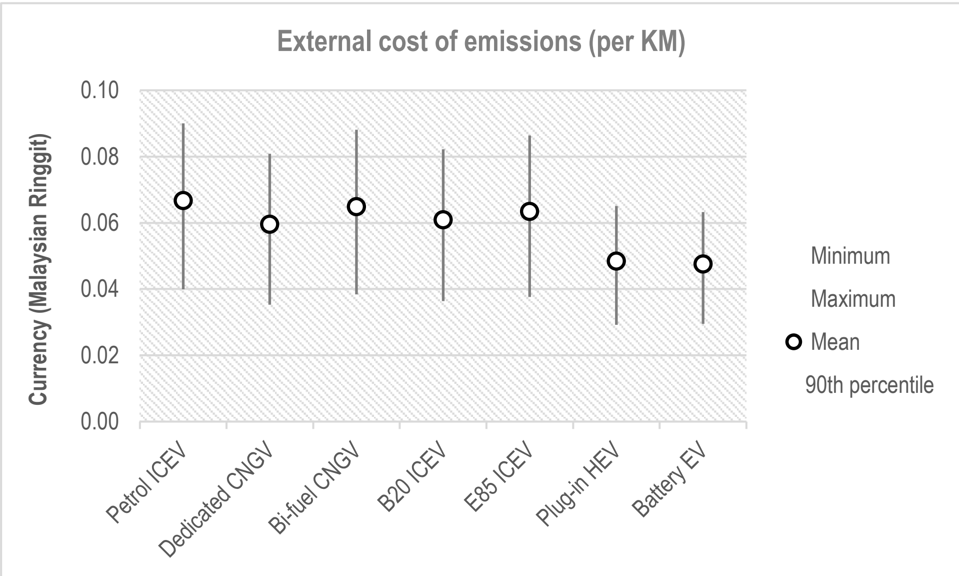


Fig. 44: Results of life cycle external cost of emissions (source: author)

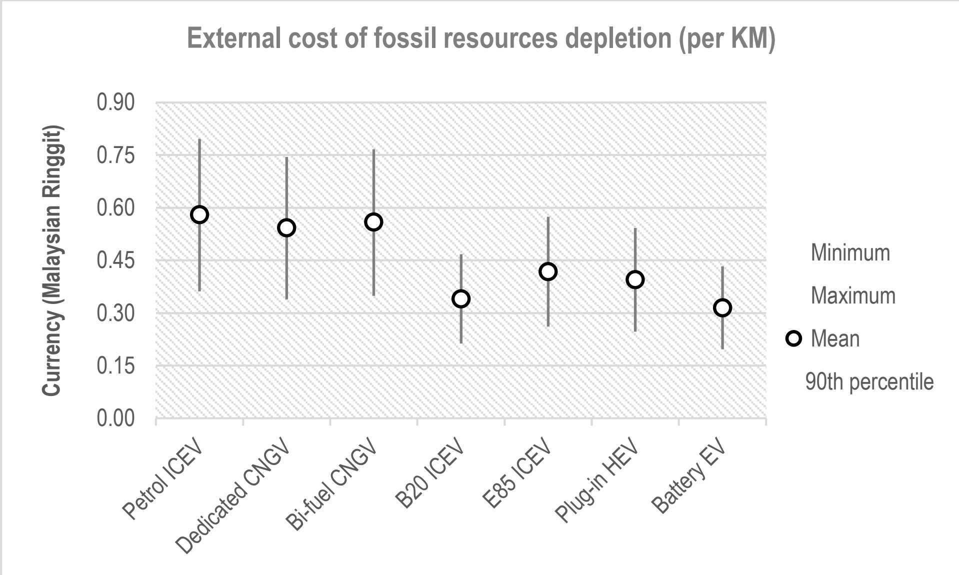
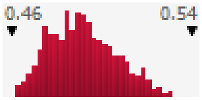
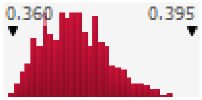
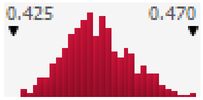
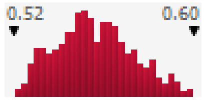
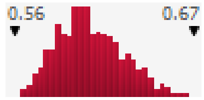
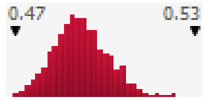
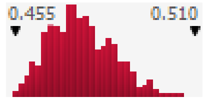
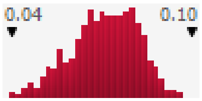
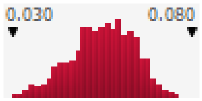
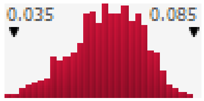
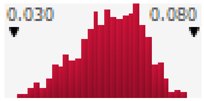
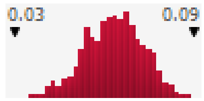
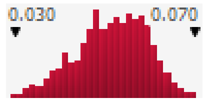
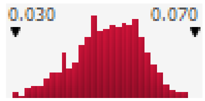
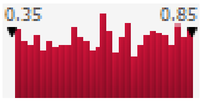
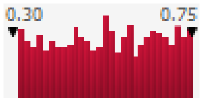
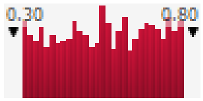
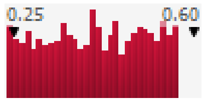
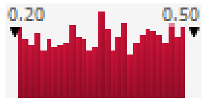
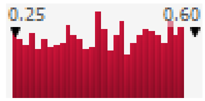
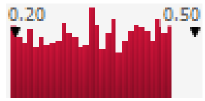


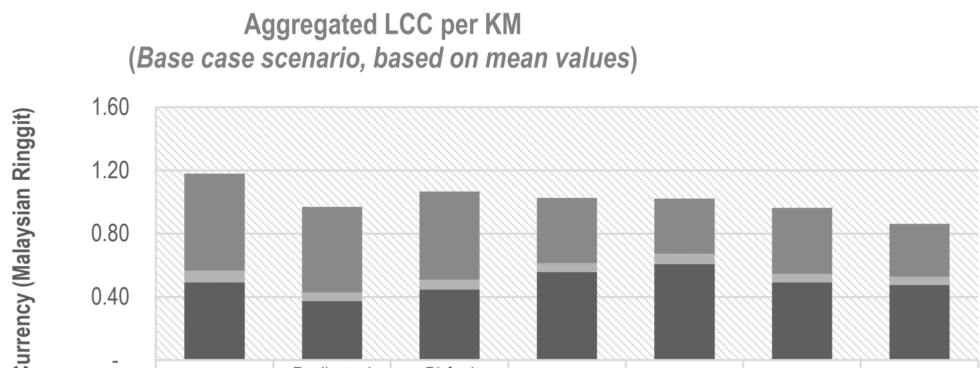
Fig. 45: Results of life cycle external cost of fossil resources depletion (source: author)

Table 17: Summary of @Risk simulations output results (source: author)

Options Indicator *(cost per KM)*	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	Biodiesel B20 ICEV	Bioethanol E85 ICEV	Plug-in HEV	Battery EV
Ownership and operating cost							
External cost of emissions							
External cost of fossil resources depletion							

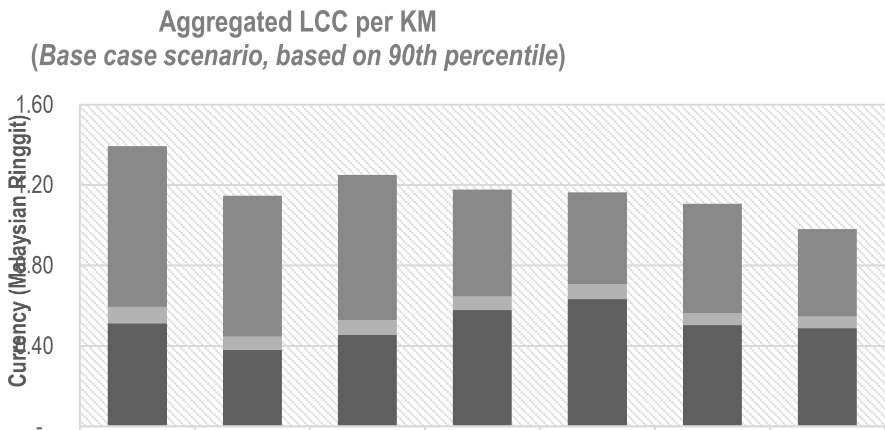
A major finding from the comparative analysis presented above is that the best or optimal AFV technology would not be competitive from a private LCC basis without internalising the externalities associated with marginal damages of GHGs and CAPs emissions, or depleting fossil resources. If the monetary cost values of TBL criteria (as presented in an earlier section) are combined into a single indicator (similar to societal LCC, as used in Ogden, Williams and Larson, 2004; Goedecke, Therdthianwong and Gheewala, 2007, but without removing taxes and subsidies), Figs. 46 and 47 show that BEV taxis perform better with lower LCCs than their counterparts when such externalities are internalised. Although this result may provide an aggregated comparative overview between all evaluated options, BEV is not the most economically efficient from the taxi operator's point of view because the capital investment is significantly higher. Instead, the most cost-effective alternative technology is Dedicated CNGV; however, the total combined cost is amongst the highest, given that the externalities represent more than 60% of this amount. The apportionment between private and external LCC thus becomes a limitation, because the inclusion of external costs can significantly change the overall outputs.

Although the aggregated LCCs may not be robust enough for comparing the performance of different technologies from a balance standpoint, they still provide a transparent representation of externalities paid by the society. On one hand, this holistic insight enables taxi companies to consider alternative fuel options not solely based on their cost-effectiveness, but also through paying attention to the benefit from adopting energy-efficient, environmentally benign technology. On the other hand, it provides policy makers and regulators with knowledge regarding the cost and financial impact to taxi operators', as a result of any regulations related to climate mitigation and air quality improvement.



	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	B20 ICEV	E85 ICEV	PHEV	BEV
External cost of fossil resources depletion	0.62	0.54	0.56	0.41	0.35	0.42	0.33
External cost of emissions	0.07	0.06	0.06	0.06	0.06	0.05	0.05
Ownership & Operating cost	0.49	0.37	0.45	0.56	0.61	0.49	0.48

Fig. 46: Mean results of the aggregated LCC per KM (source: author)



	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	B20 ICEV	E85 ICEV	PHEV	BEV
External cost of fossil resources depletion	0.80	0.70	0.72	0.53	0.45	0.54	0.43
External cost of emissions	0.08	0.07	0.07	0.07	0.08	0.06	0.06
Ownership & Operating cost	0.51	0.38	0.46	0.58	0.63	0.50	0.49

Fig. 47: 90th percentile results of the aggregated LCC per KM (source: author)

To provide a different comparative overview, the results are also presented in relative monetary savings/benefits (see Table 18). Due to the magnitude difference in terms of the savings/reduction values, it can be difficult to view the comparative results on a holistic basis, relative to one another. Therefore, Figs. 48 and 49 present the reduction in relative monetary gain/loss against the baseline petrol ICEV, based on the mean and 90th percentile values.

Table 18: Results summary of relative monetary gain/loss against the baseline (source: author)

Technology choices	Relative monetary gain/loss against baseline (in Malaysian Ringgit)		
	Operator cost (Private LCC)	Emission (External LCC)	Fossil resource (External LCC)
Dedicated CNGV	52,350	6,927	32,450
Bi-fuel CNGV	20,159	4,398	25,355
Biodiesel B20 ICEV	-27,934	6,258	89,200
Bioethanol E85 ICEV	-50,306	3,382	115,546
Plug-in hybrid EV	-128.6	8,576	85,819
Battery EV	7,264	8,962	122,697

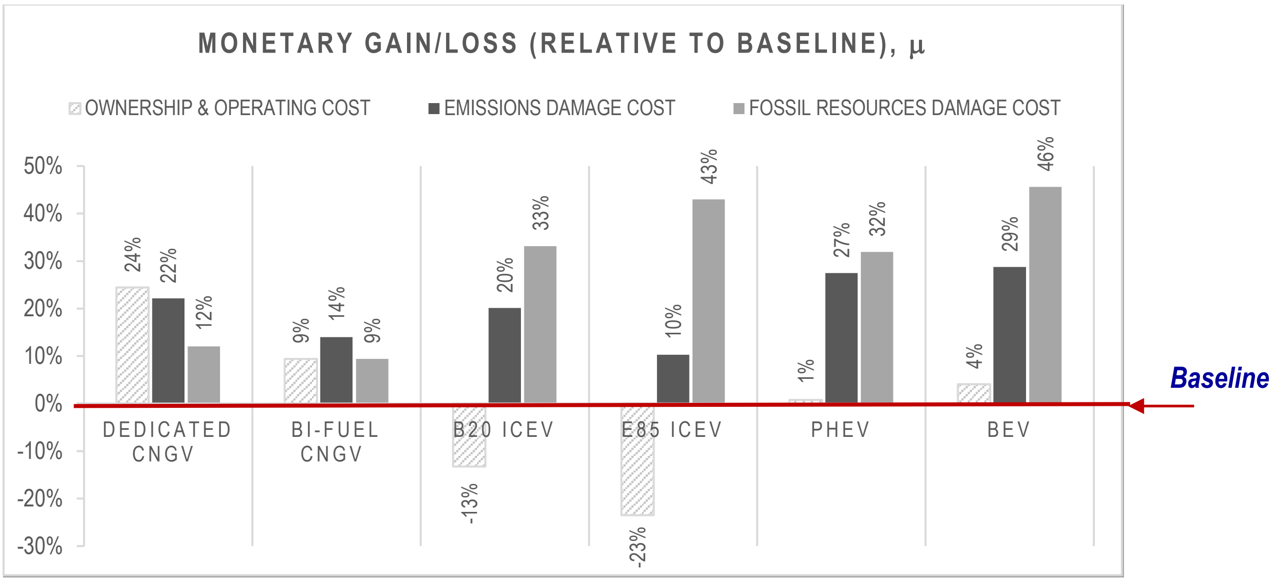


Fig. 48: Comparative results (μ) of relative LCC savings/reduction (source: author)

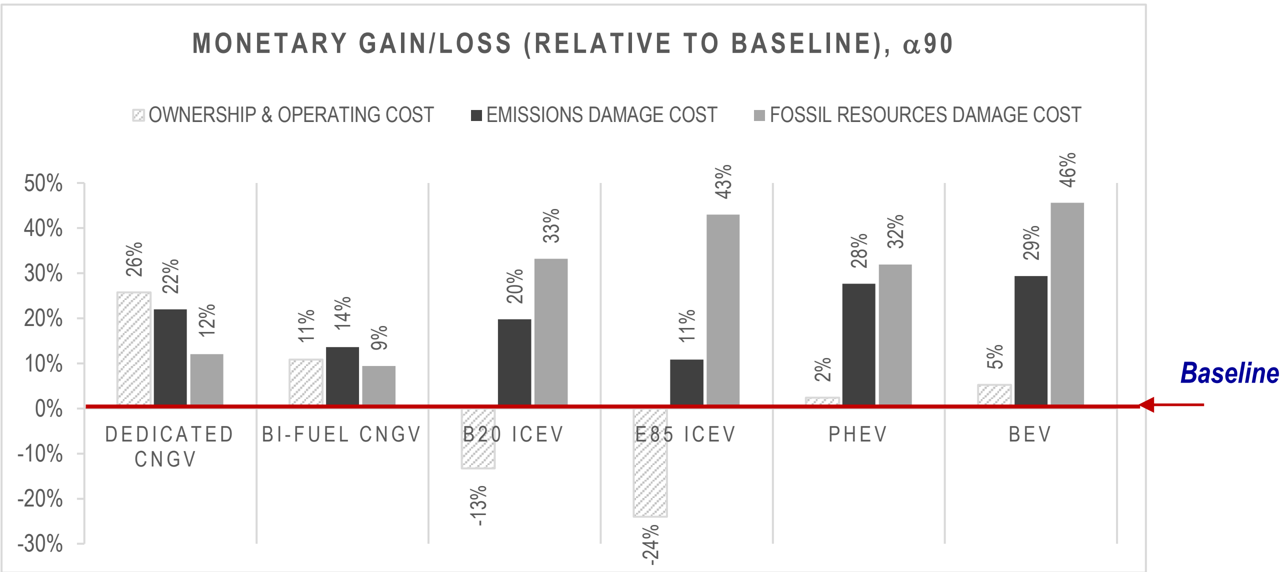


Fig. 49: Comparative results (α90) of relative savings/reduction (source: author)

It is apparent from the results presented above that there is no single best or optimal option (that performs the best in all criteria), thus trade-off is inevitable. In this scenario, a trade-off between life cycle ownership and operating cost (private LCC) and the life cycle externalities of emissions and fossil resources depletion (external LCC) can be expected. In other words, an optimisation strategy is not achievable in this context of decision making.

Fig. 50 shows an overview of the overall performance between different AFVs, which indicates that the closer the alternatives are to the central point, the better they are from a TBL performance perspective. What is interesting about the result is that the option that might have been preferred on the basis of the private LCC (which had been incurred by owner/operators) will have to be re-evaluated, considering, for example, the higher negative impacts in terms of emissions or fossil resources damage. If only fossil resources use is considered, the biofuels-powered taxi fleets operating with B20 and E85 could reduce the damage to resource cost by 33% and 43% reduction respectively, albeit at the expense of 13% and 23% increases in operating and ownership costs to taxi operators. This defines the need to assess the contradictory factors using satisficing strategy, considering the priorities of stakeholders and decision makers.

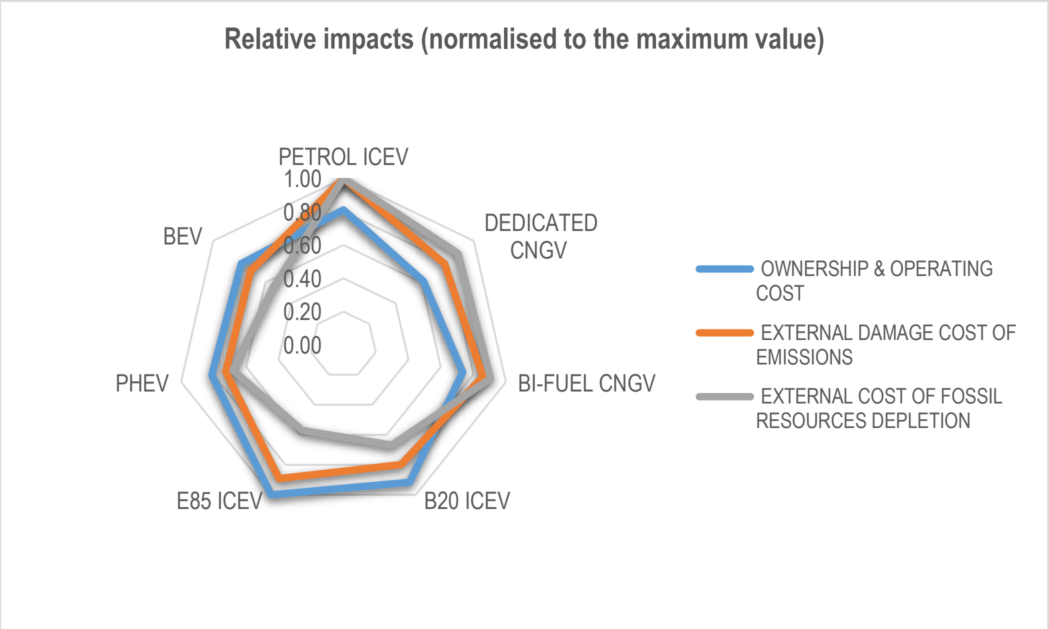


Fig. 50: Results of relative impacts by multiple indicators (source: author)

It should be noted that the trade-off relationships shown above are independent of the criteria weights. The next section presents the results of how the model can be used to explore possible trade-offs and satisfactory solution for meeting SD goals

7.5 Findings & Discussion IV: Satisfactory trade-off through scenario planning

Based on the comparative results presented in the earlier section, the monetary values of life cycle ownership and operating costs, emissions damage and fossil resources are traded off to find a reasonable balance that would satisfy SD goals. In this section, an exploratory trade-off is examined for alternative scenario B (refer to Table 14 for details and profile of this scenario), to provide an example of how the tool can be used to seek a satisfactory trade-off when optimal option is not attainable.

As shown in the comparative results presented in Fig. 51, most alternative-fuelled taxis offer emissions and fossil resources damage cost reduction, albeit at the expense of an increase in ownership and operating costs, over the operating life. Following the working procedures of the framework, an aspiration level is firstly determined to indicate the level of acceptance that would satisfy all decision makers. In this example, an aspiration level of 10% reduction from the baseline is specified as the limit or acceptance threshold. In other words, the attributes of the alternatives must be better by 10%, in all the criteria.

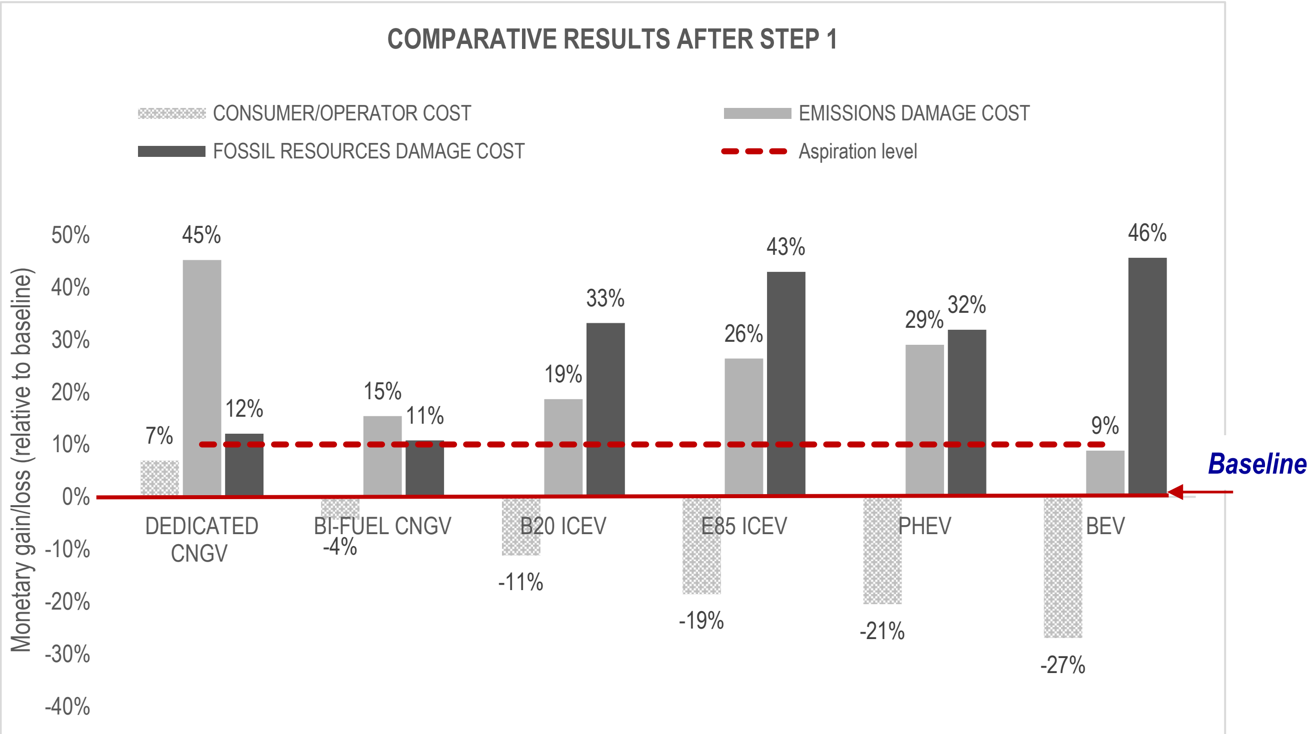


Fig. 51: Comparative results for trade-off after Step 1 (source: author)

Next, the relative monetary gain/loss is compared against the aspiration level, as tabulated in Table 19. The coloured cells indicate that the minimum acceptance limits are met. In this example, none of the alternatives meet the acceptance threshold in all the criteria evaluated, therefore they are rejected and ruled out in Step 2. Therefore, the search process continues to Step 3.

Table 19: Comparative performance against the aspiration level (source: author)

Vehicle types/technologies	Satisfice Criteria 1? (>=10%)	Satisfice Criteria 2? (>=10%)	Satisfice Criteria 3? (>=10%)	[Reject/ Accept?]
Dedicated CNGV	7% X	45% √	12% √	Reject
	RM10,304	RM6,362	RM18,838	RM35,504
Bi-fuel CNGV	-4% X	15% √	11% √	Reject
	RM-6,530	RM2,172	RM16,779	RM12,421
B20 ICEV	-11% X	19% √	33% √	Reject
	RM-16,707	RM2,627	RM51,783	RM37,704
E85 ICEV	-18% X	26% √	43% √	Reject
	RM-27,707	RM3,714	RM67,078	RM43,085
Plug-in HEV	-21% X	29% √	32% √	Reject
	RM-30,610	RM4,084	RM49,821	RM23,295
Battery EV	-27% X	9% X	46% √	Reject
	RM-40,255	RM1,243	RM71,229	RM32,217

In Step 3, new variables are introduced to explore the choices and make a necessary trade-off between the ownership and operating cost, with the emissions and fossil resources damage externalities. By way of example, the following factors are added by varying the input consecutively through scenario planning:

a. Vehicle purchase incentive: 10% (of purchase price) given to taxis with alternative fuels (one-off);
b. Fuel tax exemption and subsidy: 100% tax exemption and 25% subsidy on renewable fuels (B20, E85) and electricity, retaining the exemption (100%) and 15% subsidy for fossil fuels (petrol, CNG).

The impacts of adding the conditions as above on the simulation outputs are shown in Figs. 52-54 respectively. Fig. 52 revealed that by giving a 10% one-time purchase incentive for all taxis with alternative fuels, the relative savings performance is improved, and a satisfactory trade-off can be achieved with Dedicated CNGV. Decision makers can mutually agree and accept this choice, or they can continue the search process.

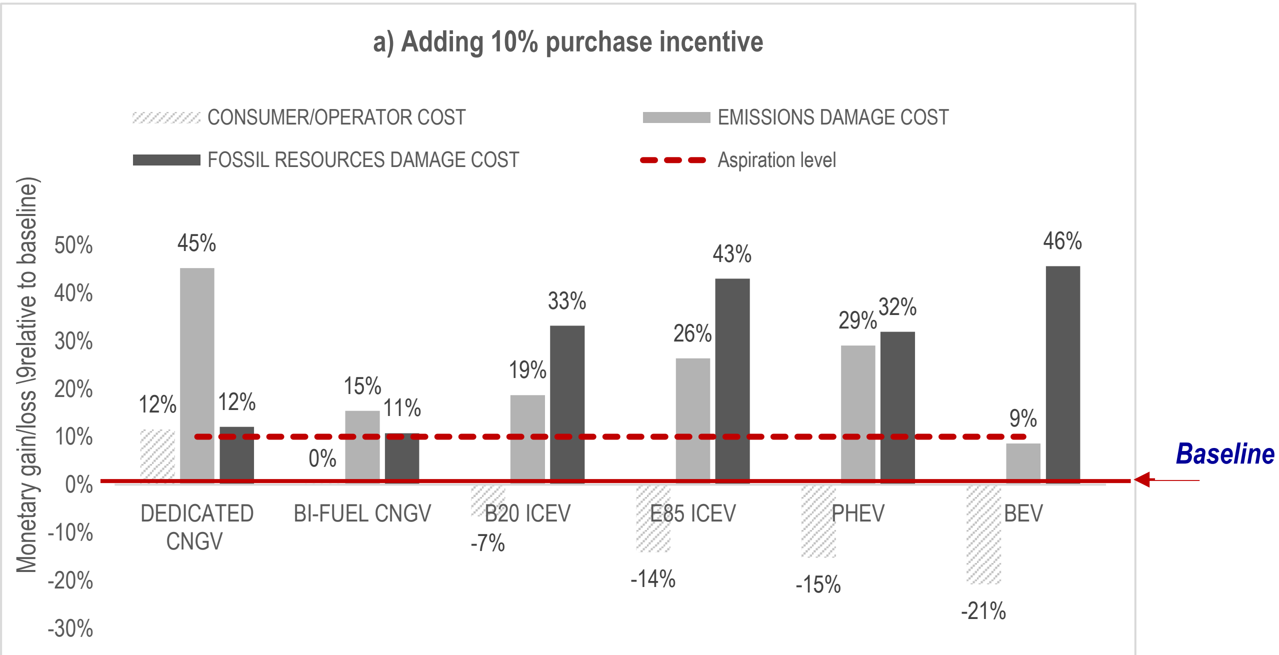


Fig. 52: Comparative results for trade-off in Step 3: adding incentive (source: author)

In another scenario, Fig. 53 illustrates the simulation results based on an increased subsidy for renewable energies (using mean values). It was observed that increasing the fuel subsidy to 25% (from the current rate of 15%) does not improve the NPVs, hence satisfactory trade-off is not achievable in this condition, given that the low-intensive operation means that the operational cost savings from lower fuel prices cannot compensate for the high initial cost for purchasing AFVs.

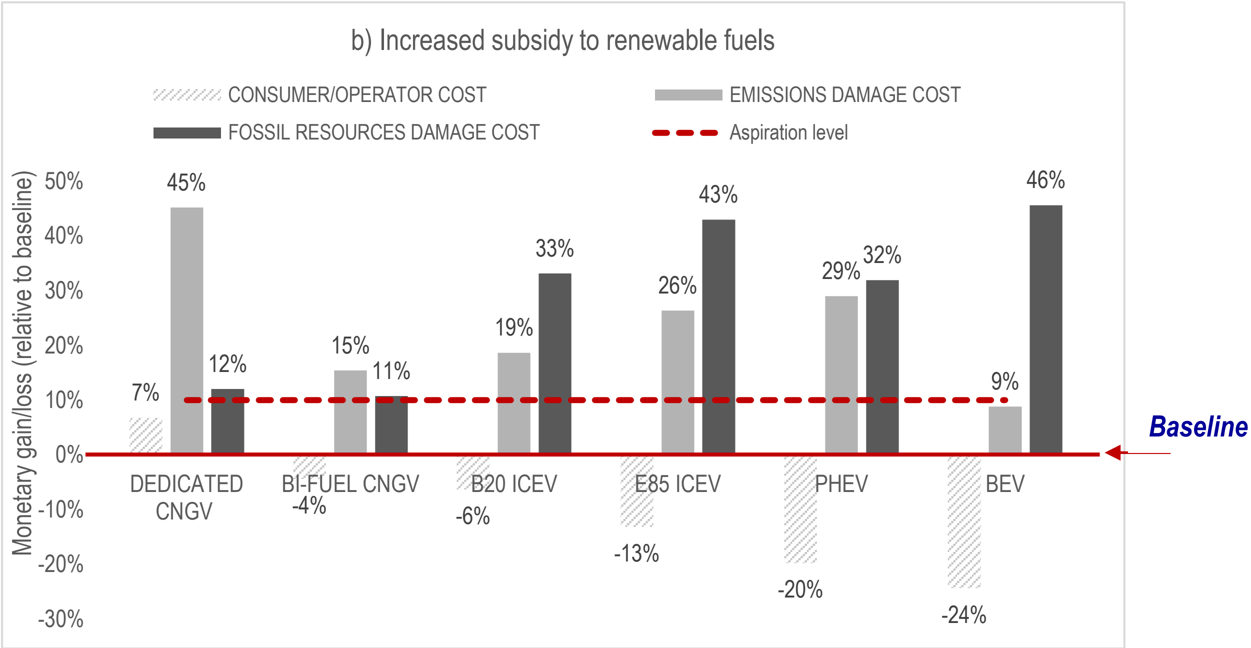


Fig. 53: Comparative results for trade-off in Step 3: increasing subsidy (source: author)

Following the results presented in Fig. 53, the search process continues, and more variables can be added in Step 3 to narrow the gap and improve the trade-off between the total costs borne by the operator and the externality damages to the society. The results from combining purchase incentive and fuel subsidy is shown in Fig. 54, where Dedicated CNGV remains the only option meeting the aspiration level. At this juncture, a decision can be made whether the search process can be stopped or continued. Assuming that all decision makers are satisficers, Dedicated CNGV is accepted and they stop the search process. In scenarios where no satisfactory solution is attainable, additional conditions can be added into the analysis (Step 3 is repeated), failing which the aspiration level can also be adjusted by lowering the threshold of acceptance limits.

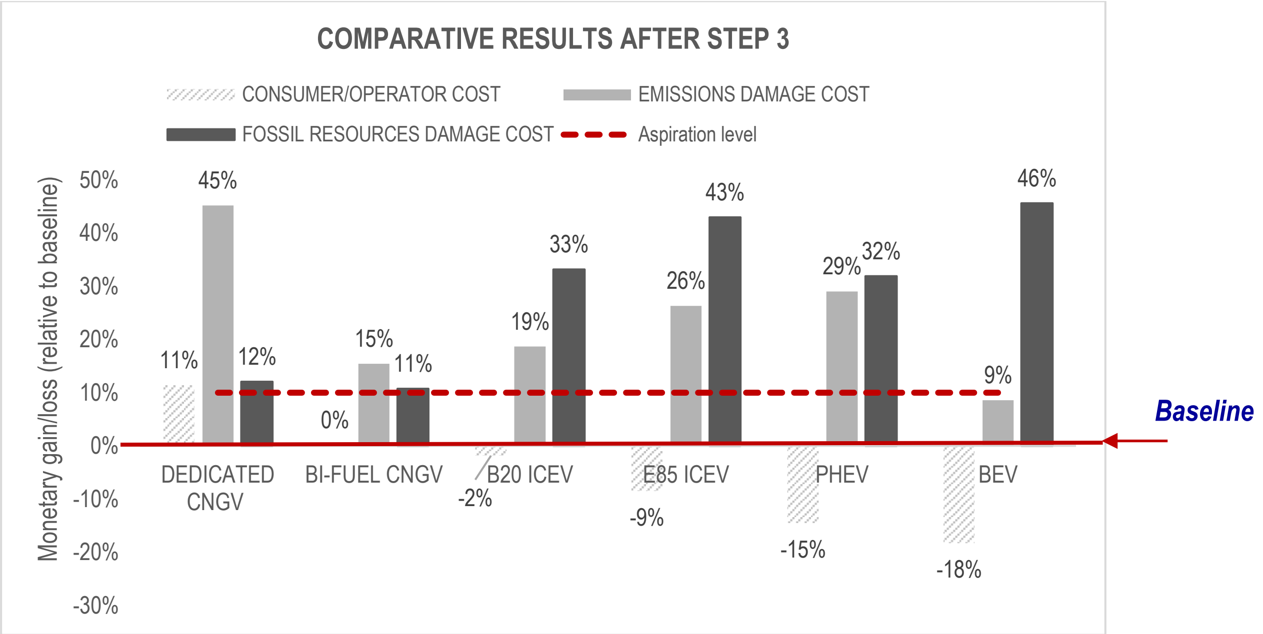


Fig. 54: Comparative results for satisfactory trade-off after Step 3 (source: author)

It has been discovered that despite all the varying factors, they do not change the conclusions that AFVs provide significant benefits in reducing emissions and fossil resource externalities, although most are not economically effective without any government support (incentives, tax exemptions, subsidies). The results presented in this section demonstrate the capability of the tool to evaluate various technologies and reveal the trade-off between conflicting performance criteria. The tool provides valuable insights to help stakeholders achieve satisfactory and consensus decision making for the selection of fuel technology for taxi fleets. Specifically, it can inform policy makers or regulators regarding the right incentives (and how much) that can be introduced to compensate the additional cost borne by fleet operators for switching to alternative-fuelled taxis, depending on the operating pattern. Examples of incentives that can be introduced include toll rebates, increased taxi fares or access to emission-free zones, which can potentially improve the trade-off decisions. Presenting the results in terms of the monetary gains per KM as tabulated in Table 20, a compensation of between 6-16 cents per KM is needed for these alternative fuelled-taxis to be considered as meeting the aspiration level of 10% savings to fleet operators (or RM0.06 per KM) over the service life.

Table 20: Relative monetary gain/loss per KM (source: author)

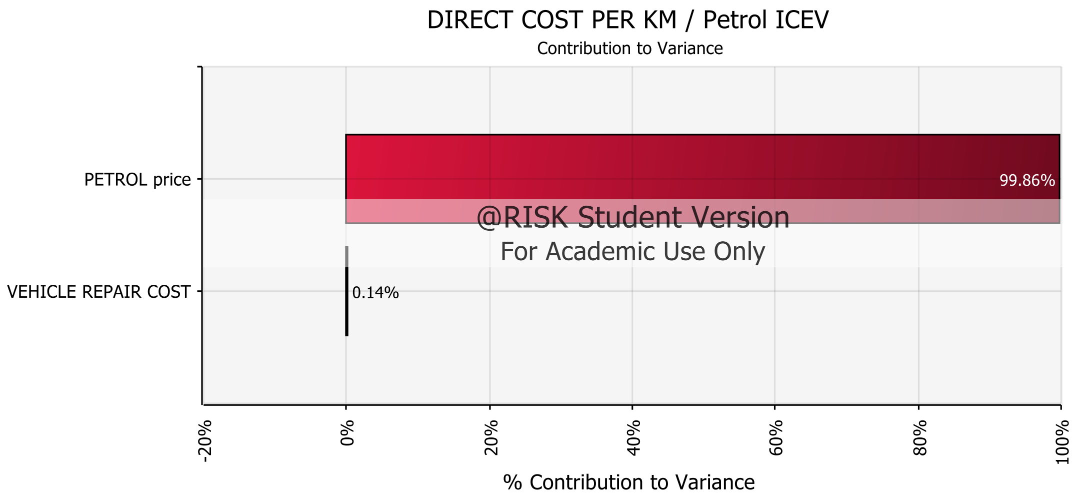
LCC Savings	CNGV	BI-FUEL CNGV	B20 ICEV	E85 ICEV	PHEV	BEV
Ownership & operating cost	RM0.06	RM0.00	RM-0.01	RM-0.05	RM-0.08	RM-0.10
Emissions damage	RM0.02	RM0.01	RM0.01	RM0.01	RM0.02	RM0.00
Fossil resources use	RM0.07	RM0.06	RM0.20	RM0.25	RM0.19	RM0.27

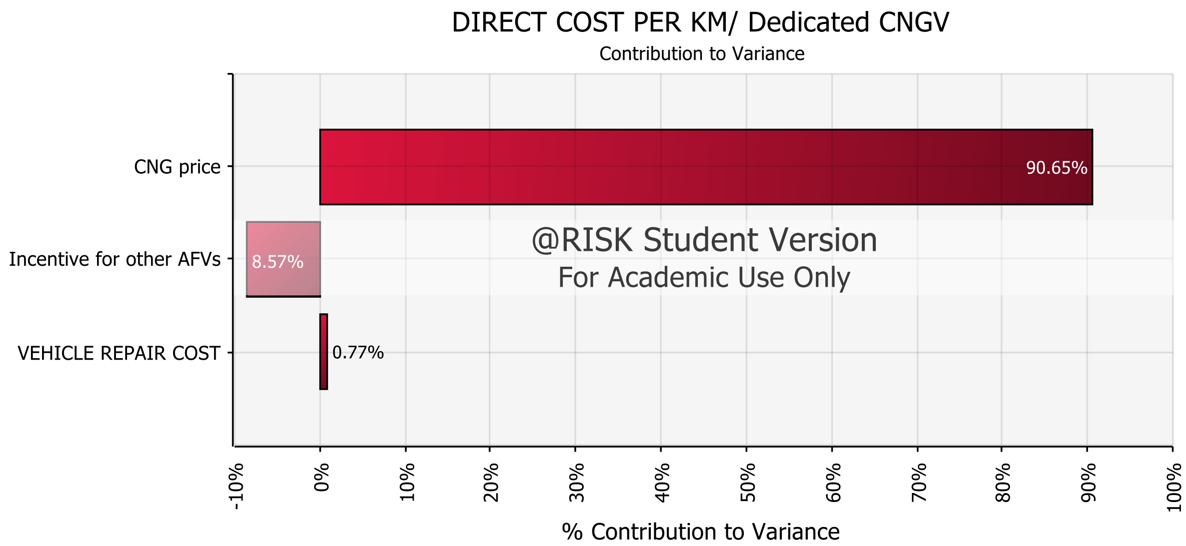
In the low-intensive operation (Scenario B), the objective is not to incur any financial, environmental or societal burdens from the switch to alternative-fuelled taxis. In this scenario, CNGV remains as the best-compromised option. The results also revealed that biofuel and electric-powered taxis can reduce emissions and fossil resources depletion quite significantly. However, they are not cost-effective in this scenario, thus they do not seem favourable to taxi operators who have to absorb increases of between 11% and 27% in operating cost. As shown in Figs. 52-54, the tax exemption, increased subsidy and incentives from the government has improved the cost-effectiveness of taxi operators.

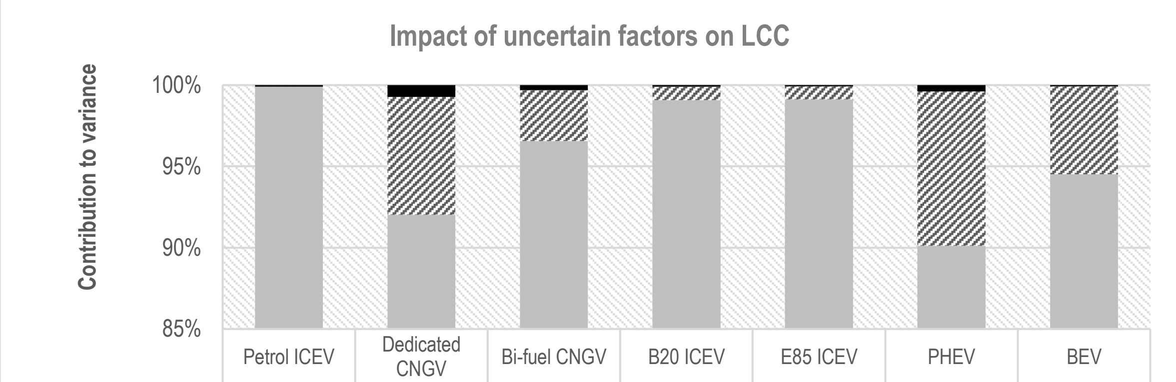
While the most recent and valid available data is being used to build the cost, energy use and emissions inventories for producing the results presented so far, it is important to acknowledge that there are large uncertainties, especially in external cost calculations, due to varied damage cost estimates in the literature. The uncertainties are examined in the next section, to identify the most influential factor and its effects on the output values. Further investigation needs to be carried out to reveal the most influential and sensitive factors that dominate the variability of outputs.

7.6 Findings & Discussion V: Uncertainty analysis

Results from the comparative analysis discussed above are further examined in uncertainty analysis, to identify the most influential factor of such variance in output values. Each simulation was run with 1000 iterations, then the most influential factor (amongst the uncertain parameters) that mostly contributes to the change in output was determined. In terms of life cycle ownership and operating cost, Fig. 55 discovered that the most influential factor across all technologies was observed for fuel/energy prices, followed by the incentive and cost of vehicle repair. The results have been tabulated by plotting the percentage contribution to the variance obtained from @Risk simulations (see example here for baseline petrol ICEV and CNGV).



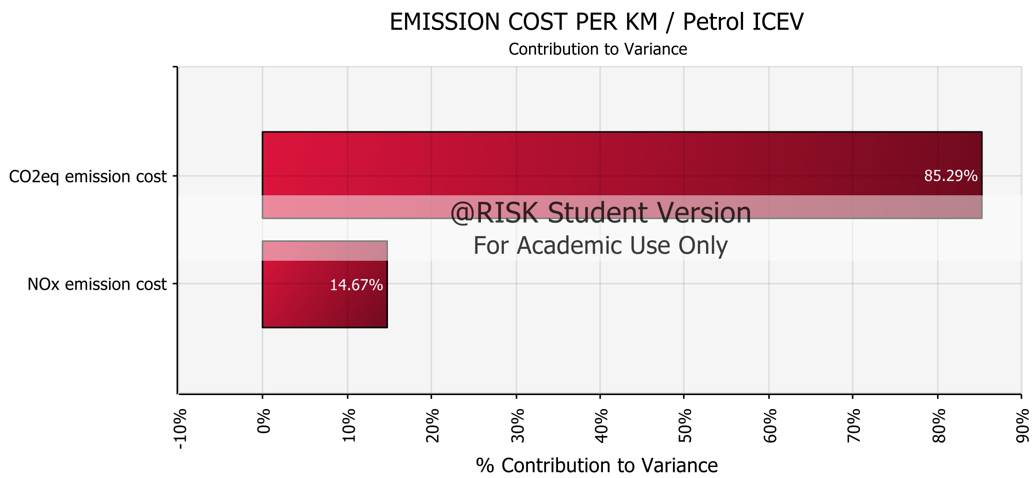


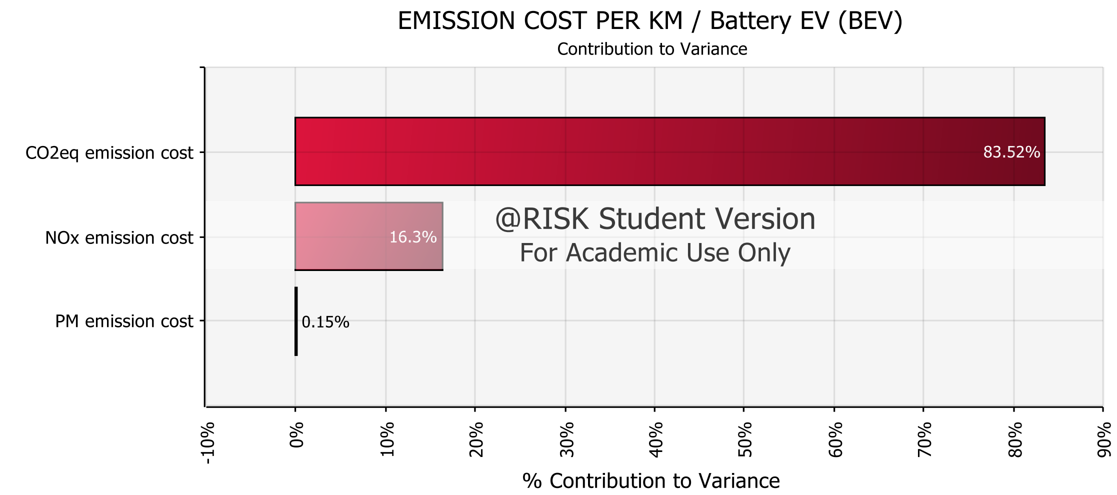


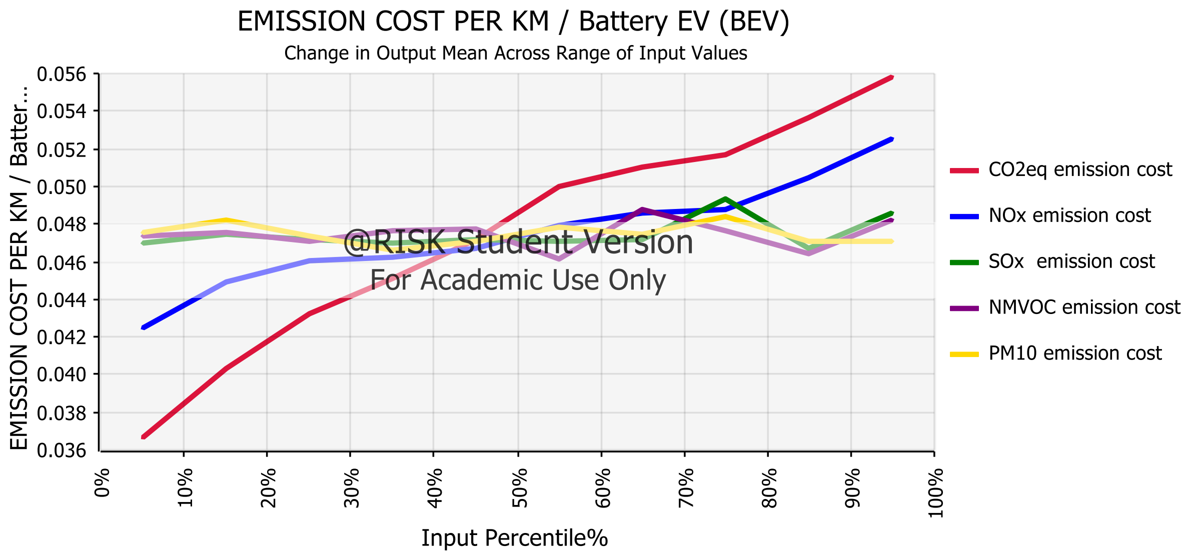
	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	B20 ICEV	E85 ICEV	PHEV	BEV
Vehicle repair cost	0.09%	0.73%	0.31%	0.09%	0.08%	0.39%	0.08%
Purchase incentive	0.00%	7.24%	3.12%	0.83%	0.81%	9.49%	5.41%
Fuel/energy price	99.91%	92.03%	96.57%	99.08%	99.10%	90.12%	94.51%

Fig. 55: Impact of uncertain factors on life cycle ownership & operating cost (source: author)

In terms of the uncertainties surrounding the emissions externalities, the LCC values are mostly influenced by the cost of carbon, followed by NOx (see Fig. 56). The compiled values are taken from @Risk simulation results, as shown in the example below for petrol and BEV. In the case of BEV, the steepest line in the spider plot represents the most influential and significant factors, which have an impact on the change of LCC. In relation to that, the most influential and significant factor is the cost of carbon, the second most influential factor is NOx damage cost, followed by SOx, VOC, and finally PM.




EMISSION COST PER KM / Battery EV (BEV)
Contribution to Variance
CO2eq emission cost
NOx emission cost
PM emission cost
83.52%
16.3%
0.15%
@RISK Student Version
For Academic Use Only
-10%
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
% Contribution to Variance


EMISSION COST PER KM / Battery EV (BEV)
Change in Output Mean Across Range of Input Values
EMISSION COST PER KM / Batter...
0.056
0.054
0.052
0.050
0.048
0.046
0.044
0.042
0.040
0.038
0.036
@RISK Student Version
For Academic Use Only
0%
10%
20%
30%
40%
50%
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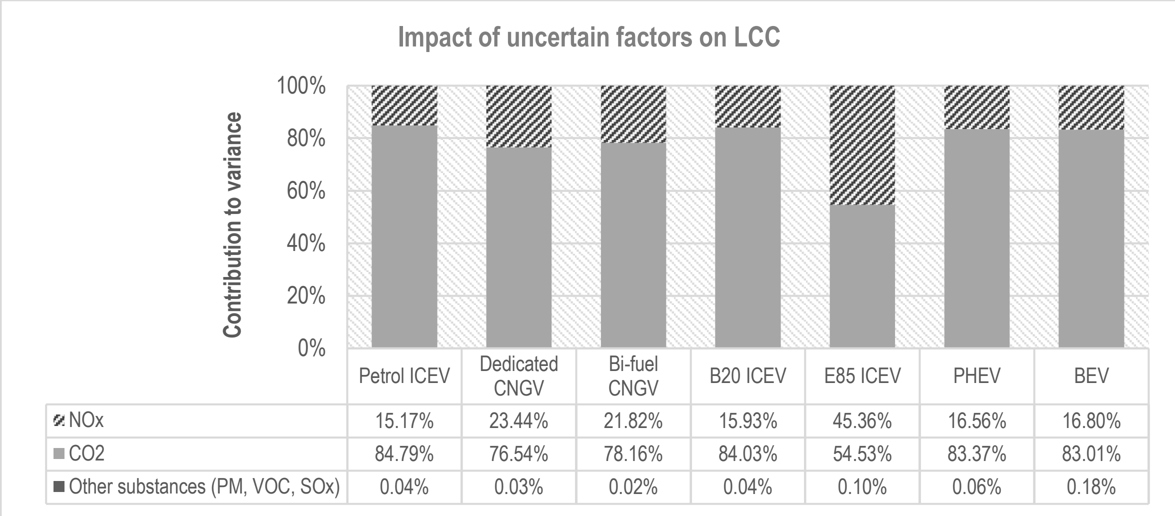
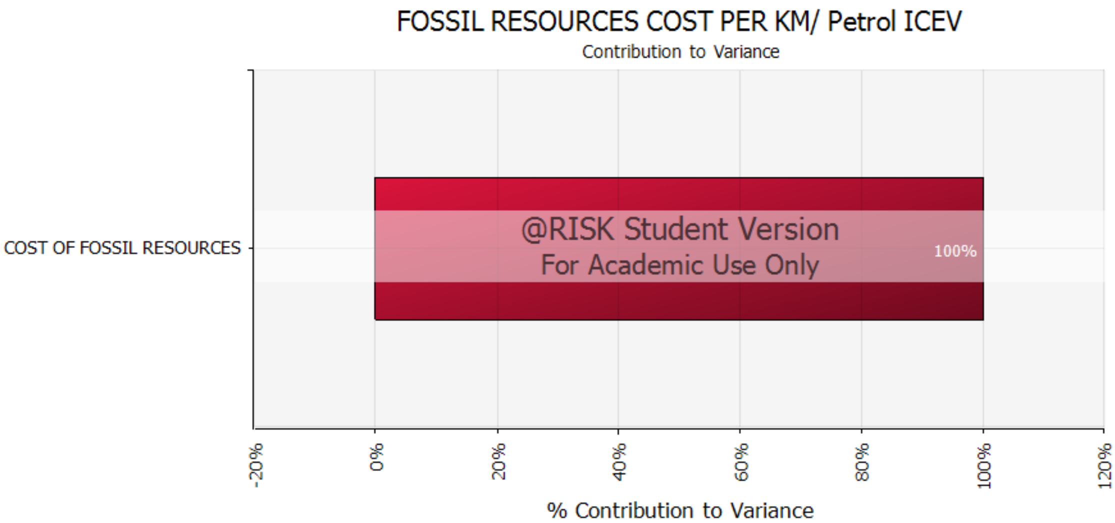
Input Percentile%
CO2eq emission cost
NOx emission cost
SOx emission cost
NMVOC emission cost
PM10 emission cost



	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	B20 ICEV	E85 ICEV	PHEV	BEV
NOx	15.17%	23.44%	21.82%	15.93%	45.36%	16.56%	16.80%
CO2	84.79%	76.54%	78.16%	84.03%	54.53%	83.37%	83.01%
Other substances (PM, VOC, SOx)	0.04%	0.03%	0.02%	0.04%	0.10%	0.06%	0.18%

Fig. 56: Impact of uncertain factors on life cycle emissions externalities (source: author)

As for the fossil resources externalities, the damage cost values fully contribute to the changes in output, since it is the only variable used for calculating the monetary cost/benefit. Fig. 57 shows the results summary, based on @Risk simulations such as the one obtained for the baseline option below.



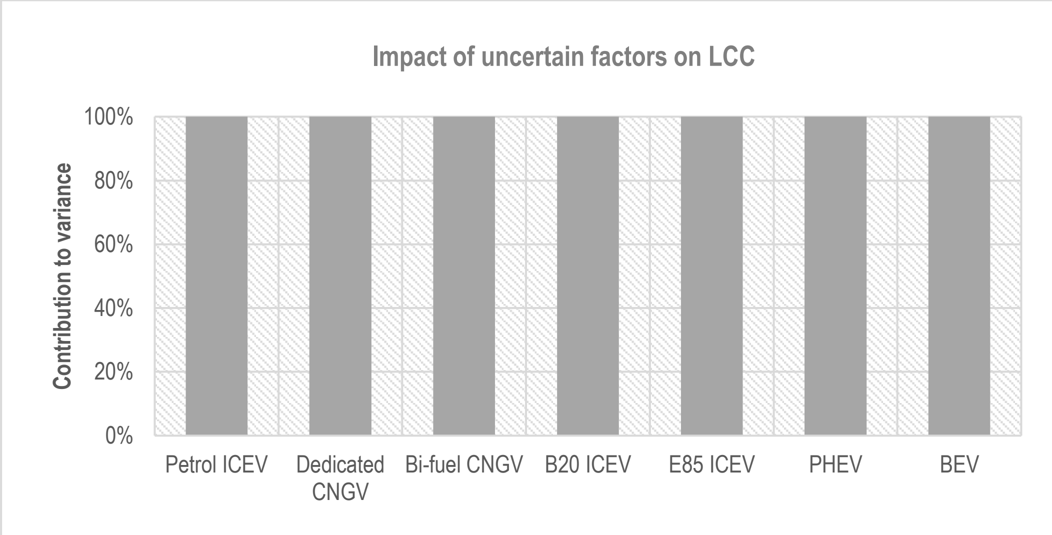


Fig. 57: Impact of uncertain factors on life cycle fossil resources externalities (source: author)

Notably, the results presented above show that only the following factors are found to heavily influence the outputs, hence the results could be significantly different when they are varied:

- Fuel/energy prices;
- Cost of carbon and marginal damage cost of NOx; and
- Fossil resources use.

Although most parameters (other than the above) have an insignificant effect on the outputs considered in this study, their effects should not be ignored when developing an analysis tool for decision-support. To ensure robustness of outputs, all uncertainties must be properly accounted for, to provide more knowledge that can help increase decision makers' confidence.

7.7 Discussion

Based on the findings from experimental analysis and case study modelling presented in this chapter, the model provides insights into the trade-off between the most cost-effective, least-fossil-resource-dependent and eco-friendly choice of alternative. The monetary gain/loss (relative to baseline) clarifies the life cycle sustainability cost/benefit of AFV technologies within the scope of this thesis. Therefore, the comparative tool can better depict if they can indeed perform better than baseline petrol ICEVs from a TBL perspective, in view of parameter uncertainties. By valuing the TBL impacts in a common metric, decision makers can weigh all the options with clearer insight and understanding, which would help in making knowledge-based trade-off decisions. Valuing the economic burden of emissions and fossil resources consumption monetarily can help tilt the balance of decisions, as it reveals the trade-off and consequences of selecting a technology with significant burdens to society (or choosing the most benign environmental technology that nevertheless causes fleet operators' financial loss), which otherwise would not be easily comprehended by non-expert users. The knowledge gained from the tool, such as that which is exemplified by the results presented in this chapter, can therefore inform stakeholders in the taxi sector and help them to make appropriate decisions that would benefit and satisfy all parties concerned.

The framework developed in this research has provided a systematic yet simplified process for decision makers to evaluate choices as the model can systematically weed out those that are unacceptable, to inform the ongoing debate over whether the benefits from reduced emissions and petroleum energy consumption can compensate for the higher LCCs of AFVs. The model is also capable of dealing with the uncertainty and varying parameters, as dynamism of the changing variables and the effects on output values are also reflected in this study. By presenting the distribution characteristics of outputs, the probabilistic approach added value to the model by providing statistical confidence in interpreting the results. This level of information is beneficial and provides decision makers with more insight and understanding of the overall variation in the comparative results, which would enhance their confidence.

Overall, the experimental LCCA shows that AFVs in general have potential benefits in two areas: reduced emissions and less reliance on fossil resources for vehicle fuel. To exemplify the usefulness of the model in providing valuable knowledge regarding the performance of

AFV technologies, and how to make trade-offs, some important findings are highlighted as follows:

(a) The best optimal choice according to individual criteria resulted in a different technology. In the base case Scenario A for instance, the best performing alternative with the lowest LCC to the owner/operator is Dedicated CNGV (MYR0.39/KM, with the mean value of 24% monetary gain). Meanwhile, the alternative with the biggest reduction in life cycle emissions and fossil resources use externalities is BEV (29% and 46% reduction respectively).

(b) Whilst Dedicated CNGV contributes fairly in reducing fossil resources use and/or emissions (12% and 22% respectively), BEV does not provide much economic advantage from the operator's point of view, with a small monetary gain of 4% (which can be vulnerable in scenarios where electrified technology is not given much financial advantage, such as tax exemptions, incentives etc.).

(c) Both options (CNGV and BEV) can potentially offer a satisfactory, middle-ground solution but the final trade-off decision and selection will be subject to a compromise between decision makers. It is assumed that the actual decisions are made by a decision maker, and the tool serves to help them in the search process, by providing knowledge and identifying the satisfactory trade-offs that would be acceptable to all decision makers.

(d) This is where the concept of satisficing can simplify the process - by ruling out alternatives that do not meet the minimum acceptance threshold. This step is made operational in the model by filtering choices (reject vs. accept). Less choices would then be considered, hence making the search process more efficient, reducing time, effort and resources for negotiating a compromised solution.

Overall, this study provides a structured process that would be useful and effective to identify a good satisficing choice through exploration of trade-offs under circumstances of risk and uncertainty. Although it does not eliminate uncertainty in its entirety, the tool is able to help estimate an almost-realistic output with its probability of occurrence, which would help in increasing decision makers' confidence. The model provides users with more knowledge through the exploration of different scenarios with varying parameters that would be beneficial in making either operational or strategic decisions. It is noteworthy to mention that the decision-making process could be made easier with models like the one developed in this study.

The applicability of the model has been tested in this research, using real data as much as possible. The model can be easily modified to meet the requirements and/or concerns related to each specific situation. While the most recent and valid available data are being used to build energy use and emissions inventories, it is important to acknowledge that this study does not aim to provide absolute values, nor to determine which technology option is the most desirable. The study is focused on the demonstration of a new framework, to provide example of how the process is carried out using the model. Ultimately, it reveals important knowledge regarding the trade-off consequences while seeking for the best-compromised, satisficing choice (that adequately meets all the aspiration levels) to inform decision makers and facilitate the selection process. The selection and decision-making process is not demonstrated in this study; however, it can be recommended for future work (as discussed in the final chapter).

7.8 Summary

This chapter presents the results and discusses findings from the survey and the experimental modelling of AFV technologies assessment in a case study context of taxi fleet in Kuala Lumpur. The results have shown that the framework (via the model) is able to provide insights and knowledge for making satisfactory trade-offs, to inform the search and decision-making process. Having tested the applicability of the decision-support model in an exemplary case study, with the findings presented in this chapter, the next chapter presents the conclusions and recommendations for future work.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

As stated in Chapter 1, this research aims to provide an integrated justification platform for evaluating AFV technology choices, that can be used to identify satisfactory trade-off solutions (considering their consequences) for supporting sustainable fleet implementation. This aim could only be achieved by implementing three main objectives, the accomplishments of which are discussed in this chapter. Then, the limitations of this present study are highlighted, followed by recommendations for future work. Finally, the concluding summary is presented.

8.2 Accomplishment of research objectives and main conclusions

As stated in Chapter 1, the aim of this research was to develop an integrated justification platform for evaluating AFV technology choices, that can be used to support collaborative decision making towards sustainable fleet implementation. This aim could only be achieved by implementing the following objectives:

Objective 1: Develop a theoretical understanding of the methodologies for evaluating AFV technologies from a TBL perspective, and a new framework suitable for integration into the life cycle model.

Conclusion: From the review of past life cycle studies, as presented in Chapter 2, it can be concluded that there is no “standard” for evaluating the TBL sustainability performance of a vehicle fleet that is applicable to all studies. The literature has shown that there is uncertainty surrounding the data and input parameters, which needs to be addressed in this framework. Furthermore, the existing studies vary in terms of scope and objectives, which reflected the different perspectives of stakeholders and decision makers. Accordingly, a new framework was developed by integrating the probabilistic life cycle sustainability cost/benefit analysis with Satisficing strategy, that can systematically simplify the evaluation process. The conceptual framework and its working procedures are presented in Chapter 3.

Objective 2: Implement the computer-aided framework using test simulation models.

Conclusion: Based on the conceptual framework, a probabilistic simulation model was implemented on a computer platform, using Microsoft® Excel with @Risk add-in. The spreadsheet-based model is simple to develop, and when tested by third parties (someone other than the researcher), the file can be shared and accessed easily by multiple users. The feedback from the initial third-party testing (as presented in Chapter 5) is representative, acknowledging the usability value of the tool.

Objective 3: Apply the model for evaluating currently available fuel/powertrain technologies in a taxi context, to support multi-stakeholder decision making.

Conclusion: When applied and tested in the illustrative case study, evidence from the results presented in Chapter 7 revealed that there is not always a clear choice of alternative that performs the best in all criteria considered, thus trade-off is imminent. Using the test model, trade-offs between multiple attributes are made transparent by revealing their monetary consequences. Accordingly, it can inform policy-makers and public transport authorities regarding the necessary incentives to help fleet operators absorb some of the additional expenses from the shift to AFVs.

8.3 Main contribution of the research

Overall, this thesis documents the process of how the tool can provide insights regarding the performance of currently available AFV technology choices and trade-off between multiple criteria, which is aimed as a shared justification platform to inform decision making in a multi-stakeholder context. Having designed and demonstrated the framework, it is important to highlight the usefulness of the framework. Firstly, this research contributes to the body of knowledge by developing a new framework that incorporates Satisficing strategy from the bounded rationality theory into the probabilistic simulation-based life cycle framework, which is made operational through an experimental model using real data collected from a representative case study. Secondly, the outcomes of this research are beneficial for practitioners by:

- Incorporating the concept of LCT in the evaluation of AFV technology choices, allowing the economic, environmental, and social impacts to be assessed holistically, using a common metric. This enables the tool to be used as a shared platform, either independently or in a joint process with multiple stakeholders.
- Providing a structured mechanism for evaluating alternatives under practical constraints of uncertainty (due to lack of data) in a stochastic or probabilistic manner, rather than by defining inputs as fixed deterministic values. Subsequently, the uncertain inputs are explicitly examined and quantified in the process;
- Providing a simplified comparative tool with potential commercial benefits for transport industry stakeholders, to support reliable and effective policy making, strategic management and operational decisions towards SD improvement strategies for urban transport fleets. The parties that can benefit from this include:
    - Fleet operators/drivers and fleet planners who would want to operate in a sustainable manner or to meet legislative requirements;
    - Policy makers and regulators who want to estimate compensation packages and/or incentives to fleet operators that are cost effective in fostering development of the alternative fuel taxi fleet, to mitigate climate change and air quality problems in cities;
    - Analysts and practitioners who seek to model technology evaluation under uncertain and varying factors, with a statistical probabilistic approach;
    - Other relevant stakeholders who seek a practical and effective mechanism to make trade-off decisions that fulfil the need and priorities of all stakeholders, to facilitate selection and decision making through a consensus process.

Ultimately, the proposed framework is set on driving sustainability through taxi fleet operations by making the performance and trade-off between multiple aspects more transparent. The information gained from the tool would enable regulators and public authorities to implement relevant policies and initiatives toward SD in transport, such as tax exemption, subsidies or purchase incentives for replacing older vehicles. The tool presented in this thesis can help decision makers find the middle ground and achieve the most compromised solution with satisfactory trade-offs, given that the best optimal solution is difficult to achieve in practice. It serves as an integrated platform that provides a mechanism to balance the need of multiple stakeholders towards reaching a common understanding. Having said that, it is intended to help create a win-win situation through sustainability-oriented decision making.

The methodology and theoretical parts of sustainability or TBL-oriented life cycle models are not novelties and have already been the theme of researches in various fields. Nevertheless, the probabilistic element developed and applied in this study has enabled a better understanding of the overall variation in input parameters and the main drivers of variation. Making the tool more robust and not static is an important step in the evaluation process, and this will support the decisions that need to be made, as decision makers can easily and quickly see the effects of changing one or multiple parameters on the results simultaneously.

The conceptual framework and its working procedures are also fundamentally different from other existing ones, due to the adaptation of satisficing strategy. It adds to the existing body of knowledge by including a process to identify the satisfactory trade-off solution. Instead of focusing on the efforts of finding the absolute best optimal option, the model seeks the best-compromised and satisficing choice – thus not the best considering all aspects, but good enough for satisfying different stakeholder interests. As a result, a satisfactory solution is more realistic and achievable for taxi fleet implementation of AFV technologies that are economically viable, environmentally friendly and socially responsible. Therefore, the subject of this study merits attention in its own right.

In summary, the original and main contribution of this research is threefold:

- This research contributes a new framework and exemplary model that can be used as a tool to inform decision making in a multi-stakeholder context, when evaluating AFV technologies.

- The proposed framework enhances the capabilities of already established life cycle methods and it can be used to guide the implementation of a simplified decision-support tool utilising monetary-based life cycle modelling, stochastic MCS and satisficing approach in an integrative way, providing a better understanding of their synergies, which may be useful for other researchers.

- This is the first time that such an integrated framework has been developed and tested for an application in the taxi sector, with a case study context of Kuala Lumpur, which is amongst the most rapidly growing urban areas in developing Asian countries. The tool is also evaluated by prospective users within the same case study population (taxi industry stakeholders), which provides useful insights for a further improvement of the framework. The tested framework is also flexible enough thus is expected to be relevant when applied in other region or cities.

8.4 Limitations

Although the integrated methodology in the proposed decision-support framework may provide additional insights that lead to a better understanding of the impacts of different technology choices and the trade-off between conflicting performance criteria, the tool is still limited in several ways. Firstly, its ability to model the overall impact of vehicle-fuel systems when evaluating the suitability of alternative fuels is not exhaustive, covering much wider sustainability aspects. As the first attempt to make the framework operational, this study deliberately focuses only on the quantitative criteria, thus is limited to the use of quantitative indicators. Nevertheless, the model can be extended to include other criteria and/or indicators, such as impacts on land use and water, congestion and noise pollution, socio-economic impacts related to income and employment generation, contribution to GDP and foreign trade. Other impact factors and quantitative indicators are recognised, and their exclusion does not indicate that they are viewed as irrelevant or unimportant; rather their non-inclusion is merely due to lack of available data. This extension can be recommended for future work.

It is important to highlight that the tool is not intended to quantify the absolute impacts of AFV technologies but rather to compare alternatives from the perspective of monetary savings of life cycle costs incurred by fleet operators (private businesses, hence the term private LCC) and the impacts on the external parties and society in general, which is valued monetarily (referred as external LCC in this thesis). It is acknowledged that there are already established tools developed for quantifying the life cycle impacts, at least 30 of them, according to the United States Environmental Protection Agency, as cited in Rose *et al.* (2013). The approach for quantification of impacts has some similarities with some of the existing tools such as AFLEET (Alternative Fuel Life Cycle Environmental and Economic Transportation), which is a tool developed by Argonne to examine the environmental and economic costs and benefits of AFV technologies, using a simple spreadsheet. In fact, the same database from GREET was used in this study, since inputs related to energy consumption and emission factors are not available locally (for the case study context of this thesis).

Secondly, despite the potential of LCSA for sustainability-oriented decision-support, the framework is not implemented through the integration between the three dimensions of life cycle methodologies (eLCA, LCC and s-LCA), as proposed in Kloepffer (2008). Given that the scope of this study is limited to quantitative analysis (using quantitative indicators), the simplified tool only takes the elements of LCSA to enable comparative assessment of alternative options based on monetary savings of life cycle private and external costs. The main goal and scope of evaluation as presented in the thesis is to compare alternatives and provide insights into the performance of technology choices, by aligning stakeholder interests to facilitate the selection of an acceptable and desirable option. Following the fundamental concept of LCC methodology, the model only captures the elements that vary, while the rest are excluded from the analysis. This would mean that only the difference between values in the comparison is presented and that the model does not yield an estimate of the total (actual) impacts. The analysis results can, at best, only be used as an indication, as the model is not intended to yield absolute values. Given that the proposed framework is focused on a satisficing instead of an optimisation approach, the results may not be optimal to a certain extent.

Despite the focus on developing an integrated justification platform for multiple users and stakeholders, their interaction or actual involvement in selecting criteria is not included in the scope of this study as the aspects covered in this thesis are for illustrative purposes only. Stakeholder attitudes and perceptions toward the criteria selected in this study are also not examined, hence the third major limitation of this thesis. In the context of this research, the aim of the study is to develop a framework and test simulation model for evaluating AFV technology choices and inform decision makers, rather than getting involved in the decision-making process itself. It is assumed that stakeholders and decision makers are left to make their own judgements and considerations on the identified satisficing choice, considering their priorities and interests. In other words, the tool is intended to provide information that can support multiple stakeholders in making decisions, not for making that decisions. The involvement of stakeholders in defining criteria in a real case study can however, be included in the scope of further research.

Having summarised the three major limitations of this research, it is worth to mention that the framework applicability and model testing presented in Chapters 5 and 7 respectively were only a beginning. Further improvement can be recommended for future work, as discussed next.

8.5 Recommendations for future work

Even though the model developed in this study offers a holistic view and comparability of AFV technologies for supporting multi-stakeholder decision making to a reasonable extent, there remains much work to be done in this area. There are many avenues for future research, including the following:

- Other relevant criteria/indicators that are pertinent for evaluating the sustainability performance of AFV technologies that are not included in this study can be added into the model. An appropriate adjustment may be necessary to deal with multiple metrics.
- The model needs further validation and verification processing for improving its usefulness, employing techniques such as multi-stage validation that entail three steps: model development; empirical testing for validating the model's assumptions; and comparing (testing) the input–output relationships of the model to the real system (Sargent, 2013).
- While validating the tool, it also creates an opportunity to include stakeholder participation and their preferences toward determining decision criteria and their weightings in the scope of the research. The model can be extended to build a systematic interaction between the analysts or modellers, and the users (decision makers). Future work can investigate this factor in a real-world case study so that their preferences regarding the various levels of any given evaluation criteria can be defined as a basis for evaluating options.
- The validated model can then be applied in multiple case studies, where the monetary savings over the vehicle-fuel life cycle can be estimated to determine the comparative performance of various technologies. This will provide more meaningful comparisons and further increase the robustness of the methodology and its applicability in real-world decision making in the transport sector.

- In line with the progress and future development of AFV technologies, more financial and regulatory related measures can be included in the analysis as part of the incentives to encourage the adoption of alternative-fuelled vehicles, e.g., rebates, reduced fees for licensing, parking, tolls, and access to emission-free zones.
- Finally, the scope of the tool can be expanded to make it functional for making decisions and selections based on valid preferences and objectives of decision makers in a real case study.

8.6 Summary

The accomplishment of primary aim and objectives of this research has been described. Accordingly, the conclusions have been presented. The main contributions of the research have been elaborated, the limitations have been highlighted, and subsequent improvements have been identified for future research.

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APPENDICES

Appendix 1 – An overview of model dashboard and main worksheets

a) Input table

A TBL-BASED SIMULATION MODEL FOR LIFE-CYCLE ANALYSIS

A tool to support multi-stakeholder decision-making towards sustainable practices in the taxi sector

Case Study Example: Evaluating Alternative Fuel Vehicle Technologies for Taxi Fleet in Kuala Lumpur, Malaysia

Known

INPUTS

General information

Vehicle operating age limit (years)		10
Vehicle lifespan (years)		12
Daily mileage driven (km)		100
Operating days per month		22
Operating condition (drive cycle)		Extra-urban
Average working hours per day		12
fuel use ratio (if bi-fuel or hybrid)	*Alt. fuel*	30%
	Petrol	70%

where

Reference vehicle (for illustrative purposes)	Proton Exora 1.6 AT
Vehicle fuel consumption (L/100KM)	7.2

Financial information

Appraisal period/time horizon (years)	15
Discount rate	1.5%
Inflation rate (CPI)	1.5%
Hire purchase loan?	Yes
Loan term (years)	5
Loan interest rate	4.3%
Downpayment (% of purchase cost)	20.0%
Vehicle base price	RM60,000

CRITERIA AND OBJECTIVE FUNCTION	Acceptance limits	Weight
Cost: Cost savings & business profitability	10%	100%
Emission: Climate & air quality improvement	10%	100%
Fossil energy: Natural resources preservation	10%	100%

Uncertain

OTHER ASSUMPTIONS

PARAMETERS	Value	Unit
FARE COLLECTED/REVENUE	RM180.00	per day
VEHICLE REPAIR COST	10%	of service cost per year

PARAMETERS	Value	Remarks
PURCHASING INCENTIVE (ONE-TIME)		
for EVs (BEV, PHEV)	10%	of purchase price
for other AFVs (CNGV,biofuels etc.)	10%	of purchase price

Uncertain

FUEL RETAIL PRICE	Tax rate	Govt. subsidy	Original sale price per unit	Tax exempt	Deduction	Net retail price* per unit
PETROL	24%	15%	3.80	100%	1.48	2.32
DIESEL	20%	15%	3.50	100%	1.23	2.28
CNG	20%	15%	1.00	100%	0.35	0.65
BIODIESEL B20	20%	15%	5.00	100%	1.75	3.25
BIOETHANOL E85	20%	15%	3.00	100%	1.05	1.95
ELECTRICITY	20%	15%	0.80	100%	0.28	0.52

*minus tax and subsidy

Known input			
ANALYSIS PERIOD:	15	YEARS	DISCOUNT RATE:
VEHICLE OPERATING AGE LIMIT (AS TAXI):	10	YEARS	INFLATION RATE:
VEHICLE LIFESPAN:	12	YEARS	LOAN INTEREST RATE:
ANNUAL DISTANCE (MILEAGE TRAVELLED):	26,400	KM	LOAN TERM :
WORKING HOURS	12	per day	

Uncertain input	Value	Unit	Distribution	Min	Most likely	Max
			Parameters of Distributions (to be specified)			
FUEL RETAIL PRICE						
PETROL	RM2.36	per litre	Pert	90%	RM2.32	120%
CNG	RM0.66	per m3	Pert	90%	RM0.65	120%
BIODIESEL B20	RM3.30	per litre	Pert	90%	RM3.25	120%
BIOETHANOL E85	RM1.98	per litre	Pert	90%	RM1.95	120%
ELECTRICITY	RM0.53	per kWh	Pert	90%	RM0.52	120%
PURCHASING INCENTIVE (ONE-TIME)						
for EVs (BEV, PHEV)	10%	per fleet	Normal	1%	10%	
for other AFVs (CNGV,biofuels etc.)	10%		Normal	1%	10%	
VEHICLE REPAIR COST	10%	of service cost per year	Normal	1%	10%	
DAMAGE COST OF FOSSIL RESOURCES	RM6.93	per kg oil eq *(to be reproduced)*	Uniform	RM4.32	RM9.54	
DAMAGE COST OF EMISSIONS						
CO2eq	RM181	per tonne	Triangular	RM92	RM205	RM246
NOx	RM96,317	per tonne	Triangular	RM38,527	RM96,317	RM154,108
PM (for PM2.5)	RM215,739	per tonne	Triangular	RM173,582	RM221,702	RM251,933
PM10	RM12,371	per tonne	Uniform	RM10,377	RM14,364	
NMVOC	RM1,780	per tonne	Uniform	RM1,281	RM2,278	

b) Calculator worksheet *(example: baseline petrol ICEV)*

OPTION		COST COMPONENT	0	1	2	3
Petrol ICEV		**CRITERIA 1: OWNERSHIP & OPERATING COSTS**				
Indicator 1		**VEHICLE TCO**				
	60,000	*Vehicle price after tax* (includes cost of loan)*	12,000	11,640	11,640	11,640
		Road tax cost	20	20	20	20
		Vehicle insurance	7,200	5,040	4,032	3,494
		One time financial incentive				
		Vehicle inspection cost				
	n+1	*Vehicle service & maintenance costs (basic/periodic)*		1,345	1,365	1,386
		Additional maintenance cost per year		200	206	216
	10%	*Vehicle repair cost*		134	137	139
		Resale value (revenue)-ve cost*		-	-	-
Indicator 2		**FUEL/ELECTRICITY COST**				
Petrol		*Fuel cost (after tax exempted & subsidy)*		4,328	4,328	4,328
		Secondary fuel cost (after tax exempted & subsidy)				
		ANNUAL COST (UNDISCOUNTED)	**19,220**	**22,707**	**21,728**	**21,222**
		CRITERIA 2: GHGs & CAPs EMISSIONS				
	1.0	**EXTERNAL COST OF GHGs/CLIMATE CHANGE**				
	273.40	*Annual emissions (tonne)*		7	7	7
	181	*CO2eq GHG-100*		1,326	1,346	1,367
	0.4	**EXTERNAL COST OF AIR POLLUTANTS DAMAGE**				
	NOx	*Annual emissions (tonne)*		0.005	0.002	0.001
	96,317	*External damage cost*		497	200	80
	PM10	*Annual emissions (tonne)*		0.001	0.000	0.000
	12,371	*External damage cost*		7	3	1
	PM2.5	*Annual emissions (tonne)*		0.0004	0.000	0.000
	215,739	*External damage cost*		78	31	13
	NMVOC	*Annual emissions (tonne)*		0.0090	0.004	0.001
	1,780	*External damage cost*		16	7	3
	SOx	*Annual emissions (tonne)*		0.0039	0.002	0.001
	1,467	*External damage cost*		6	2	1
		ANNUAL COST (UNDISCOUNTED)	-	**1,931**	**1,589**	**1,464**
		CRITERIA 3: FOSSIL ENERGY RESOURCES				
	cost per kg	**EXTERNAL COST OF FOSSIL FUELS DEPLETION**				
	0.08	*Annual fossil energy resources (in kg oil eq)*		2,239	2,239	2,239
	6.93	*External cost of fossil resources damage*		15,741	15,977	16,217
		ANNUAL COST (UNDISCOUNTED)	-	**15,741**	**15,977**	**16,217**

c) Results

INDICATORS/MEASURES	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	Biodiesel B20 ICEV	Bioethanol E85 ICEV	Plug-in Hybrid (PHEV
OWNERSHIP & OPERATING COSTS	149,312	132,191	148,989	159,359	170,360	173,473
EXTERNAL COST OF EMISSIONS	14,054	10,643	11,885	11,430	10,347	9,976
EXTERNAL COST OF FOSSIL FUEL DEPLETION	155,086	136,374	138,420	103,651	88,459	105,600
NPV	318,452	279,207	299,294	274,440	269,167	289,049

MONETARY GAIN/LOSS (PER KM)

FUEL-VEHICLE TYPE	CRITERIA TCO	 EMISSIONS	 FOSSIL RESOURCE USE
Dedicated CNGV	0.06	0.01	0.07
Bi-fuel CNGV	0.00	0.01	0.06
Biodiesel B20 ICEV	-0.04	0.01	0.19
Bioethanol E85 ICEV	-0.08	0.01	0.25
Plug-in Hybrid (PHEV)	-0.09	0.02	0.19
Battery EV (BEV)	-0.12	0.00	0.27
ASPIRATION LEVELS	**RM0.06**	**RM0.01**	**RM0.06**

Remarks: Indicate the alternatives that meet the satisficing threshold of acceptance

STATUS	TRADE-OFF VALUE	TCO	EMISSION	FOSSIL RESOURCE
ACCEPTED	RM0.00	-	-	-
REJECTED	RM0.06	RM0.06	-	-
REJECTED	RM0.09	RM0.09	-	-
REJECTED	RM0.14	RM0.14	-	-
REJECTED	RM0.15	RM0.15	-	-
REJECTED	RM0.18	RM0.18	RM0.00	-

**Remarks: The cost and trade-off values represent how much (in monetary value) the criteria has to be balanced out/alternative has to be compensated in order to meet the satisfactory level*

Appendix 2 – Participant information leaflet and Consent Form

PARTICIPANT INFORMATION LEAFLET & CONSENT FORM

You are being invited to take part in a research study. This is being carried out by me [redacted]), a Doctoral Student in Engineering Systems & Management from Aston University, United Kingdom. This doctoral program is currently funded by MARA (Majlis Amanah Rakyat – subsidiary of Malaysia Government). This study has been approved by Aston University School of Engineering and Applied Science Ethics Committee.

Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Please feel free to ask the researcher if there is anything that is not clear, or if you would like more information.

Title of the study

A Comparative Life Cycle Analysis of Alternative Fuel Vehicle Technologies for Taxis in Asian Cities: Modelling a Case Study of Greater Kuala Lumpur/Klang Valley.

Purpose of the study

This research aims to develop a comparative life cycle analysis framework, integrating the triple-bottom-line of sustainability to evaluate alternative fuel vehicle technologies for taxis in Asian cities. This study focuses on developing a monetary-based decision-support tool for taxi operators, to compare near-term alternative fuels/ vehicle technology choices such as biodiesel (from palm oil), natural gas vehicles (NGVs), electric vehicles (EVs) and hybrids, against conventional petrol and diesel vehicles. The decision-making is extended to consider not only the financial impact of the fuel/technology choices but also the environmental and social risks throughout the entire life cycle. The result of this study will also contribute in aiding policy makers and used as reference for researchers studying how to improve urban transport system to support sustainable development strategies.

Why have I been invited to participate?

You have been identified as someone who has a great deal to share about your experience as taxi operators and/or drivers in Kuala Lumpur/Klang Valley.

Do I have to take part?

Taking part in this survey is on VOLUNTARY basis. If you decide to participate then I will describe the study to you. You will be given this information sheet to keep and be asked to give your formal consent to participate in the survey. If you agree to take part and later change your mind, you are free to withdraw from the study at any time and without giving a reason. Your **PERSONAL DETAILS WILL NOT BE USED** in the study.

What is involved if I decide to participate?

If you decide to participate in this survey, questionnaires will be distributed to gather information on the operating profile and costs related to owning and operating the taxi in Kuala Lumpur/Klang Valley. The survey will last around 15-30 minutes.

Will what I say in this survey be kept confidential?

All the data will be fully anonymised and your personal and organisational details will be kept confidential at all times. No such details will be shared outside of the immediate research team (the researcher and academic supervisors)

For further information:

My supervisor will be glad to answer your questions about this study at any time. You may contact him at:-

[redacted]
Engineering Systems & Management
Engineering & Applied Science Aston University
Birmingham B4 7ET, UK
Email: b.j.price@aston.ac.uk

Thank you for your time!

Appendix 3 – Sample survey questionnaires for data collection

SURVEY TITLE: TAXI OPERATION & FLEET-RELATED COST PROFILE (FOR TAXIS IN GREATER KUALA LUMPUR/ LEMBAH KLANG)

NAME OF STUDENT/[redacted]

PURPOSE OF SURVEY: DATA COLLECTION FOR PhD RESEARCH PROJECT

SECTION 1: BACKGROUND OF SERVICE

1. What is the type of your taxi service? *Please tick (√) in one box only.*

☐ Budget ☐ TEKS1M ☐ Executive

☐ Others *(please specify)*: ____

2. What is the ownership type of your taxi license? *Please tick (√) in one box only.*

☐ Individual ☐ Company

SECTION 2: VEHICLE

3. What is the model of your taxi fleet? *Please tick (√) in one box only. If you own/operate more than one type, select the model with the largest quantity.*

☐ Proton Saga 1.3

☐ Proton Persona 1.6

☐ Proton Exora 1.6

☐ Toyota Innova 2.0

☐ Others *(please specify)*: ____

4. What is the transmission of your taxi fleet? *Please tick (√) in one box only.*

☐ Manual ☐ Automatic

5. What is the type of energy/fuel usage of the taxi fleet? *Please tick (√) in one box only.*

☐ Petrol ☐ Diesel/biodiesel ☐ Natural Gas (NGV)

☐ Electric ☐ Petrol and NGV ☐ Petrol and electric

6. What is the approved age limit for service of the taxi fleet? ________________ years.

SECTION 3: VEHICLE ACQUISITION

7. How do you acquire the taxi fleet? *Please tick (√) in one box only.*

☐ Outright purchase ☐ Hire purchase ☐ Rental/lease

For the following questions, please answer EITHER part A, B or C (one category only):

A. If you acquire through a **purchase *(without any loan);***

i. What is the total purchase price of the vehicle? RM ____________________________

Note: This cost includes mandatory taxi accessories and equipment, registration fees, applicable sale tax, GST etc. HOWEVER, excludes insurance and road tax. Also includes the price of engine/fuel system, if purchased separately.

OR;

B. If you acquire through **hire purchase *(with a loan);***

i. Initial payment for the vehicle, if any *(Optional)*: RM________________________

ii. Monthly payment: RM_____________________

iii. Loan repayment period: ________________ years

OR;

C. If you acquire through **rental/lease**;

i. Initial payment for the vehicle, if any *(Optional)*: RM______________________ (Refundable/Non-refundable)? *Please circle only one.*

ii. What is the frequency of rental/lease payment? *Please tick (√) in one box only.*

☐ Daily ☐ Monthly ☐ Others (please specify) ____________________________

iii. What is the amount of rental/lease payment: RM_________________________

iv. The rental/lease period:_______________years

SECTION 4: OPERATION AND VEHICLE MAINTENANCE

8. Taxi total distance **per day**?
_______________kilometre (KM)

9. Taxi driver average number of working days **per month**?
_____________ days

10. How many times **in a year** the vehicle is sent for general repair, service and maintenance work? *Please indicate the estimated number of occurrences per year for each category below.*

A. General repair: ___________________times a year

B. Service and maintenance *(minor)*:_____________times a year

C. Service and maintenance *(major)*:___________times a year

11. What is the estimated cost of each general repair, service and maintenance work? *Please indicate the estimated amount for each category below (example: RM150 per minor service).*

A. General repair: RM_____________________________

B. Service and maintenance *(minor):* RM________________

C. Service and maintenance *(major):* RM________________

SECTION 5: VEHICLE OWNERSHIP

12. Vehicle inspection

A. Initial cost: RM________________________

B. Recurring cost: RM____________________ per year

13. Road tax

A. Initial cost: RM________________________

B. Recurring cost: RM_____________________per year

14. Vehicle permit

A. Initial cost: RM________________________

B. Recurring cost: RM____________________ per year

15. Vehicle insurance

A. Initial cost: RM________________________

Remarks: Recurring insurance cost is excluded from the question as it follows the industry standard calculation.

16. Other vehicle related overhead, if any *(Optional)*:

____

A. Initial cost: RM________________________

B. Recurring cost: RM____________________per year

17. Subsidy or incentive received, if any (*Optional)*

A. Initial amount: RM_____________________

B. Recurring amount: RM_________________per year

SECTION 6: VEHICLE END-OF-LIFE

18. How do you @ will you do to dispose or write-off the vehicle at the end of its service/useful life? *(when it is declared as not fit to be used as taxi due to age or safety issues, etc.)*

☐ Trade ☐ Scrap ☐ Others (please specify)

____

A. The cost for the procedure, if any. *(Optional)*

RM__________________________

B. Estimated income or rebate received, if any. *(Optional)*

RM___________________________

SECTION 7: RESPONDENT DETAILS

This section does not need to be completed if Respondent wishes to keep his identity anonymous from the Researcher. In any case where details are provided, the identity of Respondent will remain confidential and will not be mentioned in any publication of this research.

Name of individual@company:
____

Telephone number @ email:
____

Thank you very much for your participation.

Appendix 4 – Model Testing and Evaluation Feedback Form

This brief questionnaire is intended to collect your feedback and opinion on the spreadsheet model (tool), which developed for evaluating alternative fuel-vehicle technology choices in an integrated TBL-based life cycle cost analysis (LCCA) framework.

Please help to complete this feedback form and return it to salehahb@aston.ac.uk at your convenience.

Name:
Organisation:
Division/Dept:
Role:

1. Please indicate how important are the functionalities below, and the level of usability (of the tool) using the scale below:

Scale of Importance: 5 – Extremely; 4 – Fairly; 3 – Somewhat; 2 – Not very; 1 – Not at all

Level of usability: 5 – Very high; 4 – High; 3 – Moderate; 2 – Low; 1 – Very low

Model characteristics and functionalities	Scale of Importance	Level of usability[6]
Q1: User -friendliness, simple and practical (ease of use) for comparing various alternatives		
Q2: Comprehensiveness of analysis *based on criteria and factors included		
Q3: Systematic and in-depth level of assessment		
Q4: Clarity of outputs with effective graphical displays for communicating results		
Q5: Holistic overview (covering multiple aspects or perspectives)		
Q6: The robustness of methodology		
Q7: Readiness for use and applicability in real process		
Q8: The relevance and usefulness to multiple user groups with different group functions		
Q9: Practicality and helpfulness to inform and aid decision-making		

[6] *Usability*: the tool provides the possibility to generate output data/deliver relevant functions with respect to the areas indicated in the question, in a user-friendly format.

2. Please indicate any part or information provided in the spreadsheet model that you find difficult to understand, possibly with comments.

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3. Please indicate what additional features or functions would you like to improve/integrate in the model.

____

4. By considering multiple aspects and priorities of other stakeholder groups, has the tool made you a) aware of the possible **trade-offs**, and b) provided you with **more insight** on how to make better decisions?

5. Please indicate what other factors you consider important in motivating you to apply tool (such as the one proposed) prior to making choices and decisions.

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6. Any other suggestions or comments.

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Thank you for your co-operation!

Appendix 5 – Results summary from @Risk simulations

a) Life cycle ownership and operating costs

Description	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	Biodiesel B20 ICEV	Bioethanol E85 ICEV	Plug-in Hybrid (PHEV)	Battery EV (BEV)
Minimum	203,154	157,619	187,250	228,955	248,215	206,237	199,477
Maximum	231,533	170,509	205,020	260,840	289,953	228,281	220,612
Mean	215,209	162,859	195,050	243,144	265,515	215,338	207,946
Std Deviation	5,769	2,424	3,135	6,732	7,889	3,519	3,822
Variance	33279790	5875150	9826131	45313200	62238230	12380400	14606330
Skewness	0.3104222	0.3537421	0.2376629	0.2277534	0.3259734	0.2661498	0.3625128
Kurtosis	2.500506	2.668649	2.738523	2.444444	2.57876	2.990139	2.731171
Errors	0	0	0	0	0	0	0
Mode	211,003	161,976	193,648	244,461	265,097	214,287	206,403
5% Perc	206,481	159,164	190,157	232,568	253,349	209,649	202,197
10% Perc	207,913	159,752	191,220	234,013	255,620	210,871	203,220
15% Perc	208,891	160,256	191,760	235,541	257,139	211,759	203,923
20% Perc	209,788	160,575	192,380	236,922	258,279	212,344	204,494
25% Perc	210,815	160,940	192,859	238,159	259,679	212,885	205,087
30% Perc	211,727	161,325	193,291	239,248	260,946	213,427	205,688
35% Perc	212,540	161,776	193,624	240,254	261,983	213,866	206,224
40% Perc	213,293	162,072	194,106	241,042	262,782	214,263	206,675
45% Perc	214,087	162,411	194,397	241,817	263,712	214,702	207,095
50% Perc	214,819	162,722	194,861	242,839	264,851	215,144	207,550
55% Perc	215,502	163,046	195,251	243,626	265,537	215,598	208,054
60% Perc	216,285	163,253	195,642	244,813	266,970	216,038	208,624
65% Perc	217,143	163,710	196,041	245,821	268,229	216,599	209,181
70% Perc	218,153	164,209	196,494	246,644	269,501	217,029	209,771
75% Perc	219,244	164,542	197,124	247,630	270,767	217,609	210,712
80% Perc	220,297	164,900	197,889	249,073	272,391	218,343	211,406
85% Perc	221,725	165,412	198,469	250,513	274,373	219,128	212,172
90% Perc	223,354	166,110	199,372	252,511	276,423	220,062	213,128
95% Perc	225,681	167,038	200,516	254,867	279,250	221,271	214,550

b) Life cycle emission damage costs

Description	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	Biodiesel B20 ICEV	Bioethanol E85 ICEV	Plug-in Hybrid (PHEV)	Battery EV (BEV)
Minimum	18,370	13,937	15,378	14,452	16,116	13,483	13,712
Maximum	41,724	32,956	36,345	33,510	38,141	30,206	29,374
Mean	31,174	24,247	26,775	24,916	27,792	22,598	22,212
Std Deviation	4,374	3,454	3,827	3,570	3,811	3,110	2,917
Variance	19129650	11928860	14649520	12747330	14522370	9669247	8508902
Skewness	-0.3354057	-0.2899553	-0.3003505	-0.3394653	-0.156984	-0.3251275	-0.3181734
Kurtosis	2.614561	2.661024	2.652476	2.612453	2.699014	2.622837	2.624657
Errors	0	0	0	0	0	0	0
Mode	34,260	24,968	28,561	23,905	24,249	21,503	20,517
5% Perc	23,347	18,131	19,997	18,551	21,300	17,097	17,026
10% Perc	24,963	19,448	21,398	19,845	22,919	18,219	18,142
15% Perc	26,259	20,444	22,526	20,924	23,807	19,066	18,942
20% Perc	27,486	21,364	23,687	21,879	24,388	19,967	19,782
25% Perc	28,419	21,969	24,259	22,613	25,100	20,630	20,332
30% Perc	28,951	22,477	24,828	23,099	25,753	21,046	20,777
35% Perc	29,605	22,969	25,357	23,632	26,274	21,482	21,145
40% Perc	30,294	23,488	25,921	24,198	26,870	21,961	21,583
45% Perc	30,956	23,991	26,538	24,740	27,421	22,428	22,044
50% Perc	31,470	24,435	27,002	25,130	27,905	22,784	22,395
55% Perc	32,096	24,954	27,562	25,662	28,452	23,255	22,827
60% Perc	32,722	25,398	28,048	26,192	28,972	23,663	23,184
65% Perc	33,355	25,853	28,588	26,711	29,411	24,130	23,624
70% Perc	33,983	26,301	29,076	27,225	29,953	24,550	24,046
75% Perc	34,546	26,873	29,742	27,687	30,457	24,965	24,411
80% Perc	35,084	27,350	30,194	28,106	31,135	25,379	24,804
85% Perc	35,730	27,903	30,818	28,660	31,928	25,849	25,259
90% Perc	36,511	28,493	31,483	29,280	32,786	26,409	25,777
95% Perc	37,689	29,450	32,577	30,272	33,739	27,221	26,547

c) Life cycle fossil energy resource damage costs

Description	Petrol ICEV	Dedicated CNGV	Bi-fuel CNGV	Biodiesel B20 ICEV	Bioethanol E85 ICEV	Plug-in Hybrid (PHEV)	Battery EV (BEV)
Minimum	166,602	146,501	150,896	111,348	95,028	113,442	90,599
Maximum	366,705	322,461	332,135	245,086	209,165	249,695	199,416
Mean	268,956	236,506	243,601	179,756	153,410	183,136	146,259
Std Deviation	58,366	51,324	52,863	39,008	33,291	39,742	31,739
Variance	3406546000	2634117000	2794535000	1521658000	1108306000	1579432000	1007391000
Skewness	-0.05364694	-0.05364694	-0.05364694	-0.05364694	-0.05364694	-0.05364694	-0.05364694
Kurtosis	1.804884	1.804884	1.804884	1.804884	1.804884	1.804884	1.804884
Errors	0	0	0	0	0	0	0
Mode	173,020	152,144	156,709	115,637	98,689	117,812	94,089
5% Perc	175,319	154,166	158,791	117,174	100,000	119,377	95,339
10% Perc	186,552	164,044	168,965	124,681	106,408	127,026	101,448
15% Perc	197,567	173,730	178,942	132,043	112,690	134,526	107,437
20% Perc	207,996	182,900	188,387	139,013	118,639	141,627	113,109
25% Perc	219,837	193,313	199,112	146,927	125,393	149,690	119,548
30% Perc	230,667	202,836	208,921	154,165	131,570	157,064	125,437
35% Perc	238,920	210,093	216,396	159,681	136,278	162,684	129,925
40% Perc	249,554	219,445	226,028	166,788	142,343	169,925	135,708
45% Perc	262,722	231,024	237,955	175,590	149,855	178,892	142,869
50% Perc	269,293	236,802	243,906	179,981	153,602	183,366	146,442
55% Perc	277,598	244,105	251,429	185,532	158,340	189,021	150,959
60% Perc	290,189	255,177	262,832	193,947	165,521	197,594	157,806
65% Perc	298,527	262,509	270,384	199,519	170,277	203,272	162,340
70% Perc	311,093	273,559	281,766	207,918	177,445	211,828	169,174
75% Perc	320,332	281,683	290,133	214,092	182,714	218,119	174,197
80% Perc	330,155	290,320	299,030	220,658	188,317	224,807	179,539
85% Perc	339,052	298,145	307,089	226,604	193,393	230,866	184,378
90% Perc	348,375	306,342	315,533	232,835	198,710	237,214	189,447
95% Perc	358,450	315,202	324,658	239,569	204,457	244,074	194,926