

INDUSTRY AND POLICY  
IMPLEMENTATION OF MATERIAL  
EFFICIENCY



Simone Cooper-Searle  
Clare College  
University of Cambridge

This dissertation is submitted for the degree of  
*Doctor of Philosophy*

February 2018

**Name:** Simone Cooper-Searle

**Thesis Title:** Industry and Policy Implementation of Material Efficiency

**Abstract:** The UK has committed to deep, long-term reductions in national greenhouse gas emissions as part of a global effort to address climate change. Material efficiency, reducing the material inputs per service output, has long been identified as a globally underexplored mitigation strategy. Previous studies show unrealised technical potential to improve the efficiency of steel use, a large contributor of industry emissions, in the UK. This thesis explores why these opportunities may be unrealised along the steel supply chain. Three topics are investigated. The first aims to understand better what guides the automotive industry's current approach to material use, including steel. Decisions and actions influencing material use are shown to be embedded in a broader vehicle design and manufacturing process, which is guided by six socio-technical factors. These factors were identified via semi-structured interviews and data analysis using coding and grounded theory development, substantiation and refinement. The factors are also used as a conceptual framework to explain why average vehicle material intensity and vehicle throughput are increasing in the UK and why opportunities for material efficiency improvements may be unrealised. The second topic investigates why, in spite of a number of potential macro-level benefits, material efficiency remains a small part of the UK policy agenda to reduce GhG emissions from cars. The Multiple Streams Framework is applied to structure a discussion. Data from semi-structured interviews with UK policy entrepreneurs were triangulated with other policy documents to develop, refine and substantiate the arguments presented. A number of features of the UK policy and political landscape are identified that disadvantage some material efficiency solutions. The final topic investigated in this thesis relates to the macroeconomic impacts of material efficiency improvements. Policymakers often use economic models to understand the likely scale and sectoral distribution of impacts from a policy intervention. However, there is little existing research on the macroeconomic impacts of improved material efficiency in the UK. A transparent multi-method approach is presented for modelling material efficiency case studies in Multi-Regional Input-Output models. Two case studies are explored, increased car club members in the UK and increased rates of steel reuse in construction. Both were shown to have a small positive immediate impact on UK employment. Building on the insights from these three topics, this thesis concludes by suggesting a number of activities for industry practitioners, policy entrepreneurs and academic researchers that could support further implementation of material efficiency innovations related to steel use in the UK.

*For Claudia*

# Acknowledgements

This work was funded by the UK Engineering and Physical Sciences Research Council PhD studentship number EP/L504920/1. I would like to thank my Supervisor Professor Julian M. Allwood for giving me the opportunity to carry out this PhD research and for his ongoing support throughout. Thanks also to my colleagues Dr Sandy Skelton, Dr. Brendan Doody and Dr. Finbarr Livesey and the wider Use Less Group for their advice and support. I would like to thank all the individuals from industry and the UK public sector who agreed to participate in interviews. Finally, I would like to thank Ian, my family and friends for always being a source of encouragement.

**Declaration:** This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. The dissertation does not exceed the word limit set by the Degree Committee.

# Publications list

## *Peer-reviewed journal articles*

- **Cooper, S.**, Skelton, A.C.H, Owen, A., Densley-Tingley, D., Allwood, J.M., 2016. A Multi-Method Approach for Analysing the Potential Employment Impacts of Material Efficiency. *Resources, Conservation and Recycling*, 109, 54-66. DOI:10.1016/j.resconrec.2015.11.014
- **Cooper, S.**, Doody, B.J., Allwood, J.M., 2017. Socio-technical Factors that Influence the Efficiency of Material Use in the UK Automotive Industry. *Journal of Cleaner Production*, 156, 817-827. DOI:10.1016/j.jclepro.2017.04.014
- **Cooper, S.**, Livesey, F, Allwood, J.M., (*in print*). Why are Material Efficiency Solutions a Limited Part of the Climate Policy Agenda? An Application of the Multiple Streams Framework to UK Policy on CO<sub>2</sub> Emissions from Cars. *Environmental Policy and Governance*.
- Rogers, J., Cooper, S.J.G., **Cooper, S.**, Densley-Tingley, D., Braithwaite, N., Moreno, M., Rodrigues, A. and Salvia, G., 2015. Product Longevity and Shared Ownership: Sustainable Routes to Satisfying the World's Growing Demand for Goods. *AIMS Energy*, 3(4), 547-561.
- Densley-Tingley, D., **Cooper, S.**, Cullen, J. 2017. Understanding and Overcoming Barriers to Structural Steel Reuse, a UK Perspective. *Journal of Cleaner Production*, 148, 642-652. DOI:10.1016/j.jclepro.2017.02.006

## *Conference papers*

- **Cooper, S.**, Allwood, J. M., Owen, A., Skelton, A.C.H. 2015 “*The Employment Consequences of Material Efficiency: An Analysis of Steel Reuse in the UK Construction Sector*”. Presentation to the 23rd International Input-Output Conference. Mexico City, Mexico. 22-26 June.
- Cooper, S.J.G., Owen, A., **Cooper, S.** and Cabrera Serrenho, A., 2015. “*Disaggregated Monetary Input-Output Tables as an Alternative to Physical Input-Output Tables*”. In: ISIE Conference 2015 - Taking Stock of Industrial Ecology, 7<sup>th</sup>-10<sup>th</sup> July. Leeds, UK.

# Contents

<b>1. INTRODUCTION .....</b>	<b>1</b>
1.1. IMPROVEMENTS IN MATERIAL EFFICIENCY TO REDUCE GREENHOUSE GAS EMISSIONS.....	1
1.2. STEEL'S CONTRIBUTION TO CLIMATE CHANGE.....	3
1.3. STRATEGIES TO IMPROVE MATERIAL EFFICIENCY IN THE UK STEEL ECONOMY.....	5
1.4. INDUSTRY IMPLEMENTATION OF MATERIAL EFFICIENCY IMPROVEMENTS.....	8
1.5. POLICY SUPPORT FOR MATERIAL EFFICIENCY.....	10
1.6. THESIS STRUCTURE.....	14
<b>2. LITERATURE REVIEW.....</b>	<b>15</b>
2.1. OPPORTUNITIES TO IMPROVE THE EFFICIENCY OF STEEL USE ...	15
2.1.1. Lightweight design.....	16
2.1.2. Reducing yield losses during manufacturing.....	19
2.1.3. Diverting manufacturing scrap.....	20
2.1.4. Extending product lifetimes.....	20
2.1.5. Using products more intensively.....	22
2.1.6. Re-using material without re-melting.....	25
2.1.7. Summary.....	26
2.2. EXPLAINING UNREALISED OPPORTUNITIES FOR MATERIAL EFFICIENCY IMPROVEMENTS IN INDUSTRY.....	28
2.2.1. Techno-economic studies on barriers to material efficiency.....	28
2.2.2. Sociotechnical studies on system stability.....	33
2.2.3. Research plan.....	37
2.3. IMPLICATIONS OF THE CLIMATE CHANGE POLICY AGENDA FOR MATERIAL EFFICIENCY.....	39
2.3.1. Models of the policymaking process.....	39
2.3.2. Application of the Multiple Streams Framework to the climate policy agenda.....	43
2.3.3. Research plan.....	45
2.4. MACROECONOMIC IMPACTS OF IMPROVED MATERIAL EFFICIENCY.....	46
2.4.1. Modelling the macroeconomic impacts of material efficiency	46

improvements.....	
2.4.2. Research plan.....	52
2.5. RESPONDING TO THE BROADER RESEARCH QUESTION	53
<b>3. INDUSTRY IMPLEMENTATION OF MATERIAL EFFICIENCY.....</b>	<b>54</b>
3.1. METHOD.....	55
3.2.1. Description of method.....	57
3.2.2. Research Limitations.....	61
3.2. FACTORS GUIDING THE VEHICLE DESIGN & MANUFACTURING PROCESS IN THE UK.....	62
3.2.1. Customer preferences.....	62
3.2.2. Market Positioning.....	63
3.2.3. Techno-economic feasibility.....	63
3.2.4. Supply chain feasibility.....	65
3.2.5. Regulation.....	66
3.2.6. Organisational attributes.....	66
3.2.7. Connections between factors.....	67
3.3. IMPLICATIONS FOR CURRENT LEVELS OF MATERIAL THROUGHPUT IN THE UK AUTOMOTIVE INDUSTRY.....	68
3.3.1. Vehicle material intensity.....	68
3.3.2. Vehicle throughput.....	72
3.4. DISCUSSION.....	73
<b>4. A MATERIAL EFFICIENCY POLICY AGENDA.....</b>	<b>76</b>
4.1. METHOD.....	77
4.1.1. Description of method.....	79
4.1.2. Study limitations.....	83
4.2. EXPLAINING WHY MATERIAL EFFICIENCY IS A LIMITED PART OF THE UK POLICY AGENDA TO REDUCE GREENHOUSE GAS EMISSIONS FROM CARS.....	84
4.2.1. Problem stream.....	85
4.2.2. Policy stream.....	88
4.2.3. Politics stream.....	91
4.2.4. Policy entrepreneurship and policy windows.....	92
4.3. DISCUSSION.....	95
<b>5. EMPLOYMENT IMPACTS OF MATERIAL EFFICIENCY.....</b>	<b>97</b>
5.1. METHOD.....	98



5.1.1. Model description and estimation of historical supply chain employment.....	100
5.1.2. Model preparation – product and sector disaggregation.....	103
5.1.3. Interviews and literature review.....	104
5.1.4. Modelling assumptions.....	111
5.2. EMPLOYMENT IMPACTS OF MATERIAL EFFICIENCY CASE STUDIES.....	116
5.2.1. Historical supply chain employment trends.....	116
5.2.2. IO modelling estimates of potential supply chain employment impacts.....	119
5.2.3. Limitations of the modelling results.....	122
5.3. DISCUSSION.....	123
<b>6. CONCLUSIONS.....</b>	<b>126</b>
6.1. CONTRIBUTION TO KNOWLEDGE.....	127
6.2. IMPLICATIONS FOR INDUSTRY PRACTITIONERS.....	132
6.3. IMPLICATIONS FOR POLICY ENTREPRENEURS.....	134
6.4. FUTURE RESEARCH AGENDA.....	139
REFERENCES.....	142
WEBSITES.....	153

# Figures

FIG. 1.1. UK STEEL FLOWS THAT WOULD BE IMPACTED BY THE IMPLEMENTATION OF MATERIAL EFFICIENCY STRATEGIES .....	7
FIG. 2.1. TARGETED STRATEGIES TO ADDRESS PRODUCT AND COMPONENT FAILURE.....	22
FIG. 2.2. A DYNAMIC MULTI-LEVEL PERSPECTIVE ON SOCIO-TECHNICAL TRANSITIONS.....	35
FIG. 2.3. SCHEMATIC OF THE MULTIPLE STREAMS FRAMEWORK AND SCENARIOS IN WHICH A POLICY AGENDA MAY OR MAY NOT BE FORMED .....	42
FIG. 3.1. OVERVIEW OF METHOD USED IN CHAPTER 3.....	56
FIG. 3.2. FROM OPEN CODING CATEGORIES TO SIX SOCIO-TECHNICAL FACTORS.....	60
FIG 3.3. INTERVIEW QUOTES ILLUSTRATING SOME CONNECTIONS BETWEEN FACTORS.....	68
FIG. 3.4. PERCENTAGE INCREASE IN AVERAGE EU VEHICLE DIMENSIONS BY SEGMENT BETWEEN THE YEARS 2001 AND 2014 .....	69
FIG. 4.1. OVERVIEW OF METHOD USED IN CHAPTER 4.....	78
FIG. 4.2. POLITICAL AND POLICY DEVELOPMENTS AND FOCUSING EVENTS THAT HAVE SHAPED THE RECENT UK POLICY MIX TO REDUCE GHG EMISSIONS FROM CARS.....	84
FIG. 4.3. DIAGRAM OF THE MULTIPLE STREAMS FRAMEWORK.....	85
FIG. 4.4. TECHNICAL OPTIONS FOR IMPLEMENTING MATERIAL EFFICIENCY IMPROVEMENTS THROUGHOUT A VEHICLE’S LIFE .....	88
FIG. 5.1. OVERVIEW OF METHODOLOGY USED IN CHAPTER 5.....	99
FIG. 5.2. STRUCTURE OF LEEDS UNIVERSITY MRIO MODEL FOR A SINGLE YEAR...	101
FIG. 5.3. SANKEY DIAGRAM CONVERTING MASS FLOWS OF STEEL PRODUCTS BOUGHT BY THE CONSTRUCTION SECTOR IN 2011 INTO EQUIVALENT MONETARY FLOWS.....	104
FIG. 5.4. ESTIMATED PRODUCT PRICES USED IN THE MRIO MODEL SHOWN AS A PERCENTAGE OF ACTUAL HISTORICAL PRODUCT PRICES & THE STANDARD ROOT...	115
FIG. 5.5. MRIO MODELLING RESULTS SHOWING HISTORICAL DOMESTIC AND INTERNATIONAL SUPPLY CHAIN EMPLOYMENT TO MEET UK DEMAND FOR CONSTRUCTION BETWEEN 1997 AND 2011. INCLUSION OF THE VALUE OF UK FINAL DEMAND OVER THE SAME PERIOD.....	117
FIG. 5.6. MRIO MODELLING RESULTS SHOWING HISTORICAL DOMESTIC AND	118

INTERNATIONAL SUPPLY CHAIN EMPLOYMENT TO MEET UK DEMAND FOR MOTOR VEHICLES BETWEEN 1997 AND 2011. INCLUSION OF THE VALUE OF UK FINAL DEMAND OVER THE SAME PERIOD.....	
FIG 5.7. MRIO MODELLING RESULTS SHOWING HISTORICAL DOMESTIC AND INTERNATIONAL UK MOTOR VEHICLE MANUFACTURING SUPPLY CHAIN EMPLOYMENT TO MEET UK AND ROW DEMAND BETWEEN 1997 AND 2011. INCLUSION OF THE VALUE OF UK AND ROW FINAL DEMAND OVER THE SAME PERIOD.....	118
FIG 5.8 (A) MRIO MODELLING RESULTS SHOWING THE NET CHANGE IN SUPPLY CHAIN LABOUR REQUIREMENTS FOR UK CONSTRUCTION DEMANDED IN THE UK AS A CONSEQUENCE OF INCREASING THE AMOUNT OF REUSED STEEL SECTIONS.....	119
FIG. 5.8 (B) MRIO MODELLING RESULTS SHOWING THE NET CHANGE IN SUPPLY CHAIN LABOUR REQUIREMENTS FOR ROW VEHICLE MANUFACTURING DEMANDED IN THE UK AS A CONSEQUENCE OF INCREASING THE NUMBER OF CAR CLUB MEMBERS.....	119
FIG. 5.8 (C) MRIO MODELLING RESULTS SHOWING THE NET CHANGE IN SUPPLY CHAIN LABOUR REQUIREMENTS FOR UK RENTAL AND LEASING DEMANDED IN THE UK AS A CONSEQUENCE OF INCREASING THE NUMBER OF CAR CLUB MEMBERS.....	119
FIG. 6.1. A SYSTEMS APPROACH FOR IDENTIFYING MATERIAL EFFICIENCY OPPORTUNITIES.....	121

# Tables

TABLE 2.1. CATEGORIES OF INNOVATION.....	16
TABLE 2.2. MATERIAL USE BY THE GLOBAL AUTOMOTIVE AND GREENHOUSE EMISSIONS INTENSITY OF MATERIAL PRODUCTION .....	18
TABLE 2.3. MATERIAL EFFICIENCY STRATEGIES, POSSIBLE MODES OF IMPLEMENTATION AND INNOVATION TYPE.....	26
TABLE 2.4. A TAXONOMY OF BARRIERS TO ENERGY AND MATERIAL EFFICIENCY..	32
TABLE 2.5. SUMMARY OF STUDIES ESTIMATING THE NET % CHANGE IN PROJECT COST OF DECONSTRUCTION RELATIVE TO DEMOLITION.....	50
TABLE 3.1. CHAPTER 3 - INTERVIEWEE EXPERTISE AND EXPERIENCE.....	57
TABLE 3.2. CHAPTER 3 - LIST OF QUESTIONS USED DURING THE QUALITATIVE INTERVIEWS.....	58
TABLE 4.1. CHAPTER 4 - INTERVIEWEES' PLACE OF WORK.....	79
TABLE 4.2. CHAPTER 4 - PRE-PREPARED INTERVIEW QUESTIONS.....	81
TABLE 4.3. QUESTIONS TO GUIDE THEME DEVELOPMENT	82
TABLE 5.1. CHAPTER 5 - INTERVIEWEE OCCUPATIONS AND EXPERIENCE WITH CAR SHARING OR STEEL REUSE.....	105
TABLE 5.2. CHAPTER 5- LIST OF PRE-PREPARED INTERVIEW QUESTIONS.....	106
TABLE 5.3. SUMMARY OF INTERVIEW RESPONSES THAT SHOW WHICH INTER- SECTOR AND INTER-STAKEHOLDER MONETARY FLOWS ARE ANTICIPATED TO CHANGE WITH THE INTRODUCTION OF EACH MATERIAL EFFICIENCY STRATEGY AND WHAT THE MAXIMUM SCALE OF CHANGE WOULD BE FOR THE YEAR 2011 .....	108
TABLE 5.4. LIST OF CHANGES MADE TO THE INPUT-OUTPUT TABLE IN THE STEEL REUSE CASE STUDY.....	112
TABLE 5.5. LIST OF CHANGES MADE TO THE INPUT-OUTPUT TABLE IN THE CAR SHARING CASE STUDY.....	113

# Glossary

<b>Term</b>	<b>Definition</b>
ACF	Advocacy Coalition Framework
B	Billion
BEIS	Department of Business, Energy & Industrial Strategy
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CC	Continuous casting
CCA	The Climate Change Act
CCC	The Committee on Climate Change
CO <sub>2</sub>	Carbon Dioxide
CO <sub>2</sub> e	Carbon Dioxide equivalent
DECC	Department of Energy and Climate Change
DEFRA	Department of Environment, Food & Rural Affairs
DfT	Department for Transport
DR	Direct Reduction
EAF	Electric Arc Furnace
EC	European Commission
EU	European Union
FIC	Foundry Iron Casting
GDP	Gross Domestic Product
GhG	Greenhouse Gas
HMT	Her Majesty's Treasury
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IG	Ingot Casting
IPCC	Intergovernmental Panel on Climate Change
ISSB	International Steel Statistics Bureau
kg	Kilogram
kt	Kilotonnes
LCA	Lifecycle Assessment
MFA	Material Flow Analysis
MRIO	Multi-Region Input Output

MSF	Multiple Streams Framework
M	Million
Mt	Megatonnes
NGO	Non-Governmental Organisation
NOx	Nitrous Oxide
OEM	Original Equipment Manufacturer
OHF	Open Hearth-Furnace
OICA	Organisation Internationale des Constructeurs d'Automobil
OLEV	Office for Low Emissions Vehicles
ONS	Office for National Statistics
PET	Punctuated Equilibrium Theory
R/F	Rolling/Forming
RoW	Rest of World
SIC	Standard Industrial Classification
SMMT	Society of Motor Manufacturers and Traders
SPC	Steel Product Casting
t	Tonne
UK	United Kingdom
ULEV	Ultra-Low Emission Vehicles
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

# 1. Introduction

Anthropogenic activity since the industrial revolution has increased the global atmospheric concentration of greenhouse gas (GhG) emissions. Rockstrom et al. (2009) examine the historical influence of human civilisation on earth-systems and conclude that in the case of climate regulation, levels of GhG emissions are already beyond a safe threshold for humanity. The Intergovernmental Panel on Climate Change (IPCC) is a Nobel-prize winning international body responsible for assessing the latest evidence of climate change. Its most recent report concluded that further increases in the concentration of GhGs would increase the likelihood of severe, pervasive and irreversible impacts to natural and human systems (IPCC, 2014). Under the UN Framework Convention on Climate Change (UNFCCC, 2009) countries have committed to reducing global GhG emissions and limiting temperature increases to less than 2 degrees centigrade above pre-industrial levels. As part of the 2015 Paris Agreement, Parties to the Convention have communicated their intention to achieve national GhG emissions reduction targets between 2021-2030 (UNFCCC, 2015). Some countries, independently of the UN process, have made longer-term emissions reduction commitments. The UK has legally committed to reducing domestic emissions by at least 80% below 1990 levels by 2050 in the Climate Change Act (CCA, 2008). Achieving this target requires changes to business-as-usual practices for many individuals and firms in the economy. New low carbon technologies, processes, business models and approaches to consumption are needed. Given the severity and urgency of the climate change challenge, and the scale of GhG emissions reduction required, no potential mitigation option should be overlooked.

## 1.1. Improvements in material efficiency to reduce greenhouse gas emissions

In a Sankey diagram of global annual carbon flows, Bajzelj et al. (2013) show that approximately a quarter of global GHG emissions are released during the transformation of ores into materials, and materials into products that deliver services. If materials were used more efficiently, less would be needed and there could be a reduction in industrial GhG emissions and energy use. Allwood et al. (2011) define material efficiency as “*providing material services with less material production and*

*processing*". In a book summarising five years of engineering research, Allwood et al. (2012) outline six strategies for improving the efficiency of material use throughout a product's lifespan which, in the absence of any rebound effect, will lead to a reduction in material demand. These are: (1) lightweight design; (2) reducing yield losses during product manufacturing; (3) diverting manufacturing scrap; (4) extending product lifetimes; (5) using products more intensively and (6) reusing material without re-melting. For over 20 years, however, improvements in material efficiency via these strategies, has remained a potentially significant yet under-explored approach to reducing GhG emissions. In 1996, a report from the Secretary General of the United Nations Economics and Social Council (ECOSOC, 1996) identified large unrealised opportunities for material efficiency improvements. A similar conclusion was reached in 2014 by Working Group III of the IPCC's Fifth Assessment report on approaches for mitigating climate change (IPCC, 2014). Emerging modelling evidence also shows that material efficiency may be critical for meeting sectoral contributions to GhG emissions reduction targets (Milford et al., 2013) and is complementary to supply-side GhG emissions reduction and energy efficiency initiatives (IEA, 2015). Many of these six strategies have also been advocated to deliver dematerialisation, resource efficiency and the circular economy.

Material efficiency is somewhat distinguishable from these concepts. Cleveland and Ruth (1998) clarify that dematerialisation refers to a reduction of in the absolute mass of material throughput in human societies. This aggregated, macro-level indicator does not explicitly consider the material mix or the variability in GhG emissions associated with extracting, producing, forming, using and disposing of different material. As a consequence, Barrett & Scott (2012) argue that limiting the focus of dematerialisation to a reduction in the absolute mass of materials would fail to address environmental and ecosystem impacts of material use. Material efficiency could therefore be viewed as one approach to dematerialisation that prioritises GhG emissions reductions over other environmental goals.

Resource efficiency also emphasises a reduction in the absolute mass of materials used but it is broader in scope than dematerialisation as it refers to all natural resources that are inputs into an economy. The European Commission (2011) Resource Efficiency Roadmap includes all metals, minerals, fuels, fish, timber, water, soil, clean air, biomass, biodiversity, land and sea in their definition of resources. This broader



characterisation reflects the fact that natural resources are interlinked and interdependent and sustainable resource management across all resource categories would require an integrated or ‘nexus’ approach that reflects these linkages. The circular economy can be understood as one approach to achieving improvements in resource efficiency. As a result, Winning et al. (2017) explain that the two concepts often go hand-in-hand.

A circular economy aims to keep biological and technical resources, including materials, in use for as long as possible to minimise waste and the need for extraction from primary sources. It challenges the current conventional ‘linear’ approach to resource use that broadly means resources are extracted, used and disposed of as waste. The engineering strategies for technical materials in a circular economy include maintenance, reuse, refurbishment and remanufacturing (Ellen MacArthur Foundation, 2013) have many parallels with material efficiency. However, in spite of these similarities, a circular economy is broader in scope than material efficiency because of the inclusion of biological resources and support for some recycling. Because of this broader scope, in the European Commission (2015) Circular Economy Action Plan, lower GhG emissions are listed as a potential outcome of the circular economy but, unlike material efficiency, are not the primary motivator.

Recognising the linkages between material efficiency, dematerialisation, resource efficiency and the circular economy, the focus of this thesis is limited to the former due to its explicit focus on GhG emissions and its origins in the discipline of engineering. However, the other concepts are useful as a comparator throughout the analysis.

## 1.2. Steel’s contribution to climate change

The six material efficiency strategies detailed in Allwood et al. (2012) can be applied to almost any material mix. Their potential mitigation impact is largest when they are applied to materials produced via GhG emissions-intensive processes. Steel is one such material. Allwood et al. (2010) use IEA data to show that steel production makes the largest contribution to global industrial CO<sub>2</sub> emissions, accounting for approximately 25% of the total. The UK government (DECC, 2015) reported that in 2014 steel production accounted for approximately 3% of total domestic anthropogenic GHG emissions and 21% of business sector emissions (measured in CO<sub>2</sub>e). Milford et al.

(2013) collate data from fifteen sources to develop global average estimates on the GhG emissions intensity of different technologies and processes involved in making crude steel. Crude steel is the name given to liquid steel that has solidified after production in a furnace. The authors show that CO<sub>2</sub> emissions are released during: sintering, coking, iron-making, steel making and casting. Further CO<sub>2</sub> emissions will be released during fabrication and casting.

There are two principle routes for steel making. Primary production involves the transformation of iron ore into pig iron in a blast furnace (BF). Pig iron is then melted, often with steel scrap, in a basic oxygen furnace (BOF) to form liquid steel. CO<sub>2</sub> emissions are generated as carbon in the pig iron combines with oxygen in the furnace. Drawing on data from their member companies and associations, World Steel (2014) estimates that the current global average emissions intensity of crude steel production via the BF/BOF route is approximately 1.8TCO<sub>2</sub>/T crude steel. In 2015, the BF/BOF route delivered 75% of global steel output by mass (World Steel, 2016). Secondary production of liquid steel from scrap occurs in an electric arc furnace (EAF). Electrical energy is used to melt steel scrap and this tends to be less emissions-intensive than the BF/BOF route. Using IEA data Carpenter (2012) estimates a global average of 0.4TCO<sub>2</sub>/T crude steel in an EAF. Emissions intensity metrics presented in Serrenho et al. (2016) model CO<sub>2</sub> emissions reductions scenarios in the UK steel sector. The authors show that the emissions intensity of secondary steel production is lower if more scrap is used and if electricity is generated from low carbon fuels.

Most CO<sub>2</sub> emissions from steel production can be attributed to the energy used. Yellishetty et al. (2010) draw on multiple sources of mining, production; energy and emissions data to show that the global average energy intensity of steel production via both primary and secondary routes has been steadily falling since the 1960s. The authors attribute this reduction to improvements in energy efficiency, substitution away from more energy intensive technologies, improved furnace efficiencies and better collection and sorting of steel scrap. In spite of these improvements, the absolute amount of CO<sub>2</sub> emissions from steel production tripled during the period of study because of increased production output. The IEA (2008) anticipates that global steel demand will double again by 2050. It is therefore critical that further emissions reduction strategies are employed in the sector. Milford et al. (2013) evaluate the emissions reduction potential from further improvements in energy efficiency. They

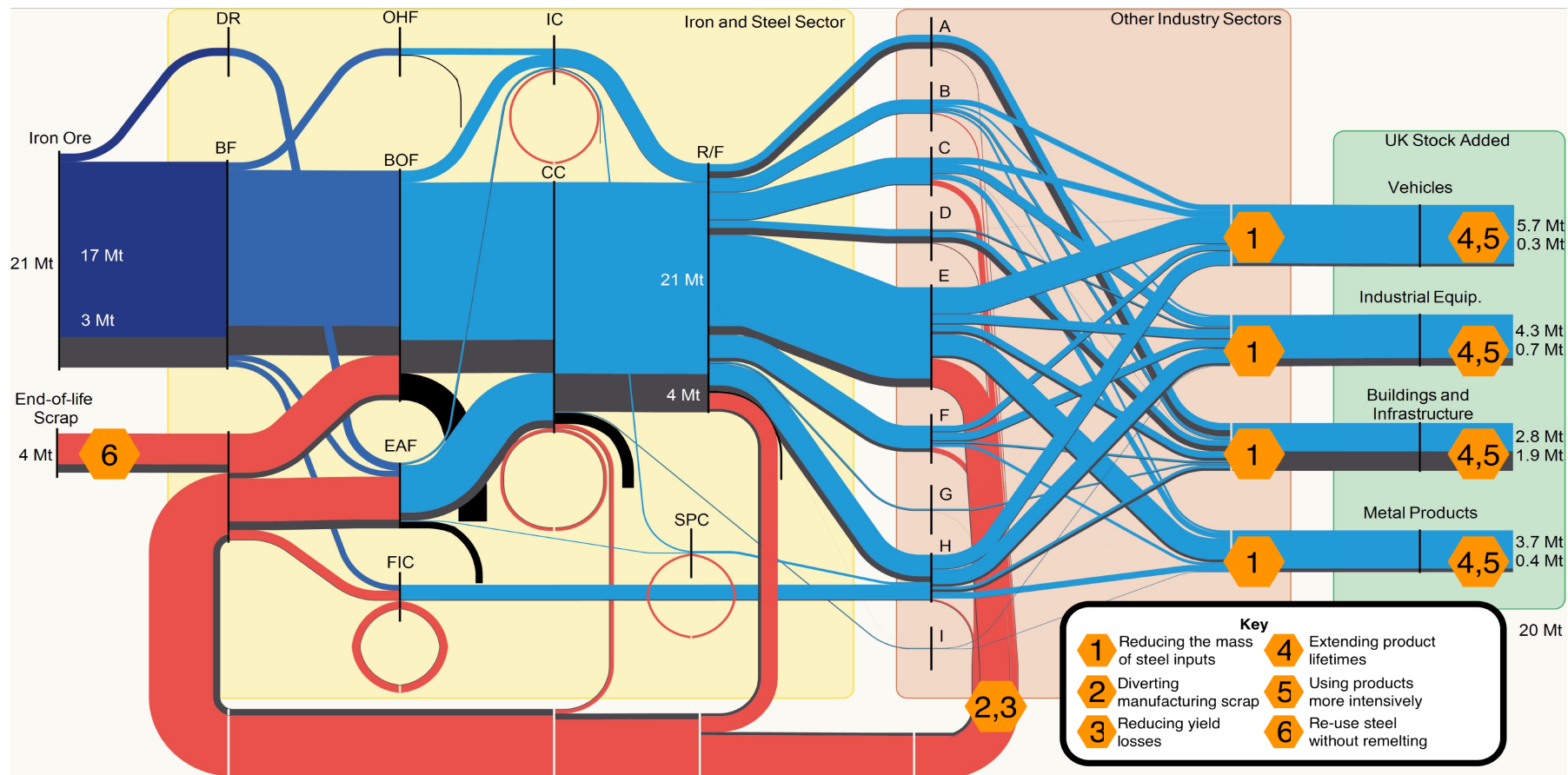
conclude that, even if all best available technologies were introduced, the emissions reductions would be insufficient to achieve the sector's share of global GhG emissions reductions because of anticipated increases in steel output. A similar conclusion is reached in Serrenho et al. (2016), which focuses on the UK. The authors model different scenarios for the steel sector to contribute to the UK's domestic 2050 emissions reduction target and conclude that UK demand for steel needs to fall. In all scenarios, the 2050 targets are partly met via steel imports indicating a relocation rather than reduction in CO<sub>2</sub> emissions. Allwood (2013) estimates that UK demand for new steel needs to fall to approximately 30% of current levels, from 530kg per capita per annum to 160kg, by 2050 to achieve the targets set in the UK Climate Change Act. These studies provide a clear indication that absolute reductions in GhG emissions in the global steel sector can only be achieved if demand side measures are also introduced. In the UK, strategies focused on more efficient steel use are a critical complement to existing supply-side initiatives to achieve long-term GhG emissions reduction targets.

### 1.3. Strategies to improve material efficiency in the UK steel economy

Understanding the technical opportunities for material efficiency improvements related to steel requires a whole supply chain perspective as it necessitates a change in the way that steel, and products containing steel, are manufactured and used over time. Allwood (2013) presents the concept of the 'UK steel economy' to assist with the systematic evaluation of material efficiency opportunities from an engineering or technical standpoint. The author defines the UK steel economy as the "*complete sequence of physical and economic activities required to deliver final services from the use of steel in the UK*". Figure 1.1, a Material Flows Analysis (MFA) presented in Serrenho (2016), shows the physical flows of iron and steel that were inputs into the UK steel economy in 2007.

The width of each flow in Figure 1.1 is proportional to the mass flow. Grey areas represent the mass flows produced by the UK steel industry. Blue and red areas represent the iron, steel and scrap mass flows supplied by the rest of the world to meet UK demand. The material flows that would be impacted by each of the six material efficiency strategies detailed in Section 1.2 have been highlighted. This visual representation of steel flows enables an overview of: the mass of steel that might be

impacted by each material efficiency strategy; whether that steel comes from primary or secondary sources; which industries might need to be engaged with implementing each strategy and where there might be trade-offs between strategies. For example, reducing yield losses might mean that less manufacturing scrap can be diverted for other uses. In light of these potential trade-offs between strategies, Allwood et al. (2013) advise that reducing the mass of steel inputs, extending product lifetimes and more intensive use of products should be prioritised as they would all lead to a reduction in demand for primary rather than secondary steel. As discussed in Section 1.2, on average the former is more CO<sub>2</sub>-intensive.



Key: DR, direct reduction; BF, blast furnace; OHF, open-hearth furnace; BOF, basic oxygen furnace; EAF, electric arc furnace; FIC, foundry iron casting; IC, ingot casting; CC, continuous casting; SPC, steel product casting; R/F, rolling/forming. Finished and semi-finished steel products: A: rods and bars for reinforcement; B: rods in coil; C: hot rolled bars and lengths; D: heavy sections, sheet piling, rails, and rolled accessories; E: sheets; F: plates in coil and in lengths; G: light sections; H: tubes, pipes, and others; I: ingots, blooms, billets, and slabs.

Figure 1.1: UK steel flows that would be impacted by the implementation of material efficiency strategies (adapted from Serrenho et al., 2016)

Lifset et al. (2013) identify trade-offs between strategies as one of the analytical challenges associated with estimating the aggregate GhG emissions impact of material efficiency improvements. Other challenges identified by the authors are; evaluating potential trade-offs in lifecycle GhG emissions between different material inputs; the risk of double counting material savings and identifying all sectors in the supply chain involved in implementing each strategy. These challenges are particularly acute for multi-material product such as cars and buildings. In spite of these methodological challenges, Allwood et al. (2012) aggregate the emissions reduction impact of implementing all six material efficiency strategies to steel products and conclude that even without maximum global deployment rates steel CO<sub>2</sub> emissions could be reduced by approximately 50%. This positivist framing demonstrates unrealised technical potential for material efficiency improvements related to steel use at the global level. Bottom up engineering and industry case studies detailed in Section 2.1. show there is unrealised technical potential for improving the efficiency steel use in the UK as well.

Although this framing outlines the technical potential, it remains unclear as to why the efficiency gains remain unrealised. The MFA shown in Figure 1.1 is only one dimension of Allwood's (2013) 'UK steel economy'. It reveals nothing of who would be involved in implementing these efficiency improvements nor what incentive structures or operating conditions they face. While an engineering MFA is a critical component of this analysis, broader interdisciplinary perspectives are needed to understand why industry practitioners and policymakers working in the UK steel economy are not using the material as efficiently as is technically possible.

## 1.4. Industry implementation of material efficiency improvements

Industrial demand for steel is derived from customers purchasing finished products, and services delivered by products comprising steel. As steel is an input to production there should be a clear cost incentive for downstream steel users to consider implementing these six material efficiency strategies.

market failures or imperfections. Sorrell et al. (2004), for example, draw insights from neoclassical and behavioural economics and organisational theory to show that a number of barriers can exist, which may inhibit firms from adopting cost-effective improvements in energy efficiency. Once identified, industry or governments can intervene to remove the incidence of any barriers or market failures. Firms, assumed to be economically rational profit maximisers, will then invest in new processes or technologies that deliver energy, or material, efficiency improvements.

Other studies from the social sciences show that firm employees do not act autonomously and any decisions on material use will also be shaped by their wider working environment. Geels and Kemp (2007) describe this environment as a ‘socio-technical system’, which can be characterised by a number of elements (e.g. technology, regulation, user practices, markets, cultural meaning, infrastructure) as well as actors and social groups (e.g. customers, manufacturers and general public). The authors also demonstrate that actors within a socio-technical system will be guided by social structures and regulative, normative and cognitive rules. Firm-level decisions that influence the mass of steel inputs to a product will be embedded in wider choices made during design, manufacture and disposal and may also be guided by habit or heuristic techniques. The efficiency of steel use associated with a particular product can be understood as the outcome of all these choices.

Elements in a socio-technical system, and the actors and rules that guide them, will differ across firms, even within the same industry. This is in part because each firm will have unique capabilities including pre-existing relationships, technical expertise, processes and culture. There is also variation in the products that they offer. These products will often deliver multiple services. The primary service of cars for example, is the provision of personal mobility. However, Wells (2010) estimates that in 2009, vehicle manufacturers were selling 3,637 car variants in the UK market which SMMT (2016), the UK vehicle manufacturers industry association, categorises into 7 distinct market segments. The services auxiliary to personal mobility (e.g. entertainment and communication systems) provided by a ‘luxury’ category vehicle will be different to a ‘mini’ category vehicle, and will communicate different messages about the owner to the wider public. Therefore, investments in material efficiency improvements will need to be compatible with firm level capabilities and any benefits from reduced material

costs will be evaluated alongside any potential impacts on different product-service streams.

This section provides a number of potential explanations of why material efficiency improvements may be unrealised in industry. First, adopting a techno-economic perspective, there may be firm-level barriers, which can distort the decision to invest in material efficiency improvements. Second, employing a socio-technical perspective, consideration must also be given to the wider set of decisions made during the product design and manufacturing process, which will be influenced by a firm's social, technical, political, cultural and economic settings. A reduction in material costs through material efficiency improvements will be one of many operational considerations.

A clearer, more systematic understanding of the factors influencing steel demand and efficiency of use by UK industry is needed. This could help with identifying how industry and government could intervene to achieve material efficiency improvements. This might include removal of firm level barriers or modifying firms and employees' operating context. A key research question is:

*Q1: Why are there unrealised opportunities to implement material efficiency improvements in UK industry?*

## 1.5. Policy support for material efficiency

As discussed in Section 1.2, reducing demand for steel via efficiency improvements is a critical complement to existing supply-side initiatives to achieve long-term GhG emissions reduction targets. Furthermore, a range of public institutions have shown that material efficiency improvements could positively impact on a number of social, environmental and economic objectives, not limited to climate change. The European Environment Agency (EEA, 2016) identify potential benefits of improved material efficiency, as reported by EU member countries, as: increased competitiveness; security of material supply and reduced reliance on imports; reduced environmental degradation associated with raw material extraction and material processing; improved production efficiencies and job creation. Waste flows would also be reduced which could help Member States comply with the EU's Waste Directive (EC, 2008) and meet targets for



the safe disposal of products such as electronic waste (EC, 2003). These widespread potential benefits have prompted many European countries to introduce policy interventions that incentivise material efficiency improvements. These include information sharing programmes. In Finland, for example, a ‘National Material Efficiency Programme’ was launched in 2013 to help industry monitor its material use and identify opportunities for efficiency improvements (EEA, 2016). Other countries are considering changes in fiscal policy. In 2016, Sweden announced a proposal to reduce value-added taxes on certain consumer goods that are repaired rather than replaced (Orange, 2016). In the UK, only Scotland has a dedicated resource efficiency strategy, which includes materials. Natural Scotland (2013) reports the aim of the strategy is to stimulate innovation in reuse, refurbishment and remanufacturing. The strategy contains a specific target for waste reduction and details a widespread program of public engagement and information sharing to influence product design, manufacturing and customer use and disposal.

The case for policy intervention to incentivise further improvements in material efficiency has also been made in academic studies. Soderholm and Tilton (2013), employ a neoclassical economic perspective and identify a number of market failures which signal that without government intervention firms will underinvest in material efficiency improvements, below the socially optimal level. The authors outline a number of information failures. For example, if the quality and availability of second hand materials and products is not fully communicated to potential customers, this may depress demand or even lead to adverse selection against high quality reused materials. In a seminal paper that later won the Nobel Prize for economics, Akerlof (1970) explains that adverse selection occurs when there is information asymmetry between buyers and sellers. When buyers have insufficient information about the quality of a product, the maximum price that buyers are willing to pay for a product is below the price set by high quality sellers. These high-quality sellers exit the market and only low quality products are sold. Soderholm and Tilton (2013) also identify the risk of bounded rationality whereby individuals make satisfactory rather than optimal decisions. This favours the status quo and may mean alternative, more materially efficient production practices are overlooked. The authors also detail a number of potential environmental and non-environmental externalities associated with material use. Externalities, as described by Her Majesty’s Treasury (HMT, 2011) result when particular activity produces benefits or costs for other activities that are not directly priced into the market.

Knowledge spillovers are an example of a positive externality. If firms who have not funded material efficiency innovation can easily appropriate new technologies or processes, the incentive to invest in innovation is reduced. The UK government (HMT, 2011) outlines that market failures, including imperfect information and externalities, provide a rationale for government intervention.

The existence of market failures would mean that there would be underinvestment in material efficiency initiatives. Evidence from policy studies and policy initiatives outside of the UK indicate that further improvement in material efficiency could yield a number of positive social, environmental and economic outcomes, not limited to reduced GhG emissions in the UK. Therefore, an important research question is:

*Q2: Why are so few material efficiency policies implemented in the UK?*

A potential limiting factor for policymakers considering interventions to support material efficiency improvements might be the challenge of anticipating all the benefits, costs and re-distributional impacts of improvements in industrial material efficiency. UK policymakers will need to balance GhG emissions reductions that could be delivered via material efficiency improvements with other macroeconomic goals including: economic growth; increased employment; productivity and competitiveness; greater income equality and stable public finances (HMT, 2016).

Policymakers and researchers often use economic models to evaluate the macroeconomic impacts of policy interventions and efficiency improvements. Some studies analyse impacts by focusing on a single macroeconomic variable. Mirasgedis et al. (2014), for example, evaluates the employment impacts associated with energy efficiency improvements in buildings. When reviewing the existing literature on this topic, the authors identify three distinct modelling approaches: (i) indices and multipliers from specific case studies, (ii) input–output analysis and (iii) top-down models, such as econometric models or computable general equilibrium models. Each of these modelling approaches will have different underlying assumptions, coverage and resolution. These distinctions guide which model might be best suited to different analytical questions. Indices and multipliers, such as those found in Wei et al. (2010), for example, may have a high degree of resolution and accuracy if they are generated from real world case studies. However, there may be limited generalizability beyond the

case study circumstances and, unlike input-output analysis and top-down models, they may not fully capture inter-sector and whole-economy interactions. The three approaches detailed in Mirasgedis et al. (2014) can also be used to evaluate the impact of efficiency improvements on multiple macroeconomic variables. A report by Cambridge Econometrics and Bio Intelligence Services (2014), for example, uses a top-down econometric macroeconomic model to evaluate the macroeconomic impacts of improvement in resource efficiency on EU28 countries. The study considers changes in GDP, investment, trade, consumption, inflation and employment. The changes differ depending on the underlying scenario assumptions around the level resource efficiency improvements and choice of policy instrument to deliver those improvements. Further clarity is needed on the potential range of macroeconomic impacts from material efficiency improvements in the UK. Consideration must be given to which modelling approach would be appropriate for understanding the impacts of the six material efficiency strategies detailed in section 1.3. There may be trade-offs between approaches and the estimated impacts could also vary depending on the underlying model structure and scenario assumptions. Greater clarity is needed on these trade-offs and on the potential impacts of material efficiency improvements. This would create certainty for policymakers considering policy interventions. A final research question is:

*Q3: What would be the macroeconomic impacts of more efficient material use in the UK?*

Each of these three questions examines why the technical potential for material efficiency improvements, as defined in engineering studies, remains unrealized and underexplored when the potential consequences of climate change are so severe. In the process of answering these questions, some of the motivations and priorities of policymakers and industry practitioners should be revealed. While steel use in the UK is the chosen case study, because of the large GhG emissions associated with its production, lessons could be learnt which would help to answer a much broader research question. Namely:

**How could good research ideas, from engineering or otherwise, be developed into strategies to encourage take up by industry practitioners and policymakers?**

## 1.6. Thesis structure

This chapter outlines six technically feasible strategies for improving the efficiency of steel use in the UK. Improved material efficiency, to reduce steel demand, is critical complement to existing supply-side initiatives to ensure the sector contributes to the UK's 2050 GhG emissions reduction target. However, there is unrealised potential to improve the efficiency of material use, including steel, in UK industry and little policy support. The purpose of this thesis is to contribute new insights on industry and policy implementation of material efficiency initiatives in the UK. The remainder of the thesis is structured as follows:

### **Chapter 2: Literature Review**

### **Chapter 3: Industry implementation of material efficiency**

*Q1: Why are there unrealised opportunities to implement material efficiency improvements in UK industry?*

### **Chapter 4: Policy implementation of material efficiency**

*Q2: Why are so few material efficiency policies implemented in the UK?*

### **Chapter 5: Employment impacts of material efficiency**

*Q3: What would be the macroeconomic impacts of more efficient material use in the UK?*

### **Chapter 6: Discussion and future work**

## 2. Literature review

This Chapter reviews existing studies that provide multidisciplinary insights into industry and policy implementation of material efficiency initiatives. These insights are also used to refine the research questions summarised in Section 1.6 and develop a detailed research plan for Chapters 3-5 of this thesis.

Section 2.1 examines the six material strategies identified in Allwood et al. (2012) in more depth. A number of engineering and industry case studies show that there are unrealised technical opportunities to improve the efficiency of steel use in the UK via many different innovative approaches. Section 2.2 summarises the findings from social sciences studies that seek to explain why industry might overlook these opportunities. Non-adoption of material efficiency improvements may prompt policy intervention. Section 2.3 provides an overview of key models that explain different aspects of policymaking process. Further consideration is given to studies that focus on the policy and political processes leading to climate policy formation. Policymakers will need to have some understanding of the impacts of any potential policy intervention. Section 2.4 summarises existing studies that quantitatively estimate the macroeconomic impacts of improved material efficiency.

### *2.1. Opportunities to improve the efficiency of steel use*

As discussed in Section 1.1, Allwood et al. (2012) identify six strategies for improving the efficiency of material use throughout a product's lifetime. These are: (1) lightweight design; (2) reducing yield losses during product manufacturing; (3) diverting manufacturing scrap; (4) extending product lifetimes; (5) using products more intensively and (6) reusing material without re-melting. This section details a number of engineering studies from academia and industry that show how each of these six strategies could be implemented to improve the efficiency of steel use in the UK automotive and construction supply chains. These sectors are of particular interest because Cullen et al. (2012) show in a material flow analysis that they account for more than half of all steel use globally. Both sectors also use large volumes of other bulk materials. The United Nations Environment Program (2007) estimates that the global

construction sector drives 40-50% of all material demand by mass, approximately 3Bt/y. The global automotive industry is a smaller source of material demand, estimated in Wells (2010) to be approximately 130Mt/y. This section shows that implementation of the six material efficiency strategies in these two supply chains may necessitate product, process or organisational innovation. These innovation types, as defined by the OECD (2005), are outlined in Table 2.1.

**Table 2.1: Categories of innovation (OECD, 2005)**

Innovation category	Definition
Product	The introduction of a good or service that is new or significantly improved with respect to its characteristics or intended uses. This includes significant improvements in technical specifications (including form and appearance), components and materials, incorporated software, user friendliness or other functional characteristics.
Process	The implementation of a new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software.
Organisational	The implementation of a new organisational method in the firm's business practices, workplace organisation or external relations.

The OECD (2005) also includes 'Marketing innovation' in its list of innovation categories. This is defined as a "*marketing method not previously used by the firm*". This type of innovation is considered to be less relevant for material efficiency as it relates to "*product placement*", "*product promotion*" and "*pricing strategies*". The manual also includes changing "*product design as part of a new marketing concept*" as an approach to marketing innovation. The definition of '*product innovation*' in Table 1.1 has been expanded to include this particular type of marketing innovation. Bleischwitz et al. (2009) explain that all three types of innovation can also lead to societal or customer behaviour change. For example, if innovation leads to a change in product use, access, ownership or service provision. This is further explored in this section where relevant.

### *2.1.1. Lightweight design*

Before a product is manufactured there are opportunities to apply lightweight design principles. This can reduce the mass of steel inputs per unit of service provision. Allwood (2013) emphasises that improvements in material efficiency should always result in the same level of service provision. However, as discussed in Section 1.4, a

single product might provide multiple services. One approach for minimising the impact of lightweight design on product service provision is to keep it hidden from the end-user.

In the construction sector, Moynihan & Allwood, (2014) review 23 steel-framed building designs in the UK and find on average that the load on beams is 50% below their designed capacity. These beams could be redesigned, with a reduction in the mass of steel used, without compromising the structural integrity of the building or impacting on its external and interior aesthetic. A similar strategy could be employed in the automotive industry for car bodies. Cheah (2010) shows that vehicle weight could be reduced by 12-35%, for a range of Sedans sold in the USA in 2007-2008, by using creative design and packaging to minimize the exterior dimensions while maintaining the same interior space. The author also demonstrates that this weight reduction could lead to secondary mass savings as the subsystems (e.g. engine, suspension, brakes) could be downsized as the performance requirements would be lower for a lighter vehicle.

Lightweight steel designs are not uniformly adopted in the automotive industry at present. WorldAutoSteel (2015) benchmarked the efficiency with which steel is used in the design of a number of components across 240 vehicles and found significant disparities. The study concludes that optimising the design of all steel components could reduce a car's kerb weight by 6.5% compared to the average design efficiency. Although the WorldAutoSteel study shows some industry efforts to reduce vehicle weight through lightweight design, average weight and dimensions have increased across all vehicle segments in Europe since 2004 (ICCT, 2016). Zervas (2010) analyses this data and partly attributes the increase to the introduction of new features, auxiliary to driving, designed to improve comfort, safety, security and emissions control and partly to increases in vehicle dimensions. One potential impact of larger, heavier and more material-intensive cars is an increase in in-use GhG emissions. Nieuwenhuis (2014) explains that holding all other factors constant, heavier cars take more energy to accelerate to a given speed and have a higher rolling and aerodynamic resistance. As a consequence, heavier cars require more fuel and will release more GhG emissions.

Material switching is complementary to lightweight design and could also lead to reductions in vehicle weight. Data from the American Chemistry Council (2015) show

that material switching is already occurring in the automotive industry. Between 2004 and 2014, lighter, higher strength steels and other lightweight materials such as aluminium, magnesium and carbon fibre have become a larger share of the total average vehicle material mix in the USA (from 30 to 37%). Switching between materials could lead to lower vehicle weight and in-use emissions. However, when adopting a lifecycle perspective, the GhG emissions impact of material switching is unclear. As shown in an impact assessment by Witik et al. (2011), total lifecycle GhG emissions depends on how a material is manufactured (see Table 2.2 for examples), how a vehicle is used and how it is treated at the end of its working life. Lightweight design, including a reduction in product dimensions, is therefore an important complement to material switching.

**Table 2.2: Material use by the global automotive and greenhouse emissions intensity of material production.**

*Sources: [www.worldsteel.org](http://www.worldsteel.org), [www.iea-coal.org.uk](http://www.iea-coal.org.uk), Wells (2010), [www.european-aluminium.eu](http://www.european-aluminium.eu), [www.world-aluminium.org](http://www.world-aluminium.org), [www.reinforcedplastics.com](http://www.reinforcedplastics.com), [www.carbonfiber.gr.jp](http://www.carbonfiber.gr.jp)*

Material	Approximate mass of material used by the global automotive industry to make cars in 2015 (Mt)	Production intensity (tCO <sub>2</sub> /t material)	emissions
Steel	80	0.4-2.5 (per semi)	
Aluminium	14	0.3 – 17 (per ingot)	
Carbon fibre	0.005	20	

Other approaches to lightweight design in the automotive sector, for example reducing vehicle dimensions, cannot be hidden from the user and may impact some of the services provided by a car. Tanoue et al. (1997) use Kansei engineering techniques, a method that translates a user’s subjective impression of a product into specific design parameters including vehicle dimensions. The authors find that user satisfaction positively correlates with the ‘roominess’ of a car, which provides some indication that customers derive utility from a spacious interior. They may also enjoy services provided by features auxiliary to personal mobility, such as entertainment systems. The potential for lightweight design through product downsizing has also been explored in the UK construction sector. Gieseckam (2015) discusses the possibility of reducing building dimensions as an option for reducing embodied emissions in the sector. However, the author also notes that a smaller building interior, while still providing shelter, may impact on occupant wellbeing and utility.



Some firms in the automotive and construction sectors are introducing initiatives to reduce the mass of steel inputs through lightweight design but these are not uniformly implemented. This indicates there are further technical opportunities for lightweight design. Reducing product dimensions is one potential approach. However, this could potentially impact the product user's experience.

### *2.1.2. Reducing yield losses during manufacturing*

As discussed in Section 1.2, production of liquid steel is CO<sub>2</sub> emissions-intensive. Once cooled, liquid steel solidifies to form crude steel before undergoing further processing. Yield losses along the supply chain mean that more liquid steel is produced than ends up in products. Figure 1.1 in Section 1.3 shows yield losses from 'Other Industry Sectors' as red output flows from that then become scrap inputs to the EAF and BOF. In the UK approximately 30% of the mass of steel purchased is scrapped and recycled without ever becoming part of a product. The largest yield losses occur during further processing of steel sheets. By investigating the supply chain yield for five steel and aluminium-intensive products, Milford et al. (2013) show that losses mostly occur during the blanking and stamping processes. Blanking involves cutting smaller shapes out of sheet metal. Stamping refers to the process of sheet metal forming in a press. Pressure is applied to form and shape the metal around a die. Horton (2016) reviews the sheet metal scrap, mainly steel and aluminium that arises from the production of 46 different vehicles. The author finds that the average material utilization rate of sheet metal is approximately 55%, but there is a wide variation between models. If all yield improvement opportunities were realised across all models, less metal would be needed. A number of studies have suggested innovations that could reduce yield losses from cutting and shaping sheet metal. Allwood et al. (2012) show how metal shapes could be better tessellated before blanking. The authors provide evidence from the textiles industry who employ this strategy and experience lower yield losses on average. Carruth and Allwood (2013) examine the potential for another type of process innovation. The authors investigate the potential material savings from partly shaping metal with a ridged die before blanking. In a case study on aluminium cans, the authors show yield losses could be reduced by 7-9% via this novel 'pre-blanking' process. Skelton and Allwood (2013b) posit that material efficiency improvements could also be delivered by organisational innovation. The authors suggest that yield losses could be

reduced if suppliers of different sized blanked parts collaborate and use the same production line, rather than optimising yields separately at each plant.

The potential material savings from reducing yield losses are greatest for steel sheet. Yield losses could be reduced by process or organisational innovation.

### *2.1.3. Diverting manufacturing scrap*

If yield losses cannot be reduced, an alternative approach would be diverting manufacturing scrap for other purposes. Figure 1.1 in Section 1.3 shows that most steel manufacturing scrap is recycled. Although recycling steel in an EAF furnace is less CO<sub>2</sub> emissions-intensive than the BF/BOF route, diverting and reusing pre-consumer scrap is preferable to recycling in the European Commission (2008) waste hierarchy. Diverting scrap would avoid re-heating and re-melting, which is shown in Worrell et al. (2010) to be the most energy-intensive process in secondary steel production. The CO<sub>2</sub> emissions intensity of the re-melting process will vary depending on the fuel mix supplying the electricity to an EAF plant.

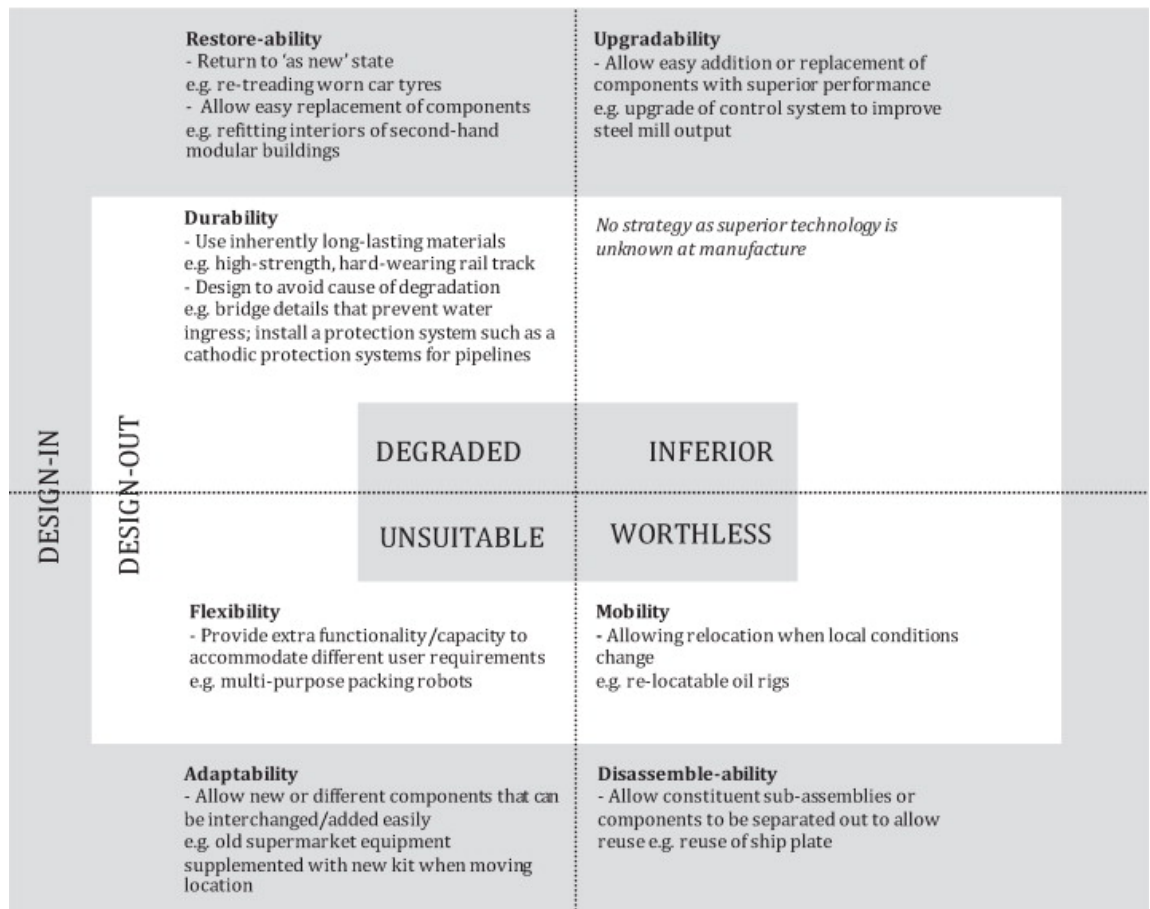
Small amounts of steel offcuts from the automotive sector are currently diverted for reuse in the UK. Catulli (2008) provides a detailed case study on Abbey Steel, a company which purchases and processes scrap sheet metal from the production lines at large UK automotive manufacturers, including Honda and Jaguar Land Rover. Allwood et al. (2012) similarly identify Abbey Steel as a company that has made scrap diversion profitable in the UK. Through discussions with the company, the authors estimate around 10,000t of steel per annum are cut from scrap sheet from the automotive industry and resold. These smaller steel shapes are bought by manufacturers of metal products such as filing cabinets and electrical connectors. Forbes (2013) report that in the USA, Blue Star Steel similarly reprocesses and sells scrap steel sheet from General Motors.

Since most manufacturing scrap is currently recycled in the UK, diverting it for other uses requires organisational innovation, which could include supply chain coordination.

### *2.1.4. Extending product lifetimes*

Once a product has been designed and manufactured, the opportunities for material efficiency improvements relate to how a product is used and treated at the end of its life. The longer a product is used, the longer a service or set of services can be delivered for a given mass of steel inputs. However, there is a potential trade-off between embodied and in-use GhG emissions with some products. Innovation may mean newer products are more energy efficient and have lower in-use CO<sub>2</sub> emissions. Skelton and Allwood (2013a) explore this trade-off for a range of products. The authors develop a model to identify optimal product life that minimises embodied and in-use energy and CO<sub>2</sub> emissions. For office buildings the optimal life is around 135 years, double the current average lifespan in the UK. For cars, the optimal lifespan is estimated at 10 years, shorter than the average UK lifespan. However, only one car model was used in this analysis. Other studies do not always explicitly consider the trade-off between embodied and in-use GhG emissions. Oguchi and Fuse (2015) use a Weibull distribution function to estimate the average lifespan of vehicles for 17 countries. The authors find that in 2008, the average lifespan of a UK vehicle was 13.5 years, down from 13.9 years in 2000. The lowest average lifespan of a vehicle was 13 years in South Korea; the highest was 22.6 years in Australia. This provides some indication of the technical potential to extend vehicle lifespans in the UK. A similar conclusion is reached in Niewenhuis (2014). The author outlines a number of industry and academic studies that conclude cars could be made to last 20-30 years without significant additional manufacturing costs. Cooper et al. (2014) explore why steel-intensive products, including cars, might be retired before their full lifespan is exploited. The authors identify four distinct reasons. Products might fail in the eyes of the user because they: (1) have degraded in performance; (2) are inferior to what is currently available; (3) are unsuitable in the eyes of the current user and (4) worthless in the eyes of all users. The authors emphasise that understanding why a product is retired early is critical for developing an appropriate response to encourage product longevity (see Figure 2.1). For example, product degradation could be overcome by increasing a product's durability. This may require product innovation if the design or material is changed or process innovation if new manufacturing techniques are required. In Figure 2.1, enabling 'upgradability' is presented as a solution to the problem of an inferior product. This might also require product innovation to enable disassembly and modification. Organisational innovation, such as shifting to product-service system business models,

may also be necessary to support product maintenance, repair and upgrade. Product System Services are defined in Mont (2002) as “a marketable set of products and services capable of jointly fulfilling a user’s need”. The author identifies “a repair-society” as one approach to product systems services



**Figure 2.1: Targeted strategies to address product and component failure (Cooper et al., 2014)**

Buildings and cars are often retired before their full technical lifespan has been exploited in the UK. Optimising product lifespans to reduce GhG emissions must reflect the relative contribution of embedded and in-use emissions. When it is preferable to extend the life of product, the cause of product failure must be considered, as this will inform the type of innovation response required.

### *2.1.5. Using products more intensively*

If products are used more intensively, there is the potential to reduce the total number of products, and material inputs, required to deliver a given level of service. However, in a “White Paper” surveying existing interdisciplinary insights on material efficiency

Allwood et al. (2011) conclude that there is currently a shortage of case study evidence on how more intense product use can reduce material demand. Milford et al. (2013) caution that a potential trade off from more intense product use is increased product degradation, which leads to shorter product lifespans. From this, it can be concluded that the potential material, and CO<sub>2</sub> emissions, savings from more intensive product use will probably vary across products.

Allwood et al. (2012) evaluate this trade-off for a number of steel-intensive products by mapping out the intensity of use against product lifetimes. Washing machines and cars are identified as products providing the lowest level of lifetime service in the UK, which indicates that lifecycle emissions could be lower if these products were used more intensively, for example through sharing. The case for more intensive vehicle use in the UK is also strengthened by the findings in a study by Serrenho and Allwood (2016). The authors model the change in vehicle stock over time and find that the material intensity of cars and number of new car registrations increased between 2002 and 2012 while the service provision, measured in average vehicle miles per annum, fell by 10%. This finding seems to indicate that privately owned cars are increasingly under-utilised in the UK but demand for the option of personal mobility remains high.

Car sharing is a potential approach for improving the productivity of a steel-intensive product through more intense use. Car sharing enables individuals to access a car, and the mobility services it provides, without ownership. Drivers can either share journeys or vehicles. The latter of which can occur through peer-to-peer sharing, where individuals retain ownership of their cars and loan them temporarily to others, or via car clubs, where vehicles are owned by a car club operator. Both vehicle rental and leasing companies and vehicle manufacturers have recently begun to operate car clubs in the UK. Zipcar, for example, is owned by Avis and BMW operates Drive Now. This change required business model, rather than product or process, innovation. The cars themselves have only undergone superficial modification to enable member access.

On average, car club vehicles are used more intensively than privately owned cars. A comparison of car club member data (Steer, Davis Gleave, 2016) with data on average private vehicle usage (DfT, 2016) shows that on each car club vehicle is driven for an extra 22,000 miles per annum and has a higher occupancy rate. Membership to a car club can also lead to a driver delaying or deterring a private car purchase. Steer Davis

Gleave (2015) estimated that in 2014 each car club vehicle in the UK displaced between 3.5 and 8.6 privately owned new and second-hand vehicles. This demonstrates that car clubs can potentially reduce demand for new cars and the need for emissions-intensive material inputs, including steel. However, there could be a potential rebound effect on CO<sub>2</sub> emissions if car sharing displaces alternative low carbon forms of transport such as walking or cycling. This was one of the findings in Cervero (2003), a study reviewing a range of impacts from the first year of a car-sharing scheme in San Francisco. Aside from a potential impact on CO<sub>2</sub> emissions, a number of other potential environmental and social benefits from car sharing have been identified in the literature. In a “Car Club Strategy for London”, Transport for London (TFL, 2015) details emerging domestic and international evidence that car sharing can reduce congestion and competition for parking spaces and improve air quality. In an appraisal of car sharing schemes in northern regions of the UK, Parker et al. (2011) also show that car sharing can potentially increase an individual’s access to employment, particularly in rural areas. These potential benefits have prompted local and central government to support the expansion of car club membership across the UK (DFT, 2014a). However, at present only 0.01% of UK population with a driver’s license currently belong to a car club (Steer Davies Gleave, 2015, DFT, 2014b). If car club vehicles remain a small proportion of the total vehicle fleet then the anticipated improvements around congestion, air quality and parking availability will also be low. Prettenthaler and Steininger (1999) question if car club vehicles can ever fully displace private vehicle ownership. The authors emphasise that while both private vehicle and car club vehicles provide mobility services, private vehicles provide additional services and benefits. First, is the benefit that a private car will always be available without wait and second that private car ownership can contribute to an individual’s identity and enhance their personal prestige. Therefore there might be a limit on the absolute population of car club members.

Using products more intensively may lead to a reduction in material demand. However, there is a potential trade-off between more intensive use and product degradation, which will vary across product types. Cars in the UK are becoming more material intensive and are under-utilised. More intensive use of cars, through sharing rather than private ownership, could therefore lead to a reduction in total material inputs required to deliver personal mobility. Car clubs, one approach for increasing the intensity of vehicle use,

are currently occurring on a very small scale in the UK. Car clubs are explored further in Chapter 5 of this thesis.

### *2.1.6. Re-using material without re-melting.*

At the end of a product's life there are opportunities to reuse rather than recycle steel-intensive products or components. Cooper and Allwood (2012) combine an extensive literature review with industry interviews to identify what fraction of steel components could be technically reused in 23 products. On average, across all products, around 27% of the mass of steel inputs could be reused without re-melting through extensive reconditioning (e.g. remanufacture) or superficial reconditioning (e.g. relocation). The authors identify that long steel products, namely structural steel and cold rolled steel sections used in the construction of buildings, as having a relatively higher reuse potential. Further reuse of these products is currently constrained by technical barriers such as component irretrievability and incompatibility with new building construction projects. However, Cooper and Allwood (2012) suggest that approximately 50-75% of the mass of long steel products could be reused with only superficial reconditioning. In spite of this reuse potential, Sansom and Avery (2014) find that in 2007, only 5-7% of long steel products extracted from UK building sites were reused. The remaining 93-95% was recycled. The authors compare this with an earlier study and find that the reuse rate of long steel products had fallen by 3-5% since 2000. Reuse of steel sections can occur either in-situ or in a new location. Reusing steel sections is technically feasible across a number of geographies and building types, as demonstrated by case studies for industrial (Pongiglione and Calderini, 2014) residential, (Chance, 2009) and commercial buildings (Gorgolewski, 2008). Increasing the rate of section reuse may require all three types of innovation. Options for innovation are outlined in Densley-Tingley and Davison (2011). Buildings themselves could undergo product innovation, for example if they're designed-for-deconstruction. This may include using connections that can be easily removed or developing a detailed deconstruction plan. The construction industry could also implement process innovation to shift from building demolition to deconstruction. Business model innovation may also be required to support the shift from recycling to reusing steel. Reused steel would need to be catalogued and stored for example.

Further reuse of steel products and components is technically feasible. The largest opportunities for material savings are from reuse of long steel products used in

process and organisational innovation along the construction supply chain. Reuse of long steel products in the UK construction sector is explored further in Chapter 5 of this thesis.

### 2.1.7. Summary

This section has shown that there may be unrealised technical opportunities for improving the efficiency of steel use in the UK construction and automotive supply chain via six material efficiency strategies. These efficiency improvements could be delivered throughout a product's lifespan through a variety of innovative approaches (Table 2.3). A number of these strategies and modes of implementation further explored as case studies in later chapters of this thesis.

**Table 2.3: Material efficiency strategies, possible modes of implementation and innovation type.**

Material efficiency strategy	Mode of implementation ( <i>source</i> )	Type of innovation		
		Product	Process	Organisational
Lightweight design	Lighter materials ( <i>Witik et al., 2011</i> )	x		
	Light-weight design of component parts ( <i>Moynihan &amp; Allwood, 2014; WorldAutoSteel, 2015</i> )	x		
	Reduce product or component dimensions ( <i>Gieskam, 2015</i> )	x		
Reducing yield losses during manufacturing	Better tessellation and gripping ( <i>Carruth and Allwood, 2013</i> )		x	
	Pre-blanking ( <i>Carruth and Allwood, 2013</i> )	x		
	Multiple companies simultaneously optimising yield losses on a single production line ( <i>Skelton and Allwood, 2013b</i> )		x	x
Diverting manufacturing scrap	Process offcuts from steel sheet in automotive ( <i>Catulli, 2008</i> )		x	x
Extending product lifetimes	Design for product disassembly, upgradability, restorability, adaptability, durability, flexibility and mobility ( <i>Cooper et al., 2014</i> )	x	x	x
Using products more intensively	Product sharing ( <i>Steer, Davis, Gleave, 2016</i> )	x		x
Re-using material without re-melting	Design for product disassembly ( <i>Densley-Tingley and Davison, 2011</i> )	x		x
	Product disassembly ( <i>ibid</i> )		x	x
	Component reuse ( <i>ibid</i> )	x	x	x



This section also shows that while innovations may be targeted at improving the efficiency of steel use, there may be wider efficiency impacts on other materials and resources. This is particularly true for product-level strategies such as: extending building lifetimes, designing buildings for deconstruction and using cars more intensively. A number of potential trade-offs between strategies may occur which can impact on lifecycle GhG emissions. The evidence from this literature review shows that this trade off differs across products and will depend on the material intensity of a product, the intensity of product use and treatment at the end of a product's life.

The studies detailed in this chapter all employ a positivist perspective, though this is not explicitly stated in any study. They all objectively describe a reality that exists – in this case, that steel is being used less efficiently than is technically possible in the UK. Furthermore, they all employ empirical quantitative methods, often using case studies and samples as the basis of their enquiry and the results are largely factual rather than value-laden. Interpretivism offers an alternative perspective that emphasises analysis should be placed in context. As such, studies underpinned by interpretivist philosophy tend to be more qualitative as researchers draw inferences and understand real world phenomena from observations in the social realm (Gray, 2014).

Although the technical potential for improving the efficiency of steel use has been demonstrated through positivist engineering studies in this chapter, these strategies are not widely adopted at present. Section 2.2 summarises insights from social sciences studies, which tend to be interpretivist, that seek to explain why this is the case.

## *2.2. Explaining unrealised opportunities for material efficiency improvements in industry.*

Chapter 2.1 illustrated the technical potential for improving the efficiency of steel use via six different strategies. This section outlines studies from the social sciences, which seek to explain why the technical potential for these material efficiency initiatives may be unrealised. These studies typically adopt either a techno-economic (Section 2.2.1) or socio-technical framework (Section 2.2.2). Insights from this literature base are used to inform a detailed research plan for Chapter 3 of this thesis (Section 2.2.3). This research plan is developed in response to question Q1 outlined in Section 1.5.

*Q1: Why are there unrealised opportunities to implement material efficiency improvements?*

### *2.2.1. Techno-economic studies on barriers to material efficiency*

Existing research explaining the low uptake of material efficiency initiatives tends to employ a techno-economic framework. These types of studies assume that individuals and firms are perfectly informed, rational and will invest in material efficiency improvements if they are cost-effective. However, individuals and firms may experience a number of barriers that distort their behaviour and this may mean that cost-effective material efficiency improvements are not adopted. Techno-economic studies investigate whether any barriers exist, with a view to removing or reducing their incidence. Techno-economic frameworks have also been applied to investigate barriers to energy efficiency improvements in different sectors and regions. The difference between the optimal level of investment and actual level of investment in energy efficiency improvements is characterised in Jaffe and Stavins (1994) as ‘energy efficiency gap’. There may be an equivalent ‘material efficiency gap’ but the techno-economic literature on material efficiency is less developed and no studies were found which characterised unrealised opportunities for material efficiency improvements using this term.

Identifying and measuring the incidence of barriers to investments in energy and material efficiency is not straightforward. In a reflection piece, Weber (1997) posits that barriers may be challenging to identify, as they are ‘not directly observable’ and ‘cannot be empirically classified’. Sorrell (2011) explains that this challenge is further complicated by the coexistence of multiple barriers, which may be both interdependent and reinforcing. A number of studies have provided guidance on how to investigate and evaluate barriers to investments in efficiency improvements. Blumstein (1980) advises that consideration should be given to a barrier’s stability or transience. Palm & Thollander (2010) clarify that a barrier might be real or perceived. D’Este et al. (2012) also distinguishes between ‘revealed’ barriers, reflecting the degree of implementation difficulty, and ‘deterred’ barriers, which prevent a firm from committing to any investment whatsoever. Reddy (2007) also advises that barriers may exist at the micro (firm), meso (industry) or macro (economy) scale and each may require a different remedial response from government or industry.

Typologies can help manage the analytical complexity associated with identifying barriers to efficiency improvements. Sorrell et al. (2004) conducted in-depth industry case studies of barriers to investments in energy efficiency improvements in different UK sectors, Germany and Ireland and develop a commonly-cited typology. Six categories of barriers are outlined, namely: risk, imperfect information, hidden costs, access to capital, split incentives and bounded rationality (see Table 2.4). As discussed, the techno-economic literature on barriers to material efficiency is less developed and no equivalent typology exists. Instead, researchers tend to identify different barriers to material efficiency for each empirical case study under investigation.

Pajunen et al. (2012) conducted semi-structured interviews with industry representatives in Finland and identified the cost of investment and high risk associated with unproven technologies as the two main barriers to effective material use. Shahbazi (2015) used a similar method to investigate barriers to material efficiency in the Swedish automotive industry. The author attributes a general lack of support for material efficiency initiatives to: low levels of awareness, inadequate economic incentives and prioritisation of other issues. This could be interpreted as evidence of bounded rationality, split incentives and imperfect information flows within companies. Shabazi et al. (2016) build on this earlier study by comparing empirical barriers in the Swedish automotive industry to theoretical barriers identified in academic studies. The authors only found empirical evidence for a subset of theoretical barriers. They conclude that these barriers

are mainly internal as they depend on a company's characteristics and processes. This includes a lack of vision and culture towards achieving material efficiency improvements and inadequate communication with employees about opportunities for material efficiency improvements. In an input-output modelling study of steel use in the UK, Skelton et al. (2013b) identify labour taxation as a large hidden cost which distorts the incentives to improve material efficiency. Flachenecker and Rentschler (2015) examine barriers to more efficient use of resources, including industry and construction materials, for countries located in Europe and Central Asia and the Middle East and North Africa regions. The authors discuss a number of investment barriers including: information constraints on the scale and solutions to achieve efficiency savings; technical, administrative and managerial capacity constraints from acting on new information; financial constraints including limited or costly access to credit and uncertain payback periods; unfavourable market structures including insufficient competition or protectionism and fiscal distortions such as subsidies. Other empirical studies focus on a single strategy or sector. Carruth et al. (2011) show that barriers to lightweight design will differ across products. For example, the authors suggest that a lightweight car body can give the impression of being inferior, even if they offer the same technical performance as heavier ones, while risk aversion in the construction sector may better explain over-specification of steel beams. Bleischwitz et al. (2009) also considers the barriers to efficient material use in the construction sector. The authors refer to a study in Germany and suggest that the prevalence of informal workers in the construction sector leads to '*blundering and bricolage buildings*'. There is a culture of using whatever materials are to hand, evidence of bounded rationality, rather than considering in advance what the most materially efficient approach might be. Densley-Tingley et al. (2017) also focus on the construction sector and consider barriers to reusing steel sections in the UK. From extensive interviews with contractors, structural engineers, architects and steel fabricators, the authors conclude that the most significant barriers relate: to additional project costs, a lack of availability of reused steel and client perceptions around the quality of reused material. These barriers may be an indication of imperfect information flows within the construction industry and with their customers. Theoretical studies such as Allwood et al. (2011) and IEA (2015) also identify various economic, social and political barriers, which may impact the decision to introduce material efficiency improvements. The theoretical market failures identified outlined in Section 1.5, from Soderholm and Tilton (2013), including imperfect

information and bounded rationality may also act as barriers to material efficiency investments

The absence of a typology of material efficiency barriers in any of these studies mean it is unclear whether the barriers listed in these studies are comprehensive. Another observation drawn from the existing techno-economic literature is that not all studies consider whether their chosen material efficiency initiatives would be cost-effective. If initiatives are not cost-effective, individuals and firms would be economically rational in ignoring material efficiency opportunities, notwithstanding any techno-economic barriers. There would be no equivalent 'material efficiency gap'

In spite of differing assumptions and evidence regarding the cost-effectiveness of material and energy efficiency investments, Table 2.4 applies the Sorrell et al. (2004) typology to show there may be parallels between barriers to material efficiency and energy efficiency in techno-economic studies.

**Table 2.4: A taxonomy of barriers to energy and material efficiency (adapted from Sorrell et al., 2000)**

Barrier	Explanation	Evidence of barrier in material efficiency literature
Risk	The short paybacks required for energy efficiency investments may represent a rational response to risk. This could be because energy/material efficiency investments represent a higher technical or financial risk than other types of investment, or that business and market uncertainty encourages short time horizons	Pajunen et al. (2012); Skelton et al. (2013b); Densley-Tingley & Davison (2011); Flachenecker and Rentschler (2015); Carruth et al. (2011)
Imperfect information	Lack of information on energy/material efficiency opportunities may lead to cost-effective opportunities being missed. In some cases, imperfect information may lead to inefficient products driving efficient products out of the market.	Shahbazi (2015); Bleischwitz et al. (2009); Soderholm and Tilton (2013); Flachenecker and Rentschler (2015); Densley-Tingley et al. ( <i>accepted</i> )
Hidden costs	Engineering-economic analyses may fail to account for either the reduction in utility associated with energy/material efficient technologies, or the additional costs associated with them. As a consequence, the studies may overestimate energy/material efficiency potential. Examples of hidden costs include overhead costs for management, disruptions to production, staff replacement and training, and the costs associated with gathering, analysing and applying information	Pajunen et al. (2012); Skelton et al. (2013b); Soderholm and Tilton (2013); Flachenecker and Rentschler (2015); Carruth et al. (2011).
Access to capital	If an organization has insufficient capital through internal funds, and has difficulty raising additional funds through borrowing or share issues, investments in energy/material efficiency may be prevented from going ahead. Investment could also be inhibited by internal capital budgeting procedures, investment appraisal rules and the short-term incentives of energy management staff.	Flachenecker and Rentschler (2015);
Split incentives	Opportunities to improve material/energy efficiency are likely to be foregone if actors cannot personally appropriate the benefits of the investment.	Shahbazi (2015); Soderholm and Tilton (2013)
Bounded rationality	Owing to constraints on time, attention, and the ability to process information, individuals do not make decisions in the manner assumed in economic models. As a consequence, they may neglect opportunities for material/energy efficiency improvements, even when given good information and appropriate incentives.	Shahbazi (2015); Bleischwitz et al. (2009); Soderholm and Tilton (2013); Flachenecker and Rentschler (2015)

Table 2.4 shows that each techno-economic study identifies a different barrier or mix of barriers to material efficiency. This provides some indication that barriers to material efficiency may differ across firms, regions, strategy and innovation type. This diversity between firms, including their operating contexts, is also considered in socio-technical studies.

### *2.2.1. Sociotechnical studies on system stability*

Socio-technical studies do not make *a priori* assumptions on costs or the rationality of, and information available to, individuals and firms. These studies are less individualistic and instead studies ‘*situate technology and technological innovation in the social contexts in which they emerge*’ (Moloney et al., 2010). In a socio-technical framework, the decisions made by individuals and firms about material use and other manufacturing options are always shaped by their social, technical, political, cultural and economic settings. The process of designing, manufacturing and selling of cars, for example, is viewed as part of a wider system of automobility, comprising infrastructures, technologies, markets, practices and regulations that sustain vehicle manufacture and use (Urry, 2004). Rohracher (2001) explains that the socio-technical system that supports the construction, maintenance and habitation of buildings is more diffuse than for vehicle manufacturing and includes a larger variety of professions (e.g. architects, landlords, engineers, households etc). The efficiency of material use will be an outcome of the actions and decisions taken by individuals. These actions and decisions will be guided by features of a broader operating context. This includes technical regulations, institutional arrangements, actor-networks and culture. Geels (2012) explains that individuals operating within a socio-technical systems are guided by cognitive routines, habits and other heuristics. Geels and Kemp (2007) also outline that their actions will be shaped by sunk investments, contracts, standards and expectations. As a consequence, existing socio-technical systems tend to favour stability, repetition and inertia. This usually results in incremental change along predictable trajectories and may mean that alternative, significantly different approaches that could deliver a step-change in material efficiency are not adopted. A number of studies have explored sources of stability in the current automobility system but not with respect to material efficiency.

Geels (2012) proposes that sunk investments in road infrastructure, vested interests, a general preference for, and positive public discourse about, cars and legitimisation of the status quo by policymakers, industry and transport planners collectively explain the continued dominance of the car over other modes of transport. In a study examining stakeholders’ influence in the transition to more sustainable practices in industry, Orsato (2004) views vehicle designers and manufacturers as dominant actors within the automobility system. Wells and Nieuwenhuis (2012) consider the sociotechnical factors that enable vehicle designers and manufacturers to maintain the status quo. These

include: high sunk costs associated with vehicle design and manufacture creating barriers to transformative change; incremental rather than radical changes to vehicle design and manufacturing; internalisation of threats by securing supply of resources or disruptive technologies; replication of products and processes throughout the industry; a privileged position with policymakers and continued demand for car ownership and use. Orsato and Wells (2007) observe that the vehicle design and manufacturing process has remained fairly constant with business models that are mainly focused on generating revenues at the point of vehicle sale.

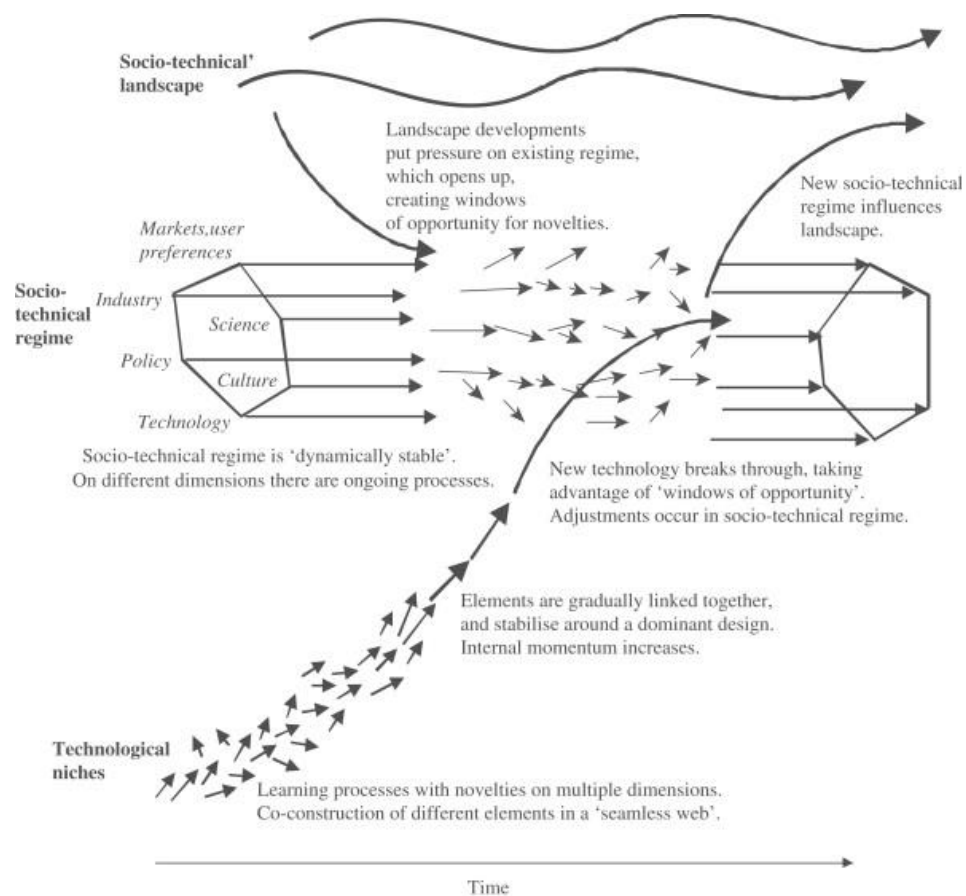
However, practices in the current automobility system have resulted in many negative environmental and social impacts. Car production contributes to resource depletion and GhG emissions. Car use creates air and noise pollution and imposes social costs such as congestion and accidents. Litman (2009) summarises a number of economic studies that quantitatively demonstrate that these environmental and social impacts are not always fully reflected in the private costs of driving a car. The negative impacts of car production and use have prompted researchers to consider what elements could feature in a more sustainable, low carbon system of automobility. Improvements in the efficiency of material use could potentially feature in an alternative, low carbon system of automobility, but this has received little attention in the literature to date.

Geels (2012) suggests an alternative and more sustainable socio-technical system of automobility could include non-fossil fuel-based powertrains, changes in car ownership and use or modal shifts away from the car. Dennis and Urry (2009) take this last suggestion further and investigate how a 'post-automobility' system might function. Wells and Xenias (2015) note that potential elements in a future, more sustainable system of automobility will each have different implications for the way that vehicles are produced, distributed, marketed, purchased, owned and used, with secondary impacts on material demand. Alternative powertrains, for example, require less change to the current vehicle design and manufacturing process and business models than a large-scale modal shift to walking, cycling or public transport. In an exploratory study, Orsato (2004) identifies that existing business models and organisational capabilities of vehicle manufacturers are key socio-technical factors that influence if and how the European automotive industry will become more sustainable. Steinhilber et al. (2013) explored why electric vehicles (EV), a potential feature in a low carbon automobility system, remained, at that time, a promising but unrealised technology in the UK and Germany. The authors examine the perspectives of different stakeholders involved in



supporting the manufacture and use of EVs. They conclude that at the time there were few policy incentives for consumers to shift away from internal combustion engines. For electricity providers, there was a lack of clarity on the ownership and expectations around managing vehicle charging infrastructure. Urban planners and policymakers needed to better understand how many EV charging points are required and where they are best located and align this with existing parking regulation. During interviews conducted for the study, vehicle designers and manufacturers also reported difficulties with securing funding for investment in research and development after the impacts of the financial crisis. This was viewed by the authors as problematic because of ongoing technical issues with vehicle batteries.

Other studies, not specific to automobility, have explored how a socio-technical system might change and to what extent that transition could be managed. The mechanisms of socio-technical systems change are explored in Geels (2002) using a multi-level perspective. As shown in Figure 2.2 socio-technical transitions can be explained using three distinct but interacting levels of analysis.



**Figure 2.2 A dynamic multi-level perspective on socio-technical transitions (Geels, 2002)**

The socio-technical system is situated at the meso-level. The rules that guides individuals and groups operating in the socio-technical system is referred to as a socio-technical regime. Established regimes are disrupted by ‘niche’ product, process or organisational innovations which exist at the micro-level. Established socio-technical regimes are also influenced and potentially disrupted by changes in the macro-level socio-technical landscape. Examples of macro-level pressures could include developments in demographic trends, political ideologies, societal values and economic patterns. The transition to a socio-technical new regime occurs when: a change at the landscape level destabilizes the current regime, an emerging niche innovation becomes mainstream and a new regime develops around this niche innovation. Within this multi-level framing, studies have discussed the extent to which a transition might be purposefully managed in favour of more sustainable pathways. Gillard et al. (2016) explain that early theorists viewed socio-technical systems as ‘unpredictable’ and ‘nonlinear’, raising the question of whether or not they could be purposefully governed. Studies such as Geels (2005) describe the mechanisms by which a socio-technical transition, from horse drawn carriage to automobiles, occurred but these and other ex-post reviews do not make any assertions around how to govern a transition ex-ante, within a specified timeframe or for a specified environmental goal such as climate change. More recently, there has been recognition that governance has some degree of influence over the characteristics of a socio-technical system. Transition management is described in Loorbach & Rotmans as the influence, coordination and bringing together of actors and activities so that they reinforce each other to compete with dominant actors and practices. Gillard et al. (2016) outline four types of governance activities that would constitute transitions management.

- Strategic - —envisioning of futures, pathways, and long-term goals
- Tactical—setting agendas through negotiating and coalition building
- Operational—experimenting with and implementing projects
- Reflexive—monitoring, evaluating and learning from feedback

However, the authors recognize the risk that the few individuals engaged in actively governing a transition would have a vested interest maintaining the status quo to some extent. This would lend credence to the observations made in Orsato (2004) and Wells and Nieuwenhuis (2012) that vehicle designers and manufacturers are the dominant stakeholder in the automobility system and for this reason it has changed little over the last 100 years.

and Nieuwenhuis (2012) that vehicle designers and manufacturers are the dominant stakeholder in the automobility system and for this reason it has changed little over the last 100 years.

Existing socio-technical studies identify many sources of stability and inertia that may inhibit the emergence of an alternative, more sustainable system of automobility. These studies also illustrate the importance of recognising that the action of individuals and firms will be guided by more than just cost considerations. While systems can and do transition, it is unclear whether they can be purposefully governed within the timeframes dictated by climate science.

### *2.2.3. Research plan*

This section has outlined two theoretical frameworks, techno-economic and socio-technical, which have been applied to explain non-adoption of more sustainable manufacturing practices, including material efficiency improvements. Socio-technical frameworks enable a more systemic perspective and unlike techno-economic studies do not impose the assumptions of perfect rationality and perfect information. Although Flacheneker and Rentschler (2014) state that these assumptions can act as a useful benchmark against which real market outcomes can be evaluated, they are unrealistic. Techno-economic studies also assume that the actions of individuals and firms are primarily guided by cost considerations. Evidence from existing socio-technical studies on stability in the automobility system brings this assumption into question. The decisions and actions taken by vehicle designers and manufacturers, key actors in the system, are shown to be guided by many features of the operating context in which they are embedded, not limited to cost considerations. A socio-technical framework is therefore considered more appropriate for investigating why there are unrealised opportunities for material efficiency improvements in UK industry at present.

Chapter 3 of this thesis aims to identify the socio-technical factors that are important in guiding the vehicle design and manufacturing process in the UK. Material throughput and the efficiency of material use can be understood as outcomes of this process. Interviews are conducted with stakeholders along the automotive supply chain and factors are identified using grounded theory. Quotes and secondary literature are used to verify and substantiate the selection and description of each factors. The identified

factors are then used as a conceptual framework to explain current trends in industry material throughput. Specifically, why there is an increase in average vehicle material intensity in Europe, the UK's main export market, and why vehicle throughput remains high. Section 2.1 of this thesis has demonstrated there is technical potential to reduce both, through lightweight design and longer life vehicles respectively. The motivation for this research is to better understand what guides the current approach to steel use in industry. However, since these are product-level strategies, the analysis is extended to all material inputs. The issue of how the transition to a more sustainable socio-technical system of automobility, that is more materially efficient, might be governed is not considered in this thesis. It is viewed as too speculative, however, areas for future efforts in this area are explored in Chapter 6.

## *2.3. Implications of the climate change policy agenda for material efficiency*

Section 2.2 detailed a number of barriers and sources of system stability, which may mean that, in the absence of government intervention, industry may underinvest in material efficiency initiatives. Policymakers may therefore be motivated to consider policies that encourage more efficient material production and use. Section 2.3.1 outlines key models in the public policy literature that attempt to explain when and under what conditions a policy agenda is formed. Section 2.3.2 summarises empirical studies that apply a specific model, the Multiple Streams Framework (MSF), to explain how different solutions become part of, or are omitted from, the policy agenda and policy mix to address climate change. Insights from these existing studies are used to inform the development of a detailed research plan, in Section 2.3.3, to answer the question:

**Q2:** *Why are so few material efficiency policies implemented in the UK?*

### *2.3.1. Models of the policymaking process*

Policy formation in the real world is complex. Sabatier (2007) explains that theoretical models of the policy process, including: the Stages Model, Punctuated Equilibrium Theory, the Advocacy Coalition Framework and the Multiple Streams Framework, help manage that complexity. In an introductory chapter comparing and contrasting these and other key models, the author emphasises that all models can help explain connections and causal mechanisms and overcome cognitive presuppositions that cause individuals to only recognise parts of the policymaking process.

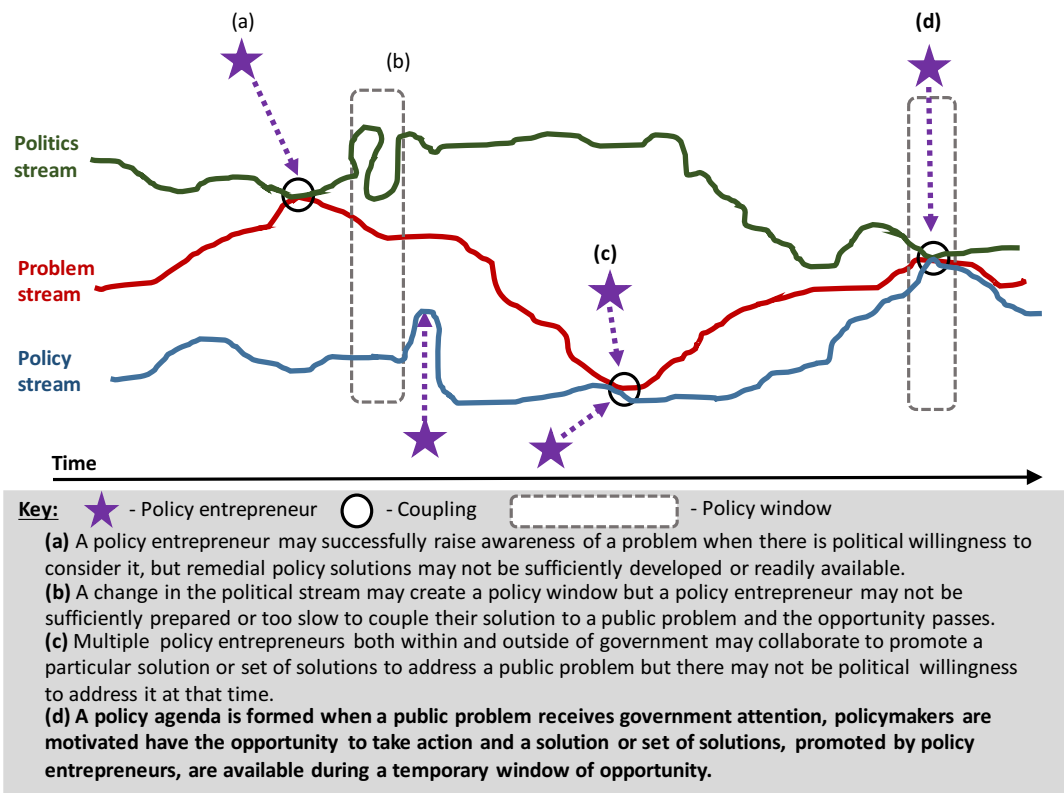
Although many public problems could be perceived, only a small number are given government attention. The set of solutions to these problems, which are discussed by institutions, the news media or the public at large, constitute the policy agenda (Birkland, 2010). Policymakers enact some of these solutions and this subset constitutes the policy mix. In the stylised ‘stages’ model of policymaking, with its origins in Lasswell (1956), problem definition and agenda-setting precede policy formation, implementation and evaluation. This process is iterative and non-linear as policy

evaluation prompts further consideration of how a public problem is defined. Sabatier (2007) outlines many academic criticisms of this model. These relate to a lack of causal mechanisms, inaccurate sequencing, omission of interactions between stages and general oversimplification of multiple, interacting cycles occurring at different levels of governance. In spite of these criticisms, the stages framework is still commonly used by policymakers in the UK. The Green Book (HMT, 2011), for example, is used by civil servants to appraise and evaluate policies in central government. The policy process is characterised in a similarly sequential, circular framework comprising: policy rationale; objective; appraisal; monitoring; evaluation and feedback.

Other models focus more on 'how', rather than at what stage in the policymaking process a policy agenda is established. Baumgartner & Jones (1993) present Punctuated Equilibrium Theory (PET) to show how information flows make issues rise and fall on the policy agenda, causing policymakers to reinforce or reconsider existing policies. Policymakers experience bounded rationality and work in organisations with similar capacity constraints. Policies usually change incrementally but, under certain conditions, decision-makers are compelled to, and have the cognitive and organisational capacity to, dramatically alter the policy agenda. The Advocacy Coalition Framework (ACF), presented in Sabatier & Jenkins-Smith (1993), also assumes individual working in policy organisations experience bounded rationality. In the ACF model, actors with similar policy beliefs form 'coalitions' to influence parts of the policymaking process. Conflicting coalitions interact, revising and refining their beliefs and eventually compromising to influence the policy agenda. The ACF and PET both focus on longer-term dynamics of policy stability and change. However, material efficiency appears to have steadfastly remained a small part of the global climate policy agenda for the last 20 years (ECOSOC, 1996; IPCC, 2014), which may mean these models are less applicable. The ACF and PET are also oriented around actors, institutions and their networks and interactions. An alternative explanatory model, which also explicitly considers the characteristics of a solution may therefore be preferable.

The Multiple Streams Framework (MSF) (Kingdon, 1995) explains how policymakers come to define and pay attention to some solutions, but not others. It consists of three largely independent metaphorical 'streams' of policies, problems and politics. In the 'problem stream' public issues are brought to policymakers' attention through

indicators, focusing events and feedback. Due to temporal, resource and cognitive constraints, Zaharariadis (2007) explains that a policymaker's ability to focus on a new problem will also depend on their existing problem 'load'. In the 'politics stream', internal government interests such as party ideology, and external drivers such as public opinion, social movements and interest group feedback motivate policymakers to consider particular problems and solutions. The 'policy stream' is a set of potential solutions to public problems. These come from a larger group of solutions which are debated, refined or discarded by a policy community. Solutions are more likely to become part of the policy agenda when they are technically feasible to implement, there is community consensus and solutions align with commonly held values. Policy entrepreneurs inside and outside of government attempt to couple their preferred solutions to a particular public problem. Entrepreneurs have increased chances of coupling their preferred solutions if they have access to policymakers, are well resourced and are strategic in their approach. Coupling occurs during occasional 'policy windows', when policymakers are more receptive to solutions. The solutions that are successfully coupled to a public problem form the policy agenda and, if enacted, become part of the policy mix. The MSF is viewed as appropriate for investigating policies that encourage more efficient material production and use, as it can also be used to examine why particular solutions are not given government attention - see (a), (b) and (c) in Figure 2.3.



**Figure 2.3: Schematic of the Multiple Streams Framework and scenarios in which a policy agenda may (d) or may not be formed (a, b, c).**



### *2.3.2. Application of the Multiple Streams Framework to the climate policy agenda.*

In a review of the empirical impact of the MSF, Cairney and Jones (2016) conclude that the metaphorical abstraction in the MSF's component parts make it universally applicable to any time and place. This abstraction, coupled with the multifaceted problems from climate change have produced a diverse literature base. Three categories of study are proposed, studies that: (1) focus on individual elements in the MSF; (2) provide an ex-post interpretation of the origins of climate policies and (3) investigate why particular solutions are not part of the climate policy mix.

#### *(1) Studies that focus on individual elements in the MSF*

Studies that fall in the first category focus on individual elements in the MSF such as 'entrepreneurship'. The literature base in this first category of study existing literature base provides some indication that the MSF may not be an exhaustive model of agenda setting. Hermansen (2015) examines how reduced deforestation was reframed as a solution to climate change in Norway and concludes that the MSF gives inadequate consideration to the role that policy entrepreneurs could play in problem framing and opening policy windows. Beeton and Stone (2012) also focus on entrepreneurship and show in an Australian case study that the MSF doesn't fully consider that the likelihood of an entrepreneur successfully coupling their preferred solution will also depend on the characteristics of the public problem. Climate change was identified as particularly contentious and this makes entrepreneurship more challenging. Following the recommendations in Zahariadis (2007), studies that fall in this first category often combine the MSF with other theories or quantitative techniques to increase its explanatory power. Buhr (2012) uses institutional theory to extend the MSF, showing institutional entrepreneurship also contributed to the expansion of the EU Emissions Trading Scheme to include aviation emissions. In an econometric study using survey data from 1400 US households, Krosnick et al. (2012) investigates the 'national mood' towards climate change in the USA. The authors demonstrate that, in addition to factors such as political rhetoric and media exposure, an individual's judgement on the seriousness of the issue will be shaped by their: understanding of the probable consequences; exposure to, and variety in, media messages; cognitive skills; trust in the source material and prior knowledge about climate change.

*(2) Studies that provide an ex-post interpretation of the origins of climate policies*

Other studies have applied the MSF to structure an ex-post discussion of the origins of a particular climate policy. Brunner (2008), for example, combines evidence from semi-structured interviews with document analysis to show how the problem of climate change was reframed as an opportunity for industrial reform in Germany. The author argues that this led to more stringent permit allocation in Phase II of the EU Emissions Trading Scheme. A common challenge in this second category of study is correctly identifying all of the relevant events and actions preceding a policy. There is also a risk that presuppositions create a bias when selecting evidence. Some studies, such as Keskitalo et al. (2012), have managed this risk by collating a large amount of primary data (94 interviews) and applying the MSF to compare adaptation policy outcomes in different European countries. Storch and Winkel (2013) also apply the MSF for comparative purposes at a regional level, showing that political conditions and public discourse around forest policy were more favourable in North Rhine Westphalia than Bavaria in Germany. Both Lorenzoni and Benson (2014) and Carter and Jacobs (2013) combine the MSF with other theoretical models to further substantiate their explanation as to what led to a change in UK political discourse on climate change between 2006-2010. This second type of study can also help to identify areas for further theoretical refinement or debate in the MSF. For example, in a case study on the origins of the Zero Emission Vehicle rule in California, Collantes and Sperling (2008) argue that the assumption of stream independence is oversimplified. They find that poor air quality in the problem stream shaped the politics stream and the policy response.

*(3) Studies that investigate why specific solutions aren't part of the climate policy mix.*

The third category of study apply the MSF to explain why particular problems or solutions are not a larger part of the climate policy agenda. Only three studies were identified in this category, each drawing different conclusions. Yusef et al. (2016) conclude that solutions to sea-level rise, due to climate change, are under-developed, under-funded and not proven as technically or financially feasible. Parag and Eyre (2010) focus more on politics and entrepreneurship to explain the lack of interest in personal carbon trading policies in the UK. They identify a lack of dedicated advocacy groups to build interest in the policy. They also suggest that personal carbon trading would force the public to confront their personal contribution to climate change and that

this may be viewed as politically unappealing. Hagerman et al. (2010) also consider entrepreneurship. The authors conduct semi-structured interviews, informal discussions and participant observation with biodiversity and climate change adaptation experts and conclude that a limited global joint conservation and climate policy agenda is partly attributable to experts' reluctance to challenge their commonly held values and beliefs, and the complexity and uncertainty surrounding the connections between the two issues. This section has shown that the MSF has been applied to diverse climate policy contexts. These existing studies either focus on individual elements in the MSF, provide an ex-post interpretation of the origins of climate policies or investigate why particular solutions are not part of the climate policy mix.

### *2.3.3. Research plan.*

The third category of study detailed in Section 2.3.2 shows that the MSF is an appropriate model for investigating why a particular solution to climate change, such as material efficiency, is not a large part of the policy agenda. A continued lack of policy attention towards material efficiency solutions in the UK is surprising. Intergovernmental organisations including the United Nations (ECOSOC, 1996), European Commission (2011) and International Energy Agency (2015) are proponents of material efficiency solutions. Furthermore, the country has committed to achieving long-term deep reductions in GhG emissions (CCA, 2008), which should prompt policymakers to consider all potential mitigation solutions. Section 1.5 of this thesis has also detailed a number of potential social, environmental and economic benefits from improved material efficiency, not limited to reduced GhG emissions. This should also motivate policy interest, particularly if market failures exist. The aim of Chapter 4 of this thesis is to investigate why material efficiency solutions are not a bigger part of the climate policy agenda in the UK. Demand for materials is derived from customers purchasing products, which deliver services. Policy initiatives aimed at incentivising material efficiency improvements may therefore need to be product-specific, reflecting differences in the way products are made, used and treated at the end of their life. Cars, which on average are principally comprised steel (ACC, 2015), are used as a case study. The MSF is applied to structure an evidenced explanation of why material efficiency solutions are currently a limited part of the UK policy agenda to reduce GHG emission from cars. Evidence from 13 semi-structured interviews, document analysis and academic studies is used to develop and substantiate the arguments made.

## *2.4. Macroeconomic impacts of improved material efficiency*

Chapter 2.1 outlined technical options to improve the efficiency of steel use throughout the lifecycle of products manufactured along the automotive and construction sector supply chains. Chapter 2.2 summarised studies that seek to explain why these initiatives are not implemented more widely in industry. Policymakers may intervene to incentivise the uptake of material efficiency opportunities in industry, as this could lead to a reduction in GhG emissions. Chapter 2.3 provided an overview of how and under what conditions climate policy agendas are formed. Prior to introducing a policy intervention, Her Majesty's Treasury (2013) advises that UK policymakers have some understanding of the probable macro-level impacts. Section 2.4.1 outlines existing studies which use economic models to evaluate the potential macroeconomic impacts of material efficiency improvements. Insights from these modelling studies are used to develop a research plan for Chapter 5 of this thesis. This plan, detailed in Section 2.4.2, responds to the research question:

**Q3:** *What would be the macroeconomic impacts of more efficient material use in the UK?*

### *2.4.1. Modelling the macroeconomic impacts of material efficiency improvements*

Possible macroeconomic consequences of greater material efficiency can include: changes in patterns of demand for intermediate and final products; changes in prices and demand for materials and material containing goods, resulting in both income and substitution effects and second order changes in patterns of demand including possible rebound effects. Economic models aim to capture the gross and net impacts of this redistribution on key macroeconomic variables including employment, trade flows and economic growth. A handful of papers have sought to estimate the macro-level impacts of material efficiency. These studies investigate different materials and material efficiency strategies, focus on different geographic regions and use models with differing assumptions. This section explores the contribution of each paper to inform the proposed research plan detailed in section 2.4.2.

Existing studies evaluating the macro-level impacts of material efficiency

Existing studies evaluating the macro-level impacts of material efficiency improvements have typically used either input-output or econometric macroeconomic models. Input-output models are a system of linear equations, which depict the distribution of an industry's product, both goods and services, throughout the economy, usually in monetary terms. Static input-output models provide a snapshot of monetary flows at a particular point in time while dynamic input-output models also incorporate demand for capital goods which accumulates as stock over multiple time periods. Econometric macroeconomic models apply econometric techniques to historical time series data to develop a set of behavioural assumptions of how different economic variables interact over the long and short term. Econometric macroeconomic models can also include environmental, energy and material extensions, which enables a quantitative investigation of the macro-level impacts resulting from improved material efficiency. A final modelling approach, which to date has been less commonly used for evaluating the macro-level impacts of material efficiency, is computer-generated equilibrium (CGE) modelling. These models simulate levels of supply, demand and price that support equilibrium across a specified set of markets (Wing, 2004). Winning et al. (2017) note that CGE models are often less disaggregated at the sectoral level and so may be less applicable if individual sectors or supply chains are the focus of investigation. Furthermore, solutions in CGE models are underpinned by three underlying assumptions of market clearance and zero profits and balanced income among the modelling agents.

Skelton and Allwood (2013) use a static input-output model to evaluate whether a policy intervention will provide a sufficient incentive for industry to implement material efficiency initiatives. The authors show a global carbon tax levied on GhG emissions arising from steel production is insufficient to incentivise switching from steel to labour. Labour and capital are both viewed inputs to production and the choice between using these different factors will be determined by the technical rate of substitution between them and their relative prices. The authors conclude that even in sectors where material efficiency improvements would lead to a reduction in steel costs, a global carbon price levied at £50/t provides little incentive to switch away from steel because labour is a larger share of total sector input costs and is made more expensive by labour taxes. This study demonstrates the importance of recognizing that the impact of any new policy intervention will be conditional on the current policy mix, particularly if the existing policy mix incentivises using material over other inputs to production. Potential

new material efficiency policies may therefore compete with, rather than complement, existing policies.

Static input-output models have also been used to identify which sectors could see the biggest GhG emissions reductions through material efficiency improvements. Barrett and Scott (2012) modify coefficients in an environmentally extended multi-region input-output (MRIO) model to characterize 13 different scenarios that would make the supply of, and demand for, materials and products in the UK more efficient. The authors do not investigate the potential economic impacts or the costs of implementation. However, their findings are useful for comparing carbon savings from material efficiency improvements with other supply-side technologies and energy efficiency initiatives. This comparison may help policymakers with prioritising efforts to decarbonize the UK economy. The authors find that of the 13 scenarios, reducing material inputs into production processes through lightweight design in packaging, structural metal products, buildings, electrical products, household goods and transport vehicles yields the biggest GhG emissions savings. However, these material efficiency initiatives could lead to a secondary rebound effect, which is not considered in the study.

The existence of a rebound effect, first identified in Jevons (1865), may mean efficiency improvements stimulate an increase in material consumption. Pfaff and Sartorius (2015) outline three types of rebound effects. First, there may be an income effect, whereby material efficiency improvements lead to a reduction in costs and an increase in income. This extra income may be spent on products and services which in turn increases demand for material inputs. Second, a reduction in material demand through efficiency improvements may lead to a reduction in the price of materials. Producers may choose to substitute other inputs for more materials, which have become relatively cheaper. Finally, there may be a growth effect. If investments in material efficiency improvements lead to positive impacts on Gross Domestic Product (GDP), firms and individuals in the economy will have more money to spend on goods and services, which comprise of material inputs. These are also referred to in the literature as accelerator effects. The existence of a rebound effect may dampen or even fully negate the intended reduction in GhG emissions via material efficiency improvements.

Pfaff and Sartorius (2015) use a static input-output model to estimate the economy-wide rebound effect, through all three mechanisms, of improving the efficiency of material use via 16 different initiatives in Germany. The weighted average rebound effects for all strategies are particularly large for steel. The income effect leads to a rebound in demand of +10% and the growth effect a further +8% rebound in demand for steel. The authors partly attribute this large rebound impact to the use of steel inputs in capital equipment to deliver efficiency savings. This study demonstrates that, without economic models, it would be challenging for policymakers to anticipate all the primary and secondary impacts associated with material efficiency improvements.

Walz (2011) also uses a static input-output model to examine the employment impacts of five material efficiency case studies in Germany, including longer life cars (30% increase in car lifespan and a 15% increase in costs) and increased car sharing leading to more intensive use (membership increases from 2.5% of the driver population to 10%). Both case studies lead to structural change in employment. There is a reduction in employment in basic metals and manufacturing sectors and an increase in the domestic service sector. Overall, these case studies both show a small net positive impact on domestic employment. The author qualifies this finding by explaining that many economic mechanisms are not fully captured in their chosen modelling approach. For example, the study doesn't consider income or accelerator effects because each case study only brings about a small change in monetary flows in the economy. Nor does the study consider any double dividend impacts because eco-tax reform is not modelled. The double dividend refers to the two potential benefit streams from environmental taxation. First from environmental improvements. Second, from using revenues from environmental taxes to reduce other taxes such as income taxes that distort labor supply and saving decisions. Although these economic mechanisms are not modelled, input-output models provide high levels of sectoral disaggregation which enables relatively detailed, bottom-up analyses for each individual material efficiency strategy.

Nathani (2009) combines a static material flows model with a dynamic MRIO model to analyse the economic impact of material efficiency scenarios in the paper sector in Germany. Combining these models requires the transfer of material flows into equivalent monetary units by multiplying it by base year prices collated from a number of industry and modelling sources. A key finding is that the net impacts on employment, energy use and exports are dependent on how foregone expenditure on paper is

reallocated to different sectors in the model as ‘compensation’. The modelling assumptions made by the author therefore have a significant impact on the results in the study and need to have a rigorous and credible basis.

A limitation of modelling studies that focus on individual strategies is that the insights may not be generalised beyond the case study under investigation. Evidence from bottom-up case studies show that the costs, material savings and labour required to implement a material efficiency initiative will often be sector and region-specific. For example, Table 2.5 summarises a selection of studies examining the net project costs for deconstruction, a precursor for material reuse, versus conventional demolition in different world regions. Estimates vary even within a region, reflecting the differences associated with labour productivity and costs associated with deconstructing, salvaging, reusing or disposing of materials across different building types and the availability of re-manufacturing and waste processing facilities. Estimates also vary between years and regions due to fluctuations in the price of virgin and scrap materials and labour.

**Table 2.5: Summary of studies estimating the net % change in project cost of deconstruction relative to demolition**

Study	Region	Building type	Net % change in project costs	
			Low	High
Coelho and De Brito (2011)	Lisbon, Portugal	Residential	-59%	+47%
Schultmann (2005).	Germany and France	Various	-66%	+69%
Dantana et al. (2005)	Massachusetts, USA	Residential	+25%	+46%
Guy and McLendon (2000)	Florida, USA	Residential	-10%	+20%

Some modelling studies have avoided the challenge of developing accurate scenarios for individual material efficiency strategies by making broader assumptions about the occurrence of material efficiency improvements. Meyer et al. (2007), for example, estimate that the total material requirement in Germany’s falls by 20% over 11 years through the provision of information and consulting services. The costs of information sharing and consultancy services are assumed to be equal to 1 year of material savings. The authors use an econometric macroeconomic model, with the assumptions of imperfect markets and bounded rationality, and find that domestic GDP and



employment both increase as a consequence of improved material efficiency. Distelkamp and Meyer (2014) similarly assume that improvements in the efficiency of resource use are achieved simultaneously in all 27 EU countries. The authors investigate the impact of a uniform 10% reduction in resource use for 30 input coefficients in a dynamic MRIO model. While this study is useful for providing a broad indication of the scale of impact from a systemic improvement in resource efficiency, the authors do not consider how this might occur (e.g. via policy intervention or technologies) or provide information on how the chosen level of improvement was selected. Broad assumptions about the scale of efficiency improvements are also made in a report by Cambridge Econometrics and Bio Intelligence Service (2014). In this report the authors use an econometric macroeconomic model to evaluate the impact of a range of resource productivity targets for the EU. A variety of macroeconomic variables are evaluated including the impacts on GDP, investment, trade, consumption, inflation and employment. A range of policy scenarios are modelled that could deliver resource efficiency improvements (e.g. publically or privately funded investments and market based policy instruments) and some consideration is given to the scale at which these targets could be achieved (e.g. for individual materials, countries or for the EU as a whole). However, the technical basis for selecting different policy scenarios and resource productivity targets and the amount of finance required to achieve them is again unclear.

Only one global CGE study was identified that explicitly investigated the economic impacts of altering steel production and use across different sectors of the economy. The ENGAGE-materials model (Winning et al., 2017) was developed with the aim of creating high sector resolution around the extraction, industrial and recycling sectors associated with different materials around the world. The model's development was guided by both technical (e.g. furnace type) and economic considerations (e.g. the common leveling of steel demand and per capita income known as the 'saturation' effect) to make the model as realistic as possible. The authors developed a policy scenario that saw a doubling of scrap availability in all regions by 2030. They conclude that the overall effects on GDP would be small and positive (as increases in secondary steel production would offset declines in primary production) and there would be a small decrease in GhG emissions. However, the authors emphasised that this was a preliminary study and outlined many ways in which the model could be adapted in the future to: capture more detail around the interactions of materials with other natural

other natural resource such as land and water and innovation from within sectors that might alter the efficiency of material use and demand. However, with this first model iteration, they signal the importance and opportunities from integrating disaggregated lifecycle material data into future CGE modelling exercises. The authors demonstrate that this is a limitation in the current modelling studies they review, including Bohringer & Rutherford (2015) and European Commission (2014). Given the nascence of material and sector disaggregation efforts for CGE models, a simpler higher resolution model might be preferable.

### *2.4.2. Research plan*

These existing modelling studies show that improvements in material efficiency may have positive macroeconomic impacts but that this might be negated by a rebound effect. The findings in each study partly reflect the chosen model and its underlying economic paradigm. The authors of these modelling studies also make further assumptions on the costs, mode of implementation and deployment rates of each material efficiency strategy. Greater transparency is needed on the process for developing the assumptions in these studies. This would enable policymakers to better and more simply evaluate the credibility and certainty of any modelling results prior to introducing policy interventions to improve material efficiency. The aim of Chapter 5 of this thesis is to present a detailed and transparent approach for developing material efficiency scenarios for use in input-output models. Two material efficiency case studies are developed for the UK: (1) reusing of steel sections in the construction sector and (2) increasing the number of car sharers. The technical basis for each case study is established through interviews with industry experts and a review of relevant industry and academic studies. The model data is also integrated with government-issued datasets grouped according to the same industrial classification system. The immediate, short-term employment impacts of increased deployment of these two material efficiency case studies are tested using a high resolution, static multi-region input-output model. Data on the price of steel products is collated from a number of sources to realistically translate monetary flows between sectors into physical flows in the model. This transparent, multi-method approach enables a discussion on the factors that contribute uncertainty and variability in the scenarios assumptions and results, which are distinguishable from those arising from the underlying model structure.

## *2.5 Responding to the broader research question*

### *2.5 Responding to the broader research question*

Section 1.5 of this thesis outlined a broader, overarching issue that this thesis seeks to address via the three research questions further detailed in this chapter. The issue of “How could good research ideas, from engineering or otherwise, be developed into strategies to encourage take up by industry practitioners and policymakers?” is unlikely to be fully resolved in this thesis but there are opportunities for interesting insights through the proposed interdisciplinary research. Khagram et al. (2010) explain that interdisciplinary research offers “the exciting promise of conceptual and practical advances resulting from the synergy of different perspectives and contributions”. In particular, this thesis will seek to reconcile the conclusions from existing positivist engineering studies with more interpretivist insights from research that draws on different paradigms from the social sciences, namely: socio-technical systems (chapter 3), theories of policymaking (chapter 4) and macroeconomic modelling (chapter 5). The research in this thesis will provide a clearer picture on the social, political and economic context in which policymakers and industry practitioners operate and reveal how they might prioritise and value information presented to them from engineering studies on material efficiency. The methods, evidence and communication of findings differ between positivist and interpretivist research philosophies and Chapter 6 will include some discussion on some of the challenges and opportunities for communicating effectively across disciplines and across stakeholders with the goal of delivering real world change.

Material efficiency as a solution to climate change is a relevant and urgent case study. Climate change is often described as a ‘wicked problem’, encompassing complexity and uncertainty at the intersection of science, economics, politics and human behaviour (Incropera, 2015). Interdisciplinary research could therefore help ensure that future promising engineering ideas are given appropriate attention by those tasked with coordinating and delivering climate change mitigation efforts.

# 3. Industry implementation of material efficiency

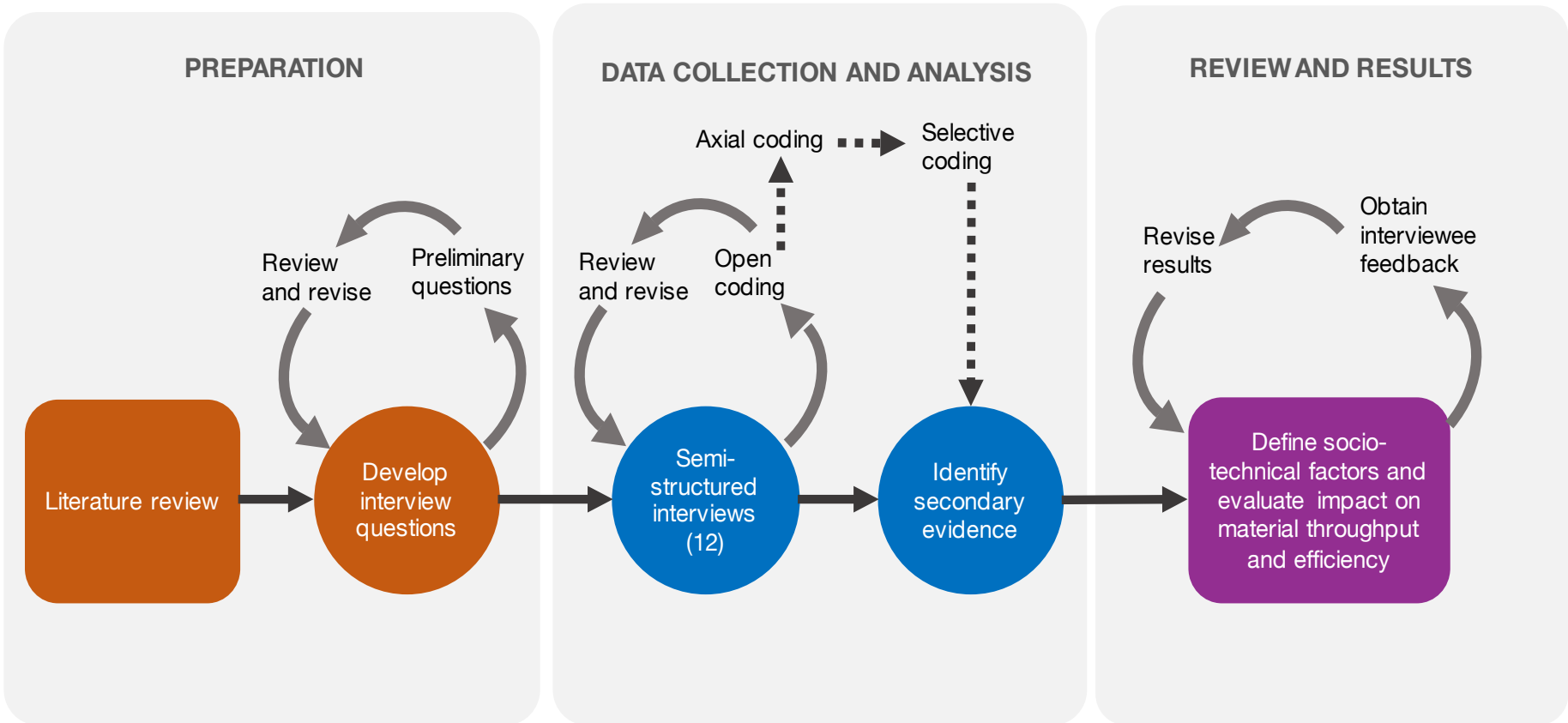
*The content of this chapter is based on a journal article published in the Journal of Cleaner Production. My co-authors Dr. Doody and Professor Allwood provided comments on draft versions of the article. Dr. Doody also provided advice on how to structure the open-ended interview questions detailed in Table 3.2. This Chapter responds to **Q1: Why are there unrealised opportunities to implement material efficiency improvements in the UK?***

The automotive industry is a large source of material demand. Wells, (2010) estimates that the global industry uses approximately 130Mt/y. In a Sankey diagram of global steel flows, Cullen et al. (2012) show that global production of cars generated demand for 88 Mt of steel in 2007, excluding any yield losses. The total amount of material throughput generated by the automotive industry will depend on how much material is embedded in each vehicle (material intensity), how many vehicles are sold (vehicle throughput) and any yield losses that occur during the manufacturing process. This chapter employs a socio-technical framework to investigate why material throughput remains high in the UK automotive industry when there are technical opportunities for material efficiency improvements. The efficiency of material use is an outcome of the vehicle design and manufacturing process. Drawing on industry interviews, supplemented by secondary literature sources, Section 3.2 outlines six interconnected factors that guide this process. Collectively, these factors can also be used to characterise the UK automotive industry's operating context. Section 3.3 employs these six factors as a conceptual framework to explain how current UK practices in designing and manufacturing vehicles are contributing to upward trends in vehicle material intensity and vehicle throughput. Insights from this chapter are summarised in Section 3.4. Understanding the factors that influence current patterns of material use can guide policy interventions and industry-led initiatives that aim to improve the efficiency of material use in the future. This is discussed further in Chapter 6 of the thesis.

### *3.1. Method*

Figure 3.1 provides an overview of the method employed in this Chapter. The research began by reviewing the socio-technical literature outlined in Section 2.2.2 of this thesis. Primary data was collected through interviews with industry stakeholders. Data collection and analysis, occurred concurrently and secondary evidence was sought to corroborate and refine the development of a grounded theory. This theory, presented in Section 3.2, outlines socio-technical factors that guide the UK vehicle design and manufacturing process. Section 3.3 details how individual factors are contributing to current levels of material throughput in the UK automotive industry.

In the engineering and technical studies outlined in Chapter 2.1, there is an implicit assumption that achieving the maximum technical potential for material efficiency is desirable. While this might be true from a climate change standpoint, there is no exploration of the subjective views of individuals and communities of actors who might have competing priorities or values. There are likely to be a host of reasons - logical, illogical, rational or irrational, conscious or unconscious - why individuals along the automotive supply chain may not be using material as efficiently as is technically possible. Structured interviews and dialogue can help elucidate these reasons. Once understood, they can be used to inform the design of more effective or targeted interventions that could support more efficient material use.



**Figure 3.1. Overview of method used in Chapter 3**

### 3.1.1. Description of method

A set of interview questions were developed after reviewing the socio-technical literature outlined in Section 2.2. The questions were designed with two aims. First to allow the interviewee to share their perspective and experience of designing and manufacturing vehicles. Second to reveal how different stakeholders involved in vehicle design and manufacturing process interact, and what guides these interactions. A preliminary interview was held with a former employee at a vehicle design and manufacturing plant. Following this preliminary interview, the questions were refined to clarify areas of misinterpretation. Thirty individuals were subsequently contacted and invited to participate in an interview. These individuals were selected because of their experience and expertise in designing and manufacturing cars in the UK and also because of their connections to the interviewer and university. It was challenging to select a truly representative sample of individuals across the entire automotive supply chain and snowballing and using personal contacts was viewed as a way of increasing response rates. Twelve of those contacted agreed to participate in the study (Table 3.1).

**Table 3.1: Chapter 3 - Interviewee expertise and experience**

Type of organisation	Years of experience	Expertise	Current role
Academia	20+	Business	Professor
High volume manufacturer	5	Engineering	Product developer
High volume manufacturer	5	Engineering	Product developer
High volume manufacturer	10	Engineering	Product manager
High volume manufacturer	20+	Engineering	Materials engineer
Industry association	20+	Engineering	Chief Executive Officer
Industry association	20+	Engineering	Research & development
Industry association	20+	Engineering	Chief Strategy Officer
Industry association	15	Social sciences	Deputy Chief Executive
Material manufacturer	15	Chemistry	Research & development
Low volume manufacturer	20+	Engineering	Chief Executive Officer
Low volume manufacturer	10	Engineering	Engineer

Interviews were semi-structured and conducted between January and March 2016 in person or via telephone. A list questions was tailored in advance of each interview to reflect each interviewee's expertise and experience (Table 3.2).

**Table 3.2: Pre-prepared list of questions used during interviews**

Personal industry background ( <i>All</i> )
How did you come to be working in your current role the automotive industry?
Designing and manufacturing vehicles ( <i>For automotive designers and manufacturers</i> )
Could tell me about the company's organisational structure?
Can you describe the working culture?
What role do different divisions have in designing and manufacturing a vehicle?
In your opinion, why do your customers choose your vehicles?
How are they different from your competitors?
What are your customer's main needs and requirements?
How do you incorporate customer feedback?
What is the process for specifying components and selecting suppliers?
How does the company take regulatory requirements into consideration during the vehicle design and manufacturing process?
( <i>For other interviewees</i> )
What role do you/your organisation have in the UK automotive industry?
How would you characterise your relationship with others in the industry?
How does your organisation work with automotive industry to design and manufacture vehicles?
UK automotive industry ( <i>For all</i> )
How would you characterise the current state of the UK automotive industry?
How has it changed over time? What factors have been important in shaping this change?
Are there any factors that could disrupt current practices in the UK automotive industry?
What scope is there to reduce the weight of vehicles further?
What factors enable or constrain the industry from reducing vehicle weight?

This list ensured topics perceived to be important were discussed within the allocated time-period, while also providing flexibility to pursue new lines of inquiry if, and when, they arose during the interview.

The interviews were transcribed verbatim and then analysed following the principles of grounded theory, an inductive method of theory development. In a definitive guide on the procedures for developing grounded theory Corbin and Strauss (1990) explain the aim is to develop a “*well-integrated set of concepts that provide a thorough theoretical explanation of social phenomena under study*”. The authors outline that a grounded theory approach is appropriate for investigating the conditions that contribute to a situation, how actors in a situation respond to changing conditions and the consequences of this. Grounded theory corresponds with a socio-technical framework in at least two ways. First, both do not make *a priori* assumptions about which factors might be important in explaining, for instance, why improvements in material efficiency are not realised. Second, both are attentive to the ways in which decisions and actions of



individuals and firms associated with material use are embedded in specific social, technical, political, cultural and economic settings.

Following the recommendations in Corbin and Strauss (1990), the transcripts were reviewed and interpreted for three different purposes. This exercise was done using Atlas.ti, a qualitative data analysis software programme. First, common themes were grouped together in categories (open coding). It was challenging to anticipate what would be relevant at the start of the study and there were repeated phases of open coding as each interview was conducted and each transcript was reviewed. A total of 23 categories were identified during open coding. The process of open coding finished when all data had been collected and all relevant parts of the transcripts were covered by existing codes. Some excerpts were ascribed to multiple categories. All text included in the 23 categories was then reviewed a second time to identify connections between themes, including correlations and directions of causality (axial coding). Boeije (2010) explains there are two primary purposes of axial coding. First to determine which categories are dominant and which are less important in explaining the phenomena under investigation and second to reduce and reorganise the data. The dominance and importance of each category was initially evaluated by reviewing the frequency and consistency of interview excerpts. These categories were then refined and condensed to the six socio-technical factors presented in Figure 3.2. The full transcripts were then reviewed a third time to identify any further insights or need for category refinement (selective coding). Each factor is detailed in Section 3.2. A mix of interview quotes and corroborating secondary evidence from industry and academic literature is used to develop a grounded theory of how each factor guides the vehicle design and manufacturing process in the UK.

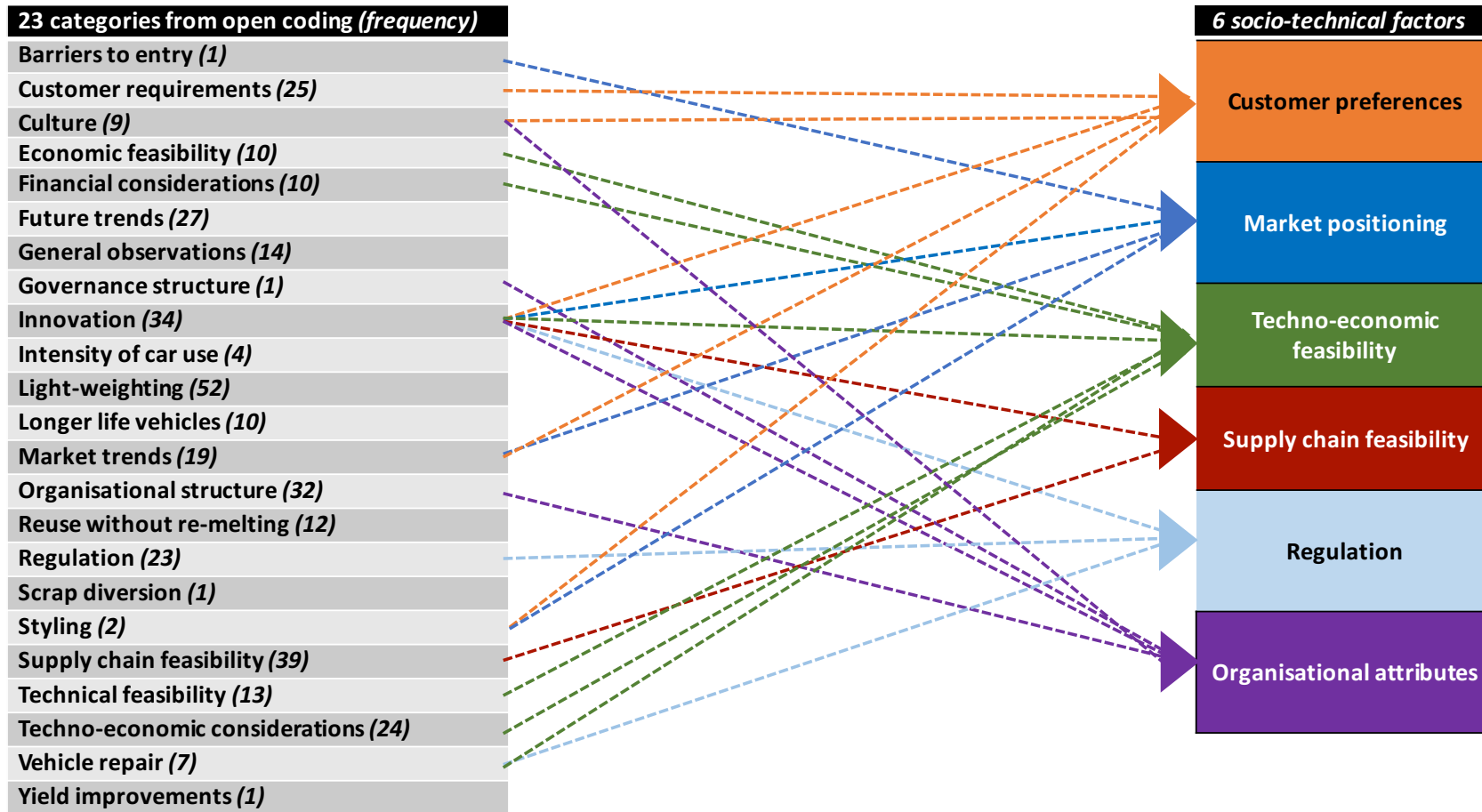


Figure 3.2. From open coding categories to six socio-technical factors

Industry material throughput and material efficiency can be understood as outcomes of the vehicle design and manufacturing process. Section 3.3 uses the six socio-technical factors detailed in Section 3.2 to structure a discussion on what is contributing to upward trends in vehicle material intensity and vehicle throughput in the UK when there is the technical potential to reduce both. Interview quotes and secondary sources of literature and data are used as evidence to inform and substantiate the arguments presented. All interviewees were invited to review and provide structured feedback on a draft summary of these two pieces of analysis. Five interviewees provided feedback and the content of Sections 3.2 and 3.3 was amended. A similar iterative approach is used in Delphi studies to ensure that interviewee responses are accurately characterised and to build consensus (Hsu and Sandford, 2007).

### *3.1.2. Research limitations*

The method shown in Figure 3.1 was designed to ensure accurate and valid results. However, there three main limitations, common to social research, which should be outlined as they influence how the results and discussion should be interpreted. First, some participants discussed commercially sensitive matters,, which were difficult to substantiate and anonymise. These were omitted from the analysis. Second, responses are considered to be representative but not exhaustive as only a sample of individuals were interviewed. Third, the study only reflects the current UK operating context, which limits the generalisability of the research findings. There are also a number of defining features of the UK automotive industry which mean that the operating context may be different for vehicle manufacturers located elsewhere. These include: national and local policies that influence car production; research collaboration between automotive supply chain and UK universities and a long industrial heritage. In the UK, there is also a unique mix of: ultra-luxury, racing, small volume specialist and large volume multinational vehicle manufacturers, which creates a similarly unique set of production capabilities and capacities in the automotive supply chain. Corbin & Strauss (1990) highlight that limited generalizability is a common challenge for studies in the ‘social realm’. A grounded theory can be verified but is difficult to apply exactly because of differing social contexts. Despite this, there is scope for the method to be replicated elsewhere, which would enable a comparison of different operating contexts.

## *3.2. Factors guiding the vehicle design & manufacturing process in the UK*

Following the principles of grounded theory detailed in Section 3.1., six distinct but interacting factors were identified that guide the process of designing and manufacturing vehicles in the UK. These are: (1) customer preferences, (2) market positioning, (3) techno-economic feasibility, (4) supply chain feasibility, (5) regulation and (6) organisational attributes. These factors influence the physical characteristics and volume of cars produced in the UK, which in turn determines total material throughput and the efficiency of material use. This section continues with a description of each of the six factors and explains its relevance in guiding the vehicle design and manufacturing process.

### *3.2.1. Customer preferences*

Customer preferences are shaped by a mixture of different wants and needs. Customer wants are assumed to coevolve with trends in the automotive industry (e.g. vehicle styling), while customer needs are independent of these trends (e.g. ageing driver population). Customer preferences will differ across countries, reflecting different driving and styling preferences, which means that a model sold in two different countries may have the same body structure but completely different interiors, vehicle performance and features. Vehicle designers and manufacturers will elicit feedback across all sales regions from both fleet and individual vehicle purchasers to account for these differences in customer preferences. Customer preferences are some of the earliest considerations in the vehicle development process. One interviewee indicated that at their company they “*start highlighting customer needs and wants about three or four years from the car entering the market*”. Vehicle designers and manufacturers will need to translate customer preferences into technical specifications. One interviewee used a hypothetical example to explain how this is done: “*Someone might say ‘I want a car that can do 0-60 in 4 seconds’... the OEM then starts to break that down into subsystem requirements...you might need to have a powertrain with **this** sort of break horse power, the weight of the car is going to have to be **this** many kilograms, we’ll probably need a gearbox and transmission that looks like **this**...*”. Customers may also be asked to provide feedback on early concept designs. Feedback, as one interviewee said, is typically elicited using qualitative research techniques with existing or potential

customers: “...we bring in a focus group of people and we’ll ask them about the current vehicle, what they like about it and what they don’t ... how they rate the current vehicle out of desirability, value for money, drivability”. The insights gathered through these and other forums provide a first proxy of demand and willingness-to-pay for different features. This enables the vehicle designer and manufacturer to approximate sales volumes and price ranges for new models.

### *3.2.2. Market positioning*

Vehicle manufacturers need to know what is currently available in the market so they can design and sell novel or improved vehicles. They will also consider areas of market growth. Vehicle manufacturers will elicit customer feedback on competitors’ products to understand which attributes to differentiate and which to replicate. One interviewee explained how this is observable in the marketplace: “You will have noticed within [the] automotive [industry] that there’s every type of vehicle body style you can imagine. That’s manufacturers trying to capture niches to have more market share”.

Complementary to product differentiation is brand differentiation. Porter (1985) explains in a seminal book on business strategy that together they can be a source of sustained competitive advantage. A number of interviewees discussed the competencies of different brands and how this is communicated and relates to different styling and technologies in vehicles. One interviewee observed brand differentiation in a single parent company: “Audi have the catchphrase ... ‘Vorsprung Durch Technik’... ‘progress through innovation’. VW has ‘Das Auto’... ‘the car’... VW is about moving people and personal mobility; Audi is about moving people in the most innovative way”. Another interviewee commented on how branding can influence the entire culture of designing and manufacturing vehicles: “[Company X] is a design company. Someone will draw a picture first. [Company Y] is an engineering company so they’ll come up with the engineering of what they want to do and they’ll make it pretty afterwards”. Vehicle designers and manufacturers will be guided by their company’s brand identity, which influences what features to differentiate and how.

### *3.2.3. Techno-economic feasibility*

Designing and manufacturing vehicles is expensive. From discussions with industry stakeholders Wells (2010) estimates that each new high volume vehicle manufacturing

plant costs an average US\$1,500 M and each new model generation approximately US\$1,000 M. New vehicles and component designs are only manufactured when they are considered to be both technologically and economically feasible. These two types of feasibility are evaluated together. As one interviewee said: *“So you sort of have to pick between the ultimate efficient thing for us to make, which only costs us £100 and what the customer wants. It’s usually a balance between finding what satisfies the customer requirements and what’s going to be feasible to manufacture”*. Technical feasibility relates to physically engineering a component in a particular way and ensuring its performance during prototyping and testing. Economic feasibility refers to the potential profitability of a design. This is dependent on costs and customer willingness-to-pay. Willingness-to-pay will in part be influenced by product and brand differentiation, while costs are more dependent on actions and decisions taken by a manufacturer. Interviewees discussed various cost reduction strategies used by the industry to improve the techno-economic feasibility of new designs and components. These included: achieving economies-of-scale via bulk purchases; shared and modular platforms; replicated features across models and reduced design time through iterative rather than radical changes to existing products. Therefore, the perceived techno-economic feasibility of a new vehicle design will also be dependent on existing models and brands. As one interviewee noted: *"most cars we’re developing are based off something we already have... it’s about what can be done for the greatest benefit without spending much money"*.

Techno-economic feasibility is not static. The prices of natural resources used as manufacturing inputs has been volatile in recent years due to increased demand and external factors such as the 2007-2009 financial crisis, which saw prices fall temporarily (Bleischwitz, 2010). If material manufacturers pass on higher costs to downstream vehicle manufacturers, component prices would also fluctuate, with implications for the profitability of automotive manufacturing. To illustrate, Cullen et al. (2012) shows that around half of the mass of steel used to manufacture vehicles is galvanised cold rolled coil (CRC). Data from steelbenchmarker.com shows that around the time of the financial crisis, global CRC prices reached a high of \$1250/t in the summer of 2008 before falling by around 60% to \$500/t the following year. Although this example is extreme and long-term supply contracts between the automotive supply chain and material suppliers might help to manage this volatility, when the average car contains around 900kg of steel (ACC, 2015) the steel price differentials would be significant. In

this illustrative case study, the cost difference would be around £675/vehicle – without factoring in the costs of shaping and forming the metal, or changes to the costs of other material inputs. The automotive industry could manage this somewhat by switching between materials or fixing the materials price well in advance of production but this may be constrained by technical feasibility and supply chain capabilities and capacity. Another option would be to vertically integrate up the supply chain to secure an independent source of raw materials - BMW for example owns Moses Lake, a carbon fibre production facility. However, this might be an expensive undertaking given the size and longevity of mining and manufacturing assets. In the short-term, car manufacturers may look to pass on additional material costs to downstream customers but this may risk losing market share if competitors do not follow suit.

Emerging technological innovations and trends will also influence the techno-economic feasibility of a new design. Interviewees discussed new component production processes, alternative powertrains and autonomous vehicles as promising future technologies for the sector. As technologies mature and diffuse, learning and economies of scale can accumulate and there is the potential for costs to fall. Interview quotes show that vehicle designers and manufacturers jointly consider the technical and economic feasibility of a new component or product design. This builds the business case to opt for one design and manufacturing process over another.

### *3.2.4. Supply chain feasibility*

Vehicle manufacturers will either produce or buy the thousands of individual parts that make up a car. Supply chain feasibility relates to whether the materials for internally made components, or purchased finished parts, can be designed, manufactured and delivered at cost and to schedule. It became apparent from the interviews that each company will have its own supplier selection process. However, desirable supplier attributes which were commonly discussed included: reliability, flexibility, capacity, capability, delivery performance and cost effectiveness. Important product attributes related to cost, quality and durability alongside a range of other criteria. One interviewee said: *“Typically a company will have 30-40 criteria...The front end of that is definitely technical. ‘Can we build using this material?’, ‘What’s the effect on the production system?’ ... But all the way down here you’ve got a whole bunch of other issues”*. The supply chain works together to design and manufacture component parts.

This requires significant forward planning by vehicle manufacturers, as selecting suppliers and specifying and testing a product takes time. There is often close and longstanding collaboration between suppliers and component purchasers. Existing working relationships is therefore another important consideration when selecting suppliers. One interviewee suggested in the UK: “*A lot of the OEMs [Original Equipment Manufacturers] have fairly sophisticated purchasing [processes] ...They know the guys and girls out there. It’s fairly mature.*” There is also some degree of supplier lock-in because, as discussed in Section 3.2.3 components are often shared across models and platforms as a way of increasing economies-of-scale and reducing costs.

### *3.2.5. Regulation*

Manufacturers need to ensure vehicles and their component parts meet a range of different hard, soft and self-imposed regulatory requirements. These requirements include safety (e.g. crash performance) and environmental regulation (e.g. tailpipe GhG emissions, the use of hazardous material, air pollution, noise), as well as more functional whole-vehicle attributes such as speed, drivability and style. This creates a complex process of testing and approval. To illustrate, one interviewee remarked: “*I had 300 regulations and requirements and rules to go through...with my one small component ... Some say you have to test it in a lab ... some require results to be sent off to a certification body ... others are kept within the company*”. ‘Soft’ regulation includes codes of conduct and guidelines and may come from industry bodies. For example, EuroNCAP (2016), a voluntary safety performance assessment program backed by the European Commission, was frequently mentioned during interviews. One interviewee observed that one of the major brand’s new model ‘*got 4 stars*’ on this assessment and ‘*they were gutted*’. Another explained that there was an industry-wide perception that ‘*if you’re not competitive with your EuroNCAP score you won’t sell vehicles*’. Self-imposed regulation comes from standards and established production processes set internally in a company.

### *3.2.6. Organisational attributes*

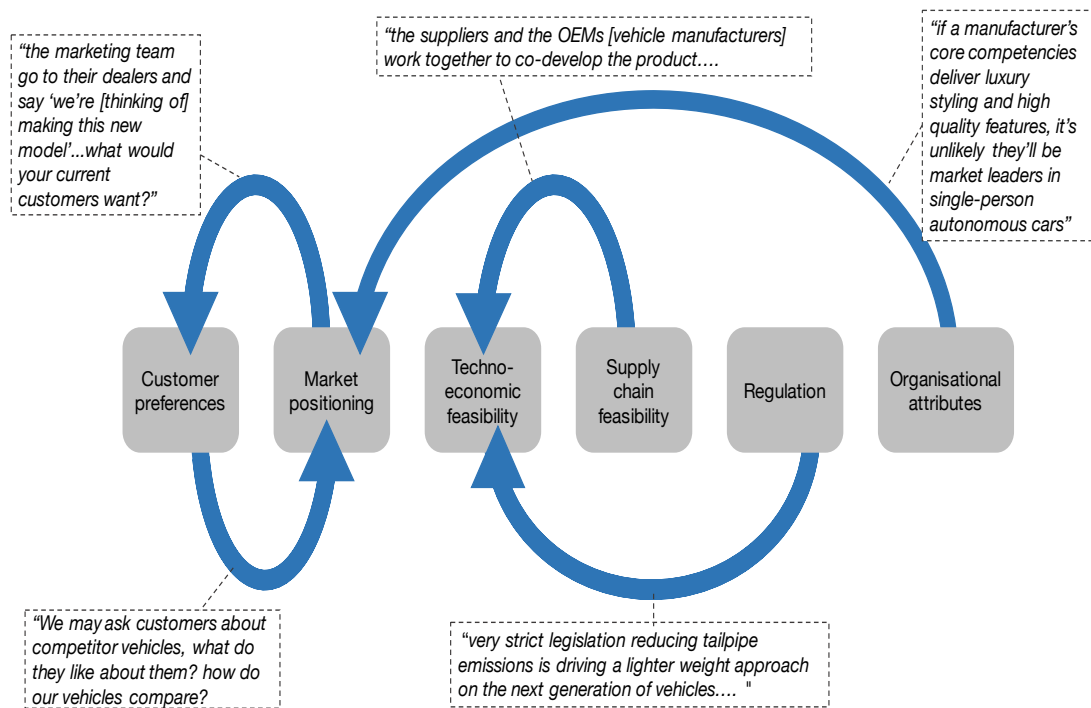
Individuals will be strongly influenced by their organisation’s governance structures, institutional memory and other features of the context in which they operate. Multidisciplinary vehicle design teams balance top-down strategic guidance on material



choice (e.g. aluminium versus steel body) and technical constraints (e.g. platform choices) with bottom-up techno-economic and supply chain considerations. As one interviewee noted this often gives rise to ‘*very, very complicated*’ governance structures which staff often ‘*don’t fully understand*’. Vehicle manufacturers will build expertise and experience over time as a way of managing product and process complexity. This institutional memory may relate to vehicle testing, component design or previous experience with suppliers. Organisational attributes relate to company culture, structure and relationships and interactions between individuals throughout the supply chain. These contribute to the formation of routines, habits and other heuristics which guide the vehicle design and manufacturing process.

### *3.2.7 Connections between factors*

These six factors are distinct but not independent. The factors interact and influence each other. For example, Nieuwenhuis (2014) proposes that regulation has partly driven innovation in alternative powertrains and the inclusion of lightweight materials. Innovation, and the investment it requires in personnel and manufacturing technologies, can change the techno-economic feasibility of a technology, production process, vehicle idea or component design. In the UK, vehicle and designers can be involved in shaping innovation priorities through the Automotive Council, a platform to strengthen dialogue and cooperation between the UK government and automotive industry. This example highlights that vehicle designers and manufacturers interact with a network of actors in a broader socio-technical system that they also help to shape. Figure 3.3 uses interview quotes to provide further examples of the ways in which these factors are interconnected.



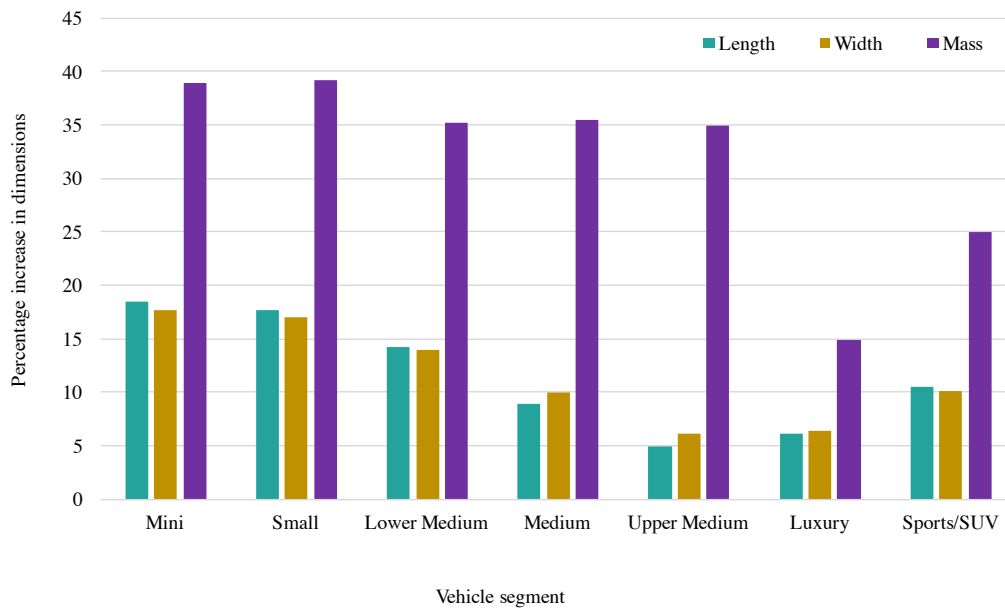
**Figure 3.3: Interview quotes illustrating some connections between factors**

### *3.3. Implications for current levels of material throughput in the UK automotive industry*

Materials are physical inputs to the vehicle design and manufacturing process. Section 3.2 has shown this process is guided by six connected socio-technical factors. This section examines how these six factors are contributing to current levels of material throughput in the UK automotive industry and why opportunities for material efficiency improvements may not be realised. Total material throughput along the automotive supply chain will depend on vehicle material intensity (Section 3.3.1) and vehicle throughput (Section 3.3.2).

#### *3.3.1. Vehicle material intensity*

Material intensity depends on a vehicle's size and the amount of material embedded in it. In Europe, the UK's main export market (SMMT, 2016), the average material intensity of vehicles appears to have grown since 2001 (Figure 3.4). Cars have become larger in size and heavier across all vehicle segments.



**Figure 3.4: Percentage increase in average EU vehicle dimensions by segment between the years 2001 and 2014 (ICCT, 2016)**

In a review of average vehicle weight and dimensions in Europe, Zervas (2010) partly attributes this increase to the introduction of new additional features and designs that aim to improve comfort, safety, security and emissions control. The introduction of these features has more than offset any weight reductions from changing the component designs or switching to lighter materials. The six socio-technical factors help structure an explanation on why this is occurring.

As the UK and European population ages, their needs change. This could be leading to increases in vehicle sizes. One interviewee surmised “*we’ve seen car doors get bigger, seat heights getting taller ... because they’re [vehicles] easy to get in and out of if you’re old*”. Wells & Xenias (2015) already noted that an ageing driver population impacts the design of vehicle features. They characterize innovations such as parking sensors and collision avoidance systems as “*enablers of continued motorisation for the elderly*”. Evolving customer wants are also driving increases in vehicle material intensity. As, one interviewee observed “*what car makers have been doing for years is shave out the steel and add in something the customer wants*”. Interviews revealed that these ‘wants’ may relate to specific features such as “*electric seats... which add 20kg*” or they may be more abstract and open to interpretation. Interviewees spoke of designing vehicles that offered “*comfort*”, “*compatibility with customer lifestyles*”,

*“desirability” and “drivability”*. Delivering these attributes could drive increases in vehicle weight or size. The interviews provided anecdotal evidence of this. One vehicle manufacturer suggested engine sizes are larger than necessary because *“customers like the feeling of having surplus power”*. Another explained that the boot size is designed with *“suitcases and golf clubs”* in mind to reflect their customers’ lifestyle. Advances in the mechanical performance of vehicles mean designers and manufacturers are placing more emphasis on ergonomic and aesthetic characteristics. You et al., (2006) show that these can create an affective response among new car purchasers. Once this response is established, it may be challenging to alter. When asked about the scope for reducing vehicle weight, one interviewee explained that the *‘nice-to-haves’* could be dropped, but as a consequence, *‘customer satisfaction would drop because they’ve become accustomed to having extra features’*.

Vehicle manufacturers may also be reluctant to drop these ‘nice-to-haves’ because of increasing market competition. Wells (2010) shows that between 1994 and 2009 there was a threefold increase in the number of model variants available on sale in the UK. When describing the process for selecting features, one manufacturer explained that *“[my company], basically end[s] up with a big table saying ‘feature x, y, z’, ... doesn’t matter how much it costs, we have to have it because our competitors have it and all the customers want it”*. This response to customer feedback means that new features, which can add weight, may be replicated throughout the industry. Feature replication may also occur for cost saving reasons as it can lead to economies-of-scale. As one interviewee suggested, *“They [vehicle manufacturers] are more likely to spend money on a feature or platform if it can be used across a range of vehicles”*.

There are opportunities to reduce vehicle material intensity during the manufacturing process through lightweight design and materials. Although this is technically feasible, interviewees indicated that optimising the material intensity of each new car model would be prohibitively costly. Reducing vehicle weight through optimised design requires more time, which means additional costs and reducing purchasing economies-of-scale if component designs are not transferable across models. Cost considerations also influence material selection. For one interviewee, this meant achieving *“the right balance of cost, weight, formability...”*. Lighter materials have tended to be more expensive to date as they either undergo more processing or are produced on a smaller scale via costlier production processes. To illustrate, carbon fibre can be used in

structural parts of the vehicle such as the frame, hood or tailgates and is 50% lighter than steel but in 2012 was around 570% more expensive (McKinsey, 2012). This price differential explains why carbon fibre and other lightweight materials such as aluminium are used more by luxury vehicle brands (e.g. Jaguar and BMW), who can pass on these costs via higher vehicle prices. As a result, there has been a smaller percentage increase in average weight among luxury vehicles (Figure 3.4).

When purchasing component parts from the wider automotive supply chain, vehicle designers and manufacturers could specify lightweight design and materials but this will be constrained by supply chain capabilities. These were judged to be ‘*weak*’ in a report by Holweg et al. (2013) for the UK Automotive Council, a public-private forum aimed at improving the sector’s competitiveness. One interviewee shared a recent experience whereby “*we said ‘yeah that’s easy’... then it came out that no supplier had the equipment to do it, or they wanted to charge us thousands of pounds per piece. So we had to use a less ideal choice because of supplier capability*”. A heavier design may therefore be selected if weight is superseded by more critical supplier or product attributes.

Opportunities to reduce the material intensity of a vehicle also remain unrealized due to vehicle manufacturers’ organizational attributes. Interviews revealed it may be less risky to modify, test and incrementally reduce the weight of existing vehicle and component designs, which could disadvantage more radical lightweight designs. One interviewee explained for them, there were “[*personal*] risks to a new [*lightweight*] design being wrong...having to do it again or spending lots of money to fix it” which contributed to their opinion that “*there’s no point in doing something completely different when you know that something works already*’. A complex approval process may also disadvantage radical lightweight designs. For one interviewee, approval was needed from, “*my manager, then my manager’s manager and then to my counterpart abroad and then to his manager*”. Many individuals with different organisational priorities would need to be convinced of the merits of radically different designs over existing ones. As a consequence, vehicle manufacturers tend to focus on optimising existing designs rather than starting with a blank piece of paper and considering what might be most materially efficient approach.

### 3.3.2. *Vehicle throughput*

Vehicle throughput in the global automotive industry is also growing. Nearly 100M cars and commercial vehicles were manufactured in 2015, almost double the output in 1997 (OICA, 2016), to meet growing demand for personal mobility. In more mature markets, such as the EU where the stock of vehicles is stable (Eurostat, 2016), demand is also for replacement vehicles. Vehicle production in the UK automotive industry is increasing (ICCT, 2016), to meet both types of demand.

Techno-economic factors and longstanding organisational attributes encourage high vehicle throughput. The large size of sunk investments in the automotive industry means plants are most profitable when they operate close to full capacity to experience economies-of-scale. One interviewee speculated that “[*manufacturing plants*] need to run at [*at least*] 85% capacity or they’re not making money, as a ballpark”. The UK automotive industry has over a hundred years of experience in designing and mass manufacturing vehicles and deriving revenues at the point of sale. Even luxury vehicle manufacturers based in the UK are manufacturing thousands of customised built-to-order vehicles per annum. Interviewees referred to this process as ‘*advanced*’, ‘*optimised*’ and ‘*based on volume*’. Reorientation to alternative business models and forms of value capture based around lower vehicle throughput requires complex organisational change and may be perceived as riskier, as the potential profitability is less well understood. In spite of these risks, the industry is beginning to explore alternative business models to supplement revenue from vehicle sales. Both Ford and BMW recently launched car sharing initiatives in the UK, where drivers pay for vehicle access. If all cars were shared rather than owned, there could be a reduction in vehicle throughput. In 2015 however, there were only 4,200 car sharing vehicles in the UK (Steer Davis Gleave, 2016). By comparison, the UK automotive industry manufactured 1.5M vehicles in 2015 (SMMT, 2016), demonstrating the continued dominance of a business model focused on high vehicle throughput.

Vehicle throughput also depends on how long a car is kept in use. Demand for new cars would fall if the existing fleet of vehicles were kept for longer. Although customers will choose when to retire their current vehicle, or make the decision to purchase a new vehicle for the first time, these decisions can be influenced by vehicle manufacturers. Following a review of a number of industry and academic studies, Nieuwenhuis (2014)

concludes that many vehicles have a shorter lifespan than is technically possible. The interviews in this Chapter revealed that this may be partly due to an industry focus on the preferences of the first customer. However, the design of a vehicle and its components will influence lifecycle operational and repair costs. One interviewee observed that *“the things that are surprise and delight for a new car buyer are usually shock and disappointment for a used car buyer. They break and cost a fortune to fix”*. This assertion is supported by anecdotal evidence in automotive trade publications such as Fleetnews (2014) and Allen (2010), that as vehicles become filled with more complex electronic features, they become costlier to repair. It can also be difficult and costly to get replacement components for older vehicles as improved product designs and production processes become techno-economically feasible over time. To illustrate, one interviewee discussed how much seats have changed over the last 30 years, *“When we looked at the base of the (1980s) seat... even the ergonomics had completely changed.... It looked unrecognisable, like a metal bench... [it] wouldn't give you the level of performance and comfort and safety you get with a modern seat”*. Older components may therefore be incompatible with newer replacement parts which could also increase the cost of repair relative to the value of the vehicle which may favour scrapping.

### *3.4. Discussion*

To recall, the question outlined at the beginning of this chapter was:

*Q1: Why are there unrealised opportunities to implement material efficiency improvements in UK industry?*

This chapter has shown that that material demand and the efficiency of material use in the UK automotive industry are outcomes of a complex, advanced design and manufacturing process, involving thousands of individuals in international supply chains with long established routines, experience and relationships. Any initiatives seeking to improve the efficiency of material use are unlikely to be successful if only the technical potential is understood.

Although it would be technically possible to reduce the material intensity of a vehicle, many features relating to vehicle designers and manufacturers' operating environment may prevent them from realising this opportunity:

- Increased market competition has created pressure to design and manufacture new vehicles that meet evolving customer preferences, which can include novel features or larger vehicle dimensions that can add to the vehicle weight, or else risk losing sales to competitors.
- A modern car comprises thousands of individually designed and manufactured component parts which are produced in a complex, international supply chains. While it may be technically possible to minimise the weight of each component part for each model, this would increase the manufacturing complexity and cost as: more design time would be required, lighter materials tend to be more expensive and could result in smaller economies of scale. The industry may view this model-specific approach to weight minimisation as prohibitively costly, particularly for lower priced vehicles. However, if this study was repeated at a time of high material prices, as seen in the summer of 2007 for steel, improving the efficiency with which material is used could become another strategy to maintain profitability along the automotive supply chain. At the time this study was conducted, supply chain capabilities and capacity were also identified as a potential constraint to the development of more materially efficient component designs. Component size or weight will be evaluated as part of a range of product and supplier attributes.
- Individual working in the automotive industry may have little incentive to deviate from existing routines and practices. Perceived personal risk and complex organisational structures can disadvantage more novel lightweight designs. New component designs are routinely based on existing ones, which usually only results in marginal changes to the material intensity of vehicles and their component parts.

Keeping vehicles for longer is another potential material efficiency opportunity and vehicle longevity is in part influenced by the actions and decisions taken by designers and manufacturers. Two broad reasons have been identified in this chapter that indicate these actions and decisions may not be aligned with longer life vehicles:



- Vehicle features are added that appeal to new car buyers. However, as vehicles become filled more electronics and equipment, the cost of repairs increases. When the repair-to-value ratio is sufficiently high, the vehicle is usually scrapped.
- High sunk costs, longstanding experience and expertise in high volume manufacturing and sales and highly complex organisational structures may make it challenging for vehicle designers and manufacturers to reorient to new business models based on lower vehicle sales.

Chapter 6 of this thesis builds on the insights presented in this Chapter. A number of suggestions are offered on how the automotive industry's operating context could be purposefully altered, either through policy or industry-led interventions, with a view to improving the efficiency with which material is used. Further academic research, which would support this transition is also outlined.

## 4. A material efficiency policy agenda

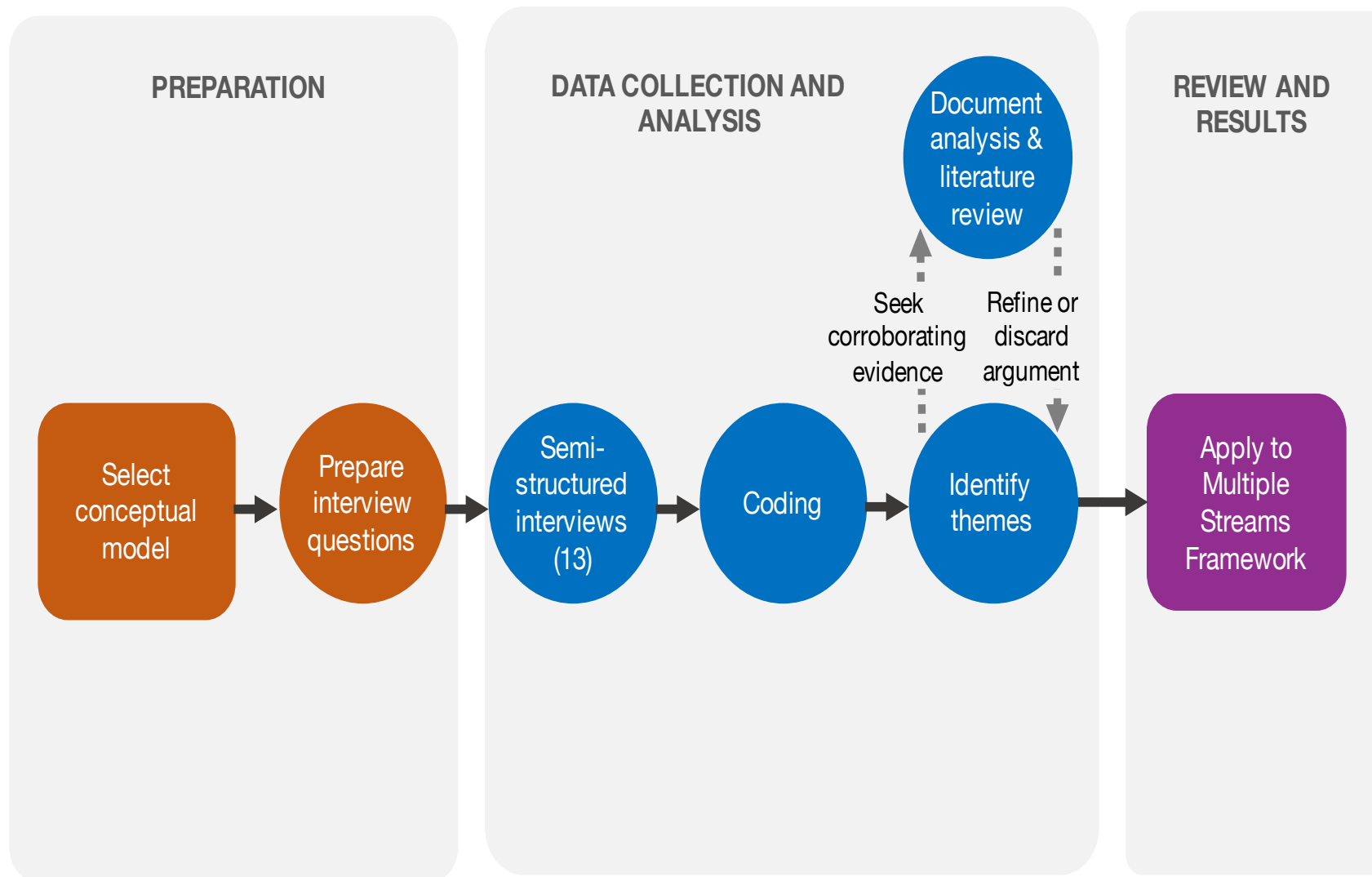
*The content of this chapter is based on a journal article in print by Environmental Policy and Governance. My co-authors Dr. Livesey and Professor Allwood provided comments on draft versions of the article. This Chapter responds to **Q2: Why have there been so few material efficiency policies implemented in the UK?***

Many mitigation policies have been instigated in the UK and the rest of the world, to reduce lifecycle GhG emissions from cars. However, material efficiency remains a limited part of the UK policy agenda and policy mix. The purpose of this chapter is to explore why this is the case. To recall, Birkland (2010) describes a policy agenda as the set of potential solutions to public problems that are discussed by institutions, the news media or the public at large. Some of these solutions will be enacted by policymakers to form a policy mix. Interviews were conducted with 13 individuals involved in shaping the UK policy agenda to reduce GhG emissions from cars in the UK. From these interviews, key features of the current UK policy mix are identified. Interview insights, supplemented by document analysis and a literature review, are also used to develop an evidenced explanation of why material efficiency is a currently a limited part of the UK policy agenda to reduce GhG emissions from cars (Section 4.2). This discussion is structured around the Multiple Streams Framework and its main component parts (Kingdon, 1995). The aim of this research is to provide new perspectives on how the policy agenda for materials efficiency has evolved. Section 4.3 summarises the key insights from this chapter. Chapter 6 of this thesis builds on these insights and outlines a number of actions for academic research and policy entrepreneurship that could mean material efficiency solutions are considered in a future policy mix.

## *4.1. Method*

A summary of the method is presented in Figure 4.1. A qualitative mixed method approach was employed following the precedent set in the majority of studies detailed in Section 2.3.3. The study method included semi-structured interviews and document analysis. Interviews were required to gather evidence that is not currently published elsewhere. These interview insights were triangulated with other sources of secondary data to develop, refine and substantiate the discussion presented in Section 4.3. This discussion is structured around the component parts of the Multiple Streams Framework (Kingdon, 1995).

The chosen qualitative approach is considered suitable for this exploratory study as it provides flexibility to identify multiple-interactive processes that shape the current UK policy and political context. Furthermore, it may be challenging to operationalize the MSF components using measurable, quantitative variables. The chosen topic of study complements and supports the engineering research outlined in Allwood and Cullen (2012). While it is useful for policymakers to know that there is technical potential to improve the efficiency of material use and this will have an impact on upstream GHG emissions, this information would need to be communicated and understood in a way that resonates with their operational and departmental priorities. The chosen framework, the MSF, also enables an exploration around how entrepreneurship and timing would help or hinder engineering solutions rise to prominence.



*Figure 4.1: Overview of method used in Chapter 4.*

### 4.1.1. Description of method

Twenty-one individuals shaping UK policies to reduce GhG emissions from cars were invited to participate in semi-structured interviews. Thirteen agreed to participate and were interviewed between May–September 2016 (Table 4.1). Interviews lasted between 30–60 minutes. Some interviewees were from the same organisation. Individuals from Transport & Environment, WRAP and the Ellen MacArthur Foundation were invited to interview because public sector interviewees indicated their understanding of material efficiency solutions and GhG emissions reduction opportunities related to cars were informed by the work of these organisations, though not exclusively.

**Table 4.1: Chapter 4 - Interviewees’ place of work**

Name of Organisation	Roles and responsibilities in UK policymaking
<b>Her Majesty’s Treasury</b>	Economics and finance ministry. Coordinates and allocates public spending between department - including grants for ultra low emissions vehicles (ULEVs), setting tax policy - including road tax. Aims to ensure government spending delivers value for money and achieves long-term sustainability objectives.
<b>Department of Business, Energy &amp; Industrial Strategy*</b>	Ministry brings together responsibilities for business, industrial strategy, science, innovation, energy, and climate change. Responsible for the UK's industrial strategy including ambitions for automotive supply chain decarbonisation and long-term competitiveness. Collates and publishes data on domestic GhG emissions (production-based accounting)
<b>Department of Environment, Food &amp; Rural Affairs</b>	Ministry responsible for safeguarding the UK's natural environment. Broad policy remit including: treatment of end-of-life vehicles, local air quality, resource efficiency and the circular economy. Collates and publishes data on GhG emissions embodied in goods and services purchased in the UK (consumption-based accounting).
<b>Office for Low Emissions Vehicles</b>	Cross-ministerial team providing research and investment support for ULEVs. Responsible for encouraging new business initiatives, supporting manufacturing capacity

building and developing charging infrastructure strategy for ULEVs.

<b>The Committee on Climate Change</b>	Independent body advising the government on how to meet the 2050 carbon target and interim carbon budgets. Monitors the UK's progress in reducing domestic emissions and conducts economic and policy analysis.
<b>Innovate UK</b>	National innovation agency. Runs frequent competitions for funding. Works with OLEV and the Advanced Propulsion Centre to deliver public sector financing for product, process and business model innovation in the automotive sector.
<b>Transport &amp; Environment</b>	Brussels-based NGO promoting sustainable development in transport through research, debate and campaigns. Recently campaigned to revisit GhG emissions testing procedures in the European automotive industry and pushed for policies that support the uptake of electric vehicles.
<b>Ellen MacArthur Foundation</b>	UK-based NGO working to promote a circular economy agenda among government, business and academia.
<b>WRAP</b>	UK- based NGO working with government, businesses and communities to deliver practical solutions to improve resource efficiency.

*\* During the interview period the Department of Energy and Climate Change merged with the Department of Business, Innovation and Skills to form the Department of Business, Energy and Industrial Strategy.*

An initial set of open-ended questions were prepared in advance of all the interviews to ensure important topics were covered (Table 4.2). These were informed by the questions used in Kingdon (1995), Collantes and Sperling (2008) and Hagerman et al. (2010). These studies all applied the MSF to investigate transport and climate policy agendas. Questions were designed to elicit information about each of the five categories in the MSF, namely: (1) problem stream; (2) policy stream; (3) politics stream; (4) policy entrepreneurship and (5) policy windows, while maintaining a natural continuous discussion. Additional questions were added before each interview to reflect each interviewee's policy or operational focus.

**Table 4.2: Chapter 4- Pre-prepared interview questions**

---

<b>1. Personal background</b>
<ul style="list-style-type: none"><li>• What is your role in the organisation?</li></ul>
<b>2. Programs</b>
<ul style="list-style-type: none"><li>• What are the main programs relevant to emissions from cars that you and your colleagues are working on?<ul style="list-style-type: none"><li>○ Is there an order of importance?</li><li>○ What is the split between embedded and in-use emissions?</li><li>○ Why do you think these particular initiatives are being considered?</li><li>○ How did these come to be the main topics?</li><li>○ What other options were considered?</li></ul></li><li>• Has anything happened during your time in the organisation that has made you re-evaluate GhG mitigation efforts related to car?</li><li>• What indicators do you collect on these programs?</li></ul>
<b>3. Collaboration</b>
<ul style="list-style-type: none"><li>• How do you and your colleagues work with other organisations?<ul style="list-style-type: none"><li>○ Who do you work with?</li><li>○ How is your work informed by other organisations?</li></ul></li></ul>
<b>4. Looking ahead</b>
<ul style="list-style-type: none"><li>• What proposals will be prominent in 2-5 years' time for reducing emissions from cars?</li><li>• What does a low carbon transportation system in the UK look like in 2050?</li></ul>
<b>5. Material Efficiency</b>
<ul style="list-style-type: none"><li>• What is your understanding of the term 'material efficiency'?</li><li>• Do material efficiency strategies feature in your work?</li><li>• What potential do you see for material efficiency strategies in the short, and long, term to reduce emissions from cars?<ul style="list-style-type: none"><li>○ Why?</li></ul></li><li>• Is there anything else you would like to add?</li></ul>

---

Interviews were transcribed verbatim, analysed and coded to reflect where the text related to the five categories in the MSF. All transcripts were reviewed three times. First, to identify and categorise interview excerpts that refer a component of the Multiple Streams Framework. For example, text was allocated a 'problem stream' code when interviewees discussed 'indicators' and any synonyms. Second, using Atlas.ti, a qualitative data analysis software program, all excerpts in each code category were examined together to establish themes. A theme, as described in Braun and Clarke (2006), represents some level of patterned response within the data, which can then be used to formulate meaning. It is the outcome of a coding exercise and necessitates researcher judgement and interpretation. A set of questions were developed to guide the theme development in each of the five MSF coding categories (Table 4.3). The aim of these questions was to challenge the validity and reliability of emerging themes.

**Table 4.3. Questions used to guide theme development (adapted from Braun and Clarke; 2006, Bernard and Ryan, 2010)**

- Is there a common theme or set of themes in each category?
- Is there a difference in the degree in which a theme is articulated?
- Are all excerpts correctly categorised? Is there an alternative categorisation?
- Are the excerpts exhaustive or is there more relevant information in the interview transcripts?
- Can disagreements among interviewees be explained using objective secondary evidence?
- What objective secondary evidence can be source to increase the reliability of the theme's interpretation? Does the theme need to be refined?
- Does the secondary evidence independently support a common theme? Can this theme be supported by an alternative categorisation of the interview transcripts?

Secondary evidence included: ministerial policies and strategies, press releases, responses to policy consultations, innovation funding briefs, NGO reports, minutes of committee meetings and publically reported government datasets. Following the guidance on document analysis in Bowen (2009), each were skimmed (superficial examination), read (thorough examination), and interpreted to establish content and correlate themes with those identified from the collection of interview excerpts. Interviewees were invited to review excerpts from their transcripts to ensure accurate characterisation.

Braun and Clarke (2006) caution that themes could be refined *ad infinitum*. The authors recommend that researchers should stop reviewing themes when “*they have a fairly good idea of: what the different themes are, how they fit together, and the overall story they tell about the data*”. This will always be subjective. However, the aim of triangulating interview excerpts and secondary evidence was to build a rigorous, robust and systematic explanation of why material efficiency is currently a limited part of the UK policy agenda to reduce greenhouse gas emissions from cars.

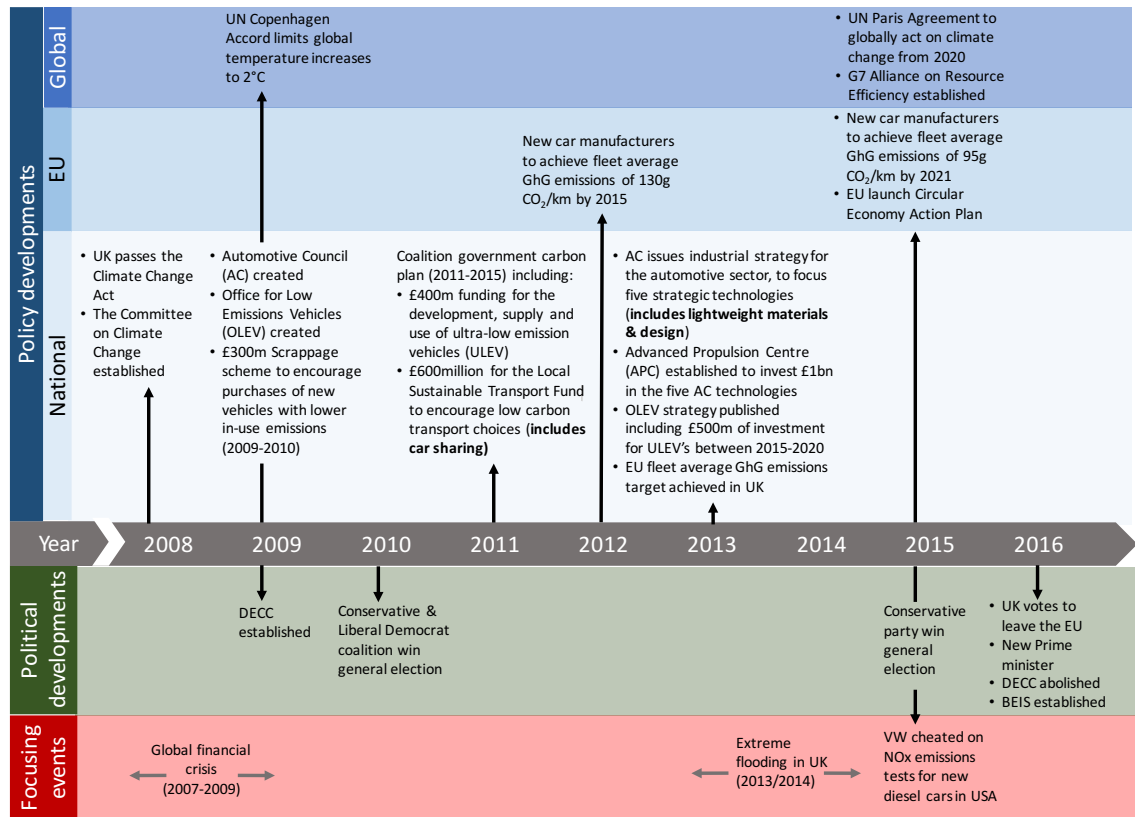


### *4.1.2. Study limitations*

The method described in Section 4.1.1 is informed by Cairney and Jones (2016), a good practice guide for applying the MSF. The process of data collection and analysis are designed around the MSF and its component parts, building on existing studies. In spite of these efforts, a number of limitations remain. As outlined in Section 2.3, there is ongoing academic debate about the comprehensiveness of the MSF when applied to climate change policy development. However, since this study is exploratory, the MSF is viewed as appropriate for identifying the main reasons why material efficiency is a limited part of the UK climate policy agenda. Another limitation comes from the challenge of selecting a representative sample of interviewees. Efforts were made to ensure individuals worked on different policy issues, had different operational responsibilities and were different levels of seniority. In spite of this, there is still a risk that interview findings are not exhaustive. A third limitation is the focus is on the national climate policy agenda. As shown in Storch and Winkel (2013), there may be differences in policy discourse around climate change solutions at the regional level. This may not be fully captured in Section 4.2 and could be a topic of further investigation.

## 4.1. Explaining why material efficiency is a limited part of the UK policy agenda to reduce GhG emissions from cars

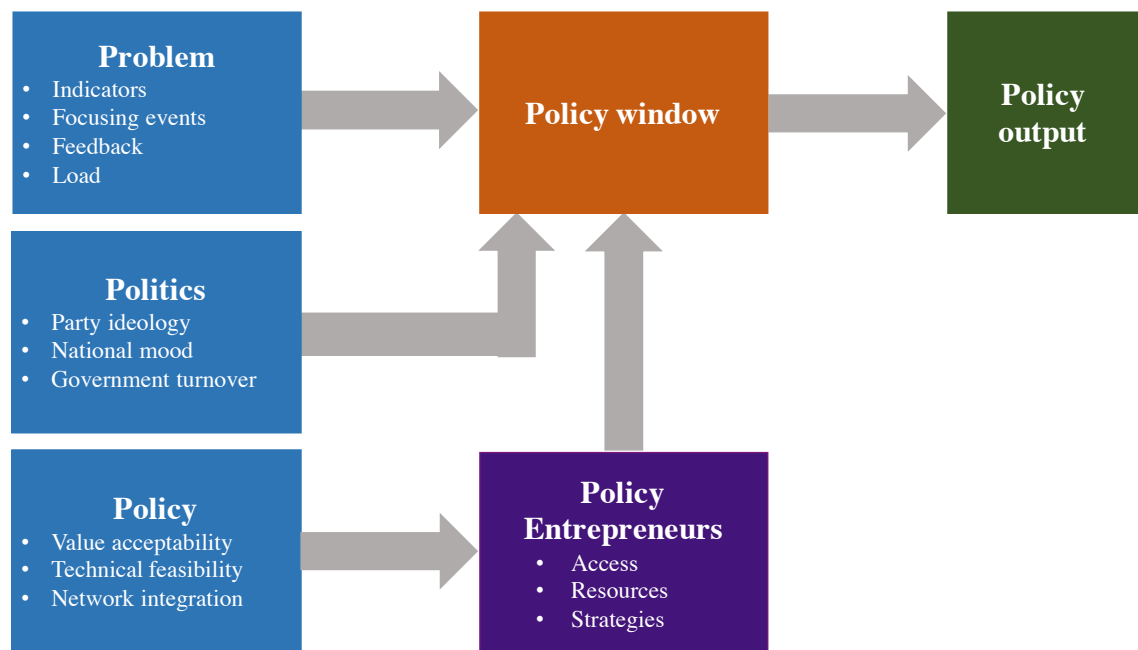
Two outputs were derived from the study method outlined in Section 4.1. First, a timeline providing historical context of policies, political developments and focusing events that shape the current UK policy mix (Figure 4.2). Second, an explanation structured around the MSF (Sections 4.2.1-4.2.4) of why material efficiency is a limited part of the UK policy agenda to reduce GhG emissions from cars.



**Figure 4.2: Political and policy developments and focusing events that have shaped the recent UK policy mix to reduce GhG emissions from cars**

Kingdon (1995) cautions that tracking the origins of policies is an exercise in ‘infinite regress’. Figure 4.2 begins in 2008, when the UK legally committed to long-term reductions in domestic GhG emissions in the Climate Change Act (CCA, 2008). The elements in Figure 4.2 are not exhaustive but highlight important events and policy decisions discussed by interviewees. UK policies are informed by, and align with EU

targets on in-use vehicle emissions and a global commitment to address climate change. No policies are explicitly presented as material efficiency solutions. However, there is currently government support for reducing the mass of material inputs through lightweight design and materials and increasing the intensity of car use via car clubs. Material efficiency solutions can currently be considered a small part of the UK policy mix to reduce GhG emissions from cars. The MSF (summarised again in Figure 4.3) can help explain why this is the case.



**Figure 4.3: Diagram of the Multiple Streams Framework (adapted from Zahariadis, 2007)**

#### *4.2.1. Problem stream*

In the problem stream, public issues are brought to policymakers' attention by indicators, focusing events and policy feedback. A policymaker's capacity to focus on a new issue will also depend on their existing problem load.

Indicators help with evaluating the magnitude of a problem and monitoring changes over time. However, Kingdon (1995) emphasises that the choice of what to measure and how will inform how a problem is interpreted. The UK government currently collects and reports data on domestic GhG emissions split by sector, fuel-type and end-users. In 2014, in-use car emissions were the second largest source of end-user GhG emissions, accounting for 15% of the total (BEIS, 2016). Data on GhG emissions from material use

throughout a car's lifespan is less readily available. Although the UK government reports the total and per capita mass of material consumed domestically per annum (in ONS, 2016), it doesn't provide details on the sectoral or end-user of different materials. Some academic studies, for example Serrenho et al. (2015), have calculated mass flows for individual materials through the UK economy but data is ad-hoc, creating difficulties with monitoring changes in material flows over time. GhG emissions associated with these material flows could be calculated by estimating emissions associated with individual processes in life-cycle assessments (LCAs). Interviewees discussed the importance of LCAs but listed a number of challenges which limit their appeal. These include: a lack of standardization which inhibits comparison and may lead to gaming; a lack of public interest in lifecycle emissions; difficulties tracing the country of origin of material along the supply chain and challenges with capturing the range of emissions intensities from different manufacturing processes. As a consequence, one interviewee questioned "*how confident would people be [in using LCA data], and how readily understandable would any information be?*". Another suggested "*you would have to allow a wide margin of calculation [and error]*". The uncertainty and complexity associated with measuring supply chain manufacturing and end-of-life vehicle emissions may partly explain why the UK has focused on measuring and monitoring in-use emissions. These calculations are based on fuel sales and are comparatively easy to measure.

Even if LCA data was available, increasing the number of indicators and the complexity and subjectivity of their interpretation would increase policymakers' workload. In the MSF, policymakers face temporal, resource and cognitive constraints, limiting the number of problems that can be given attention. Interviews indicated that UK policymakers already face capacity constraints. One interviewee characterised the automotive team in BEIS as '*really small, with a huge remit*'. The team aims to support growth, investment, employment, productivity and innovation in the sector. Although the Office for Low Emissions Vehicles has an explicit focus on reducing GhG emissions, programs are multi-modal and include infrastructure, particularly around EVs. The 10-person team in the Treasury working on climate change also cover energy, environment and agriculture policy. Due to this existing workload, one public sector interviewee stated that lifecycle GhG emissions arising from inefficient material use "*not a priority*". Another emphasised '*there are so many issues to address before then*'.

These interview quotes speak to a wider challenge within government of balancing multiple policy priorities and five-year political cycles with a longer-term problem such as climate change. While the Committee on Climate Change monitors the UK's progress in reducing domestic emissions in line with the 2050 target, policymaking will also be full of unexpected urgent, short-term distractions, which would also impact on what policymakers prioritise. To illustrate, there are usually two full time members of staff in the UK government who liaise with the steel industry across all policy areas, including climate change. In March 2016, Tata steel announced that it would sell its Port Talbot plant, the UK's last remaining blast furnace, risking unemployment for its 4000 employees with implications for the local economy in south Wales. One interviewee reported that 33 extra civil servants were pulled into the steel team on a short-term basis in response to this announcement.

From this experience with Tata Steel and interview responses, it is reasonable to say that the current approach to UK materials policy is ad-hoc and sectoral. One interviewee explained that action is taken for “*issue-specific things, [not limited to GhG emissions], that industries have raised or problems we discover*”. No team currently has complete material supply chain oversight. BEIS focuses on materials and vehicle production, The Department for Transport and OLEV are responsible for in-use vehicle emissions and the Waste team at the Department of Environment, Food and Rural Affairs focuses on end-of-life vehicle treatment. These institutional arrangements may constrain how policymakers interpret the problem of GhG emissions arising from inefficient material use.

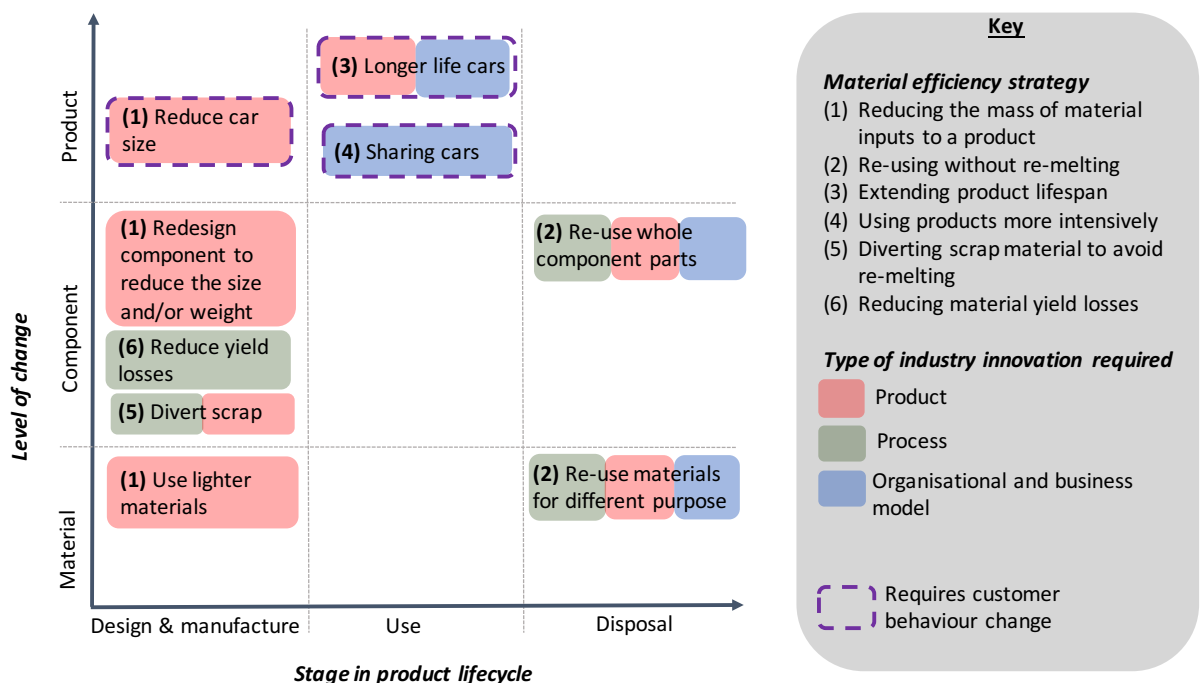
Focusing events,. In 2016, VW were fined \$14.7B for interfering with in-use Nitrous Oxide emissions tests in the USA for a range of new diesel cars. Transport & Environment (2013) show similar manufacturer discrepancies with fuel consumption and CO<sub>2</sub> emissions tests. Interviews revealed the ‘VW scandal’, has reinforced UK government attention to the problem of in-use, rather than lifecycle emissions. One interviewee explained that “*at the start [of the UK's efforts to reduce GhG emissions], no one thought the testing procedures were going to cause a problem*’. Another displayed skepticism the problem definition to include LCAs by stating “*You've seen the problem with measuring in-use emissions... now imagine the gaming that could go on [with lifecycle emissions]*”. Progress towards meeting existing policies objectives

shows the UK met its 2015 EU target in-use GhG emissions for new cars in 2013, which creates little incentive to redefine the problem to include lifecycle GhG emissions.

Indicators, focusing events and policy feedback mean inefficient material use is currently only perceived as a problem insofar as it increases in-use vehicle emissions. There appears to be a lack of capacity, interest and certainty around expanding the problem framing to include lifecycle vehicle emissions, including those that are attributable to material use.

### 4.2.2. Policy stream

In the policy stream potential solutions are debated, refined or discarded by a community of policymakers and advocates. Policymakers are more likely to pay attention when: there is community consensus; solutions are viewed as technically feasible and align with their values. Figure 4.4 builds on Table 2.2 in Section 2.1 of this thesis. It shows that there are many technical options and types of innovation that can deliver material efficiency improvements throughout a vehicle’s life. Policymakers can then consider policy interventions that incentivise their uptake, including support innovation.



**Figure 4.4: Technical options for implementing material efficiency improvements throughout a vehicle’s life (adapted from Allwood et al. 2012)**

The variety in options for implementation may partly explain a lack of consensus on how to define material efficiency. Some interviewees limited their definition to vehicle design and manufacture, i.e. *“being more efficient in the manufacture and use of materials”* or *“minimising the amount of inputs you need to produce a thing”*. A third of interviewees understood materials to mean all resources. For one this included *“emissions produced and embedded water”*. Three interviewees reported low levels of awareness of the concept of material efficiency. One said *“it’s probably the first time I’ve heard [about] it”*, another said their understanding was *“not huge”*. Another admitted they were *“a bit less familiar with it [the term material efficiency]”*. Almost all interviewees however, recognized one or more of the six strategies featuring in their work. Of these, light-weighting materials and component designs were the most commonly recognized strategies. Nine interviewees indicated they had engaged with policy discussions about these options. A lack of common definition may mean material efficiency solutions that deliver GhG emissions reductions are evaluated inconsistently among policymakers. The legislative landscape will also influence how policymakers evaluate material efficiency solutions. The Climate Change Act (CCA, 2008) frames the problem as excessive domestic GhG emissions only. Solutions will therefore be valued more highly by policymakers if emissions reductions occur in the UK. This explains government support for lighter vehicles in Figure 4.2. Nieuwenhuis (2014) explains that holding all other factors constant, lighter vehicles require less fuel to accelerate to given speed and have lower in-use emissions. Car sharing has also received government support. Car clubs are the most prevalent form of car sharing in the UK. The car club fleet is relatively new and Steer Davis Gleave (2016) report that in-use vehicle emissions are 30% lower for car club vehicles than the average UK vehicle.

Interviewees revealed policymakers place more value on solutions that have potential economic co-benefits. One interviewee explained that the UK government aims to *“support the technology that gets you to zero emissions, and identify the areas where we [the UK] have a [competitive] advantage”*. Similarly, the Office for Low Emissions Vehicles aims to achieve *“the joint goals of encouraging ultra-low emissions vehicles uptake and encouraging inward investment”*. This aligns with the government’s reported strategy, in OLEV (2013), to *“relentlessly support wealth-generating*

*economic activity and ensure motoring is environmentally sustainable*". Current understanding of the economic co-benefits from material efficiency solutions related to cars is limited. The IEA (2015) identifies that material efficiency strategies can potentially: save energy; decrease environmental harm; accelerate economic growth and provide jobs. However, empirical evidence in the UK to support these assertions is sparse and relates to individual solutions (see the car club case study in Chapter 5 for example).

As discussed in Section 2.4, the HMT (2013) Green Book on policy appraisal advises that UK policymakers should assess in advance if a policy intervention is technically feasible to implement and have some confidence in the scale of costs and impacts. Some interviewees expressed concern about the certainty of emissions reductions that could be generated from material efficiency strategies requiring customer behavior change (see Figure 4.4). One interviewee explained that *"getting people to change their behaviour is just more uncertain, [as is] what you [the policymaker] need to do and the [likely] outcomes"*. Perceived riskiness or uncertainty may also deter policymakers from including material efficiency solutions in public sector modelling exercises. This is problematic as the UK government uses modelling insights on costs and abatement potential of different technical solutions to inform the development of macro and sector-level decarbonisation pathways. In the case of car sharing, for example, one interviewee said that *"until it becomes clear that this is something that can deliver [GhG emissions reductions], we'll have to wait a bit to include it in the modelling"*. Another modelling challenge is that current material efficiency levels are unknown. The UK government reports data on the stocks and cars in use (DfT, 2016a) and passenger kilometres (DfT, 2016b), however there no material inputs ascribed to these product and service outputs. Serrenho and Allwood (2016) link material inputs to cars in the UK and conclude they are becoming more materially intensive, travel shorter distances and are idle for more time. However, unlike energy efficiency, which as discussed in Cullen and Allwood (2010), has defined theoretical and practical limits for conversion devices, only a handful of studies exist which outline current best available practices for efficient material use related to cars (see Milford et al., 2013 and Allwood et al., 2012 for examples). It is therefore harder to evaluate current practices and assess the scale of material savings, and GhG emissions reductions, that could be achieved. A lack of real-world evidence on the costs of implementing material efficiency initiatives further compounds these implementation challenges.



There is no common definition of material efficiency solutions in UK government. Its appeal is limited by the absence of real world and modelling evidence to demonstrate technical feasibility and potential economic co-benefits. There is further uncertainty regarding the GhG emissions reductions that could be achieved from material efficiency improvements and how much this would cost.

### *4.2.3. Politics stream*

The politics stream in the MSF consists of the public mood, pressure-group campaigns and government turnover. These elements motivate and give policymakers the opportunity to consider different public problems and possible solutions.

There appears to be declining public concern about the problem of climate change. In 2015, around two thirds of the British population were reported to be '*fairly*' or '*very concerned*' about the problem, down from 80% in the mid-2000s (Capstick et al., 2015). Giddens (2009) argues that the intangible, delayed and invisible impacts of GhG emissions means that climate change often becomes a back-of-the-mind issue. The absence of existing policies to incentivise material efficiency solutions and the indirectness of material demand by UK consumers means that the public population is unlikely to connect the contribution of inefficient material use to the problem of climate change. No evidence could be found of pressure-group campaigns around material efficiency solutions which might prompt the general public to consider the GhG emissions impacts of inefficient material use.

Between 2008-2016, there have been three UK governments, four Prime Ministers and a national referendum vote in favour of leaving the European Union (EU). During this period, more efficient use of resources, including materials, appears to be a lower priority political issue. Both the Labour and Conservative parties referenced 'resource efficiency' in their 2010 election manifestos. However, in 2015, only the Liberal Democrats and Greens, both minor parties, outlined support for resource efficiency initiatives. No manifesto referred to specific resources, sectors or supply chains, indicating that the political discourse around elections tends to be high level and non-technical.

There was evidence from one interview that material efficiency solutions requiring direct customer behaviour change might be politically unpopular as it is misaligned with

the current government's political ideology. When discussing the option of reducing vehicle weight through downsizing, the interviewee said, "*I don't think, from talking to politicians there's any interest because it was perceived as being 'too interventionist'*". Insights from the energy efficiency literature might further explain this political reluctance to changing customer behaviour. Janda and Topouzi (2015) suggest that a 'hero story', in which a clever technology such as electric vehicles, reduces GhG emissions without any effort from consumers, is more politically appealing. Parag and Eyre (2010) also suggests that blaming large corporations for environmental problems offers a more compelling political narrative than trying to force individuals to consider their personal contribution to the problem.

In late 2016, much political attention was given to the UK's departure from the EU, the so-called "Brexit". As Figure 4.2 shows, the UK policy mix to reduce GhG emissions from cars is guided by EU legislation and it is unclear what Brexit will mean for the short-term UK climate change policy agenda. In the long-term, the Climate Change Act (CCA, 2008) should ensure climate change policy continues to develop. EU legislation influences many other policy areas in the UK and politicians, policymakers, industry, the media and the general population will be preoccupied with the details of the UK's departure from the EU. Existing policies and public problems will need to be revisited, requiring significant government and political resources. More efficient use of resources, including materials, will likely remain a low priority. As one interviewee explained, "*Post-Brexit, everything has been reorganised, we've got somewhat bigger problems to deal with [than the consequences of inefficient material use]*".

In 2016, there appears to be decreased public concern around climate change. Political parties appear to be less interested in initiatives that promote resource efficiency improvements. In the short term, much of the government, media and public attention will be focused on the UK's departure from the EU.

#### *4.2.4. Policy entrepreneurship and policy windows*

The limited inclusion of material efficiency initiatives in the UK policy mix may also be due to challenges with coupling the three streams. In the MSF coupling can be orchestrated by policy entrepreneurs who promote their particular ideas as solutions to public problems. Coupling occurs during 'policy windows', when policymakers are temporarily more receptive to ideas. In a summary of the MSF, Zarahariadis (2007)

explains that entrepreneurs are most successful when they: can access policymakers; have resources (in the form of time, money and energy) and are strategic in their approach.

Aside from a community of academics, no dedicated NGOs or interest groups promoting material efficiency as a set of possible solutions for reducing lifecycle GhG emissions from cars could be found. However, some entrepreneurship was identified for individual strategies or modes of implementation. Carplus, Transport for London (TFL) and Local Authorities, for example, advocate increasing the intensity of car use through car sharing. These organisations emphasise a broad range of benefits not limited to reduced GhG emissions including: reduced congestion; improved air quality; access to mobility and reduced demand for parking (TFL, 2015). Other organisations including WRAP and the Ellen MacArthur Foundation subsume materials efficiency strategies into a bigger set of solutions to achieve resource efficiency and the circular economy. As outlined in Section 1.1, a circular economy keeps resources in use for as long as possible to minimise waste and the need for extraction from primary sources. Stahel (2016) defines a circular economy as one where resources are reused then recycled and products are repaired then remanufactured. The EC (2015) asserts that a circular economy could: increase competitiveness, protect business against resource scarcity and price volatility, create jobs, increase social integration and cohesion, save energy and avoid depleting finite resources. Lower CO<sub>2</sub> emissions are presented only as a '*wider [potential] benefit*'. This may mean entrepreneurs are working to couple material efficiency solutions to a different policy agenda. There is a risk that material efficiency strategies are overlooked as a solution for reducing GhG emissions from cars.

Interviews revealed that the Automotive Council is an important forum for entrepreneurs to shape the policy agenda. The main Council comprises the most senior individuals from industry and the public sector. Working Groups comprise of a similar mix of less senior individuals. One interviewee said the Automotive Council gave the industry "a single voice" and allowed it "[to] agree on a direction and then align that with government". Other interviewees characterised this collaboration as: "*honest*", "*open*", "*exemplar*", "*refreshing*" and "*joined-up*". Policy entrepreneurs in the NGO and academic community tend to operate outside the Automotive Council and have less access to policymakers. One interviewee also commented on a lack of NGO integration, describing them as '*scattered*'. As discussed, policy entrepreneurs

promoting material efficiency solutions are a sub-section of this community and have dispersed motives, which may further limit their effectiveness.

As shown in Figure 4.2, solutions that reduce in-use GhG emissions are aligned with EU indicators and targets. However, if in-use emissions fall to zero, for example via electric vehicles and a fully decarbonised power grid, the relative contribution of manufacturing and end-of-life GhG emissions would increase and may mean that material efficiency solutions could become a larger part of the policy agenda in the future. One interviewee explained that although they “*definitely anticipate this [change in share of lifespan emissions]*”, there “*isn’t a policy forum to lobby on that now...*”, which may constrain current entrepreneurship on material efficiency solutions.

Interviews revealed many sources of policy lock-in and path dependency which mean a policy window is not anticipated. This limits the potential to expand the policy agenda to include material efficiency solutions. The UK’s long-term focus on domestic emissions in the Climate Change Act (CCA) will continue to disadvantage material efficiency solutions that lead to emissions reductions outside of the UK. Interim ‘carbon budgets’ dictate what technological solutions, including their deployment rates, will be required in the future to meet CCA targets and will guide current innovation investment, contributing to policy lock-in. Wells (2010) also explains that the long lead times between designing and mass manufacturing cars also means policies and regulations tend to be decided on and announced years in advance to enable vehicle manufacturers enough time to develop new models that are compliant. It is currently unclear whether Brexit will contribute to a policy window to reshape the policy agenda to include material efficiency options. The discussion in Section 4.2.3 indicates there may be little spare capacity in government to expand the policy load. However, it is possible that all policies linking to European institutions will be need to be revisited as part of the UK’s departure.

The few individuals promoting material efficiency solutions are not well integrated and may be focused on different public problems. GhG emissions reduction trajectories and supporting policies appear to be ‘locked-in’ years in advance and a policy window is not currently anticipated.

### *4.3. Discussion*

To recall, the question outlined at the beginning of this chapter was:

***Q2: Why have there been so few material efficiency policies implemented in the UK?***

Prior to implementation, public problems, and possible solutions, are discussed by institutions, the media and the public and these discussions constitute the ‘policy agenda’. Currently, material efficiency solutions are only a small part of the climate policy agenda to reduce GhG emissions from cars. In the UK, the legislative landscape, policy indicators and the 2015 VW ‘scandal’ mean inefficient material use is currently only perceived as a problem by policymakers insofar as it increases in-use vehicle emissions. These in-use emissions are a large contribution to total UK domestic GhG emissions. This focus on in-use emissions favours material efficiency solutions that reduce vehicle weight by lightweight design and increases the intensity of vehicle use via car sharing. The appeal of other material efficiency solutions is further limited by the absence of data and modelling evidence on: potential emissions savings; technical feasibility; costs of implementation and potential economic co-benefits. Policymakers appear to have little spare capacity to consider GhG emissions associated with inefficient material use. The Brexit process may create further capacity constraints, as all public problems and policies which are guided by EU legislation will need to be reviewed. A small community of policy entrepreneurs are promoting some material efficiency solutions but they focus on different public problems, which may limit their effectiveness. There is also policy lock-in, which means a policy window is not anticipated.

These findings show why a promising engineering solution for reducing greenhouse gas emissions doesn’t automatically lead to policy support. There also needs to be entrepreneurship, community building along with analysis on the social and economic impacts of implementation. Timing and capacity will also determine how well a new engineering idea will be received by politicians and policymakers alike. All of these factors need to be considered if material efficiency solutions are to become a larger part of the UK policy mix.

Future research that aims to shape GhG emissions reduction policy, whether engineering or from the social sciences, would benefit from using a conceptual model, such as the Multiple Streams Framework to systematically evaluate the multiple, interacting factors that determine how real world decisions are made. The framework guides what data should be collected and helps with managing potential research biases around determining what information is important or less relevant. Having a pre-prepared set of questions to guide theme development, as outlined in table 4.2, also creates transparency around why particular quotes or secondary data sources were selected.

Looking ahead, there may be a window of opportunity to redefine GhG emissions reduction efforts to include material efficiency in the future. If in-use vehicle GhG emissions fall to zero, the focus will shift to manufacturing and end-of-life emissions. Although the timing of this is unclear, action could be taken now by researchers and policy entrepreneurs to ensure material efficiency solutions are sufficiently developed to be included in a future policy agenda. This is discussed further in Chapter 6 of this thesis.

# 5. Employment Impacts of Material Efficiency

*The content of this Chapter is based on a journal article published in Resources, Conservation and Recycling (Cooper et al. 2016). Dr. Skelton and Dr. Allwood provided comments on draft versions of the article. Dr. Owen developed the Multi-Regional Input Output model that was used in the analysis. Interviews for the construction sector case study were conducted with Dr. Densley-Tingley. I asked questions pertinent to this study and Dr. Densley-Tingley asked questions that informed the analysis in Densley-Tingley et al. (2017). I presented some preliminary findings of this research at the 23<sup>rd</sup> International Input-Output Conference in Mexico City. This Chapter responds to **Q3: What would be the macroeconomic impacts of more efficient material use in the UK?***

Material efficiency initiatives require a change in the way materials, components and final products are used along the supply chain. This will have associated impacts on production output and employment. Employment is highlighted in HMT, (2013) as both a motivation for, and an important evaluation indicator of, government intervention in the UK. Policymakers considering policies to improve the efficiency of material use will often use economic models to try and understand the likely scale and sectoral distribution of employment impacts of any potential policy intervention. Section 2.4 has shown that the results of these modelling exercises are often contingent on a number of assumptions, which are not always fully explained. This chapter presents and tests a transparent multi-method approach for estimating the immediate supply chain employment impacts of improving the efficiency of material use. This method is applied to two case studies that could improve the efficiency of steel use in the UK. Namely: (1) increasing the number of car club users and (2) increasing the number of reused steel sections in construction projects. Interviews with experts from industry, supplemented by a literature review reveal how sector labour intensity, product prices and sales volumes might change along the mobility and construction supply chains in the short-term as a consequence of introducing these two material efficiency initiatives. A simple static multi-regional input-output model is used to estimate the immediate

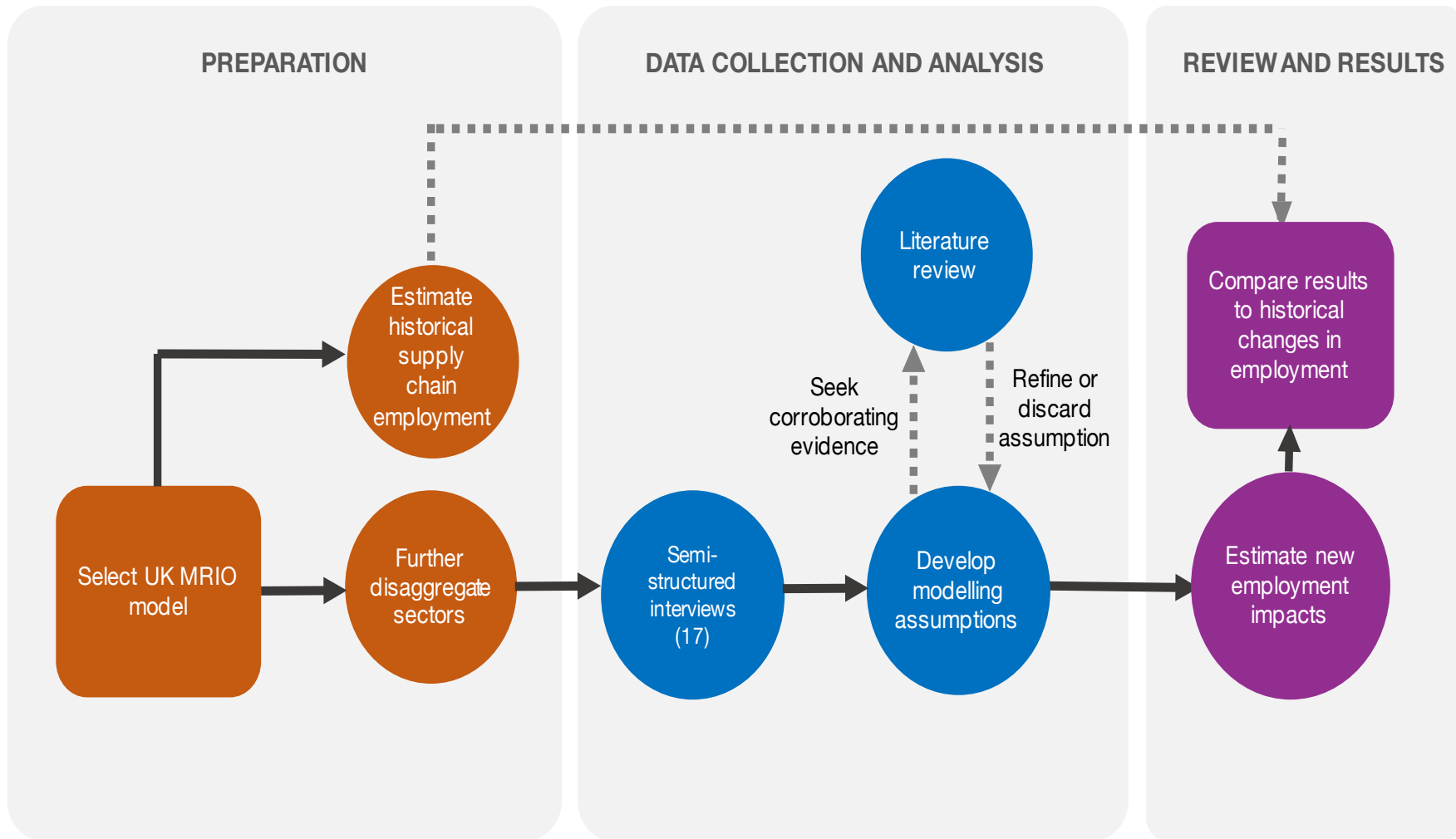
direct and indirect supply chain employment impacts of both these strategies. These impacts are compared to historical changes in employment to better evaluate the scale of change in employment that can be anticipated from material efficiency improvements. Developing and modelling these case studies reveals a number of factors, which contribute uncertainty and variability in modelling results. A greater understanding of these factors would allow policymakers to assess the certainty of any modelling results that are generated to inform policy development.

## 5.1. Method

An overview of the method used in this chapter is presented in Figure 5.1. A multi-region input output (MRIO) model was used to estimate historical domestic and international supply chain employment to meet UK demand for construction and cars. Two material efficiency case studies were selected and interviews were conducted with individuals in both supply chains to identify how each case study could be implemented in the UK. The model was disaggregated and modified to reflect these supply chain changes. Each scenario led to a change in the structure of the UK economy with associated impacts on employment. These changes were compared to historical trends in supply chain employment. Sections 5.1.1 – 5.1.4 explain these stages more detail. The results are presented and discussed in Section 5.2.

This multi-method approach was necessary to ensure that: (1) the material efficiency case studies were realistic and technically feasible, (2) the economic modelling framework was robust and commonly used and understood and (3) the modelling results could be analysed and related back to underlying trends in the sector and macro-economy. As a consequence, it is hoped that academics, industry practitioners and policymakers will find this study of interest and potential use in informing their work. This chapter expands on the work in Allwood and Cullen (2012) by estimating some of the economic impacts associated with material efficiency improvements. Rather than focusing on technical potential from an engineering standpoint, this study also considers the economic potential of material efficiency and any associated trade-offs that would come from reconfiguring the economy towards more efficient material use.





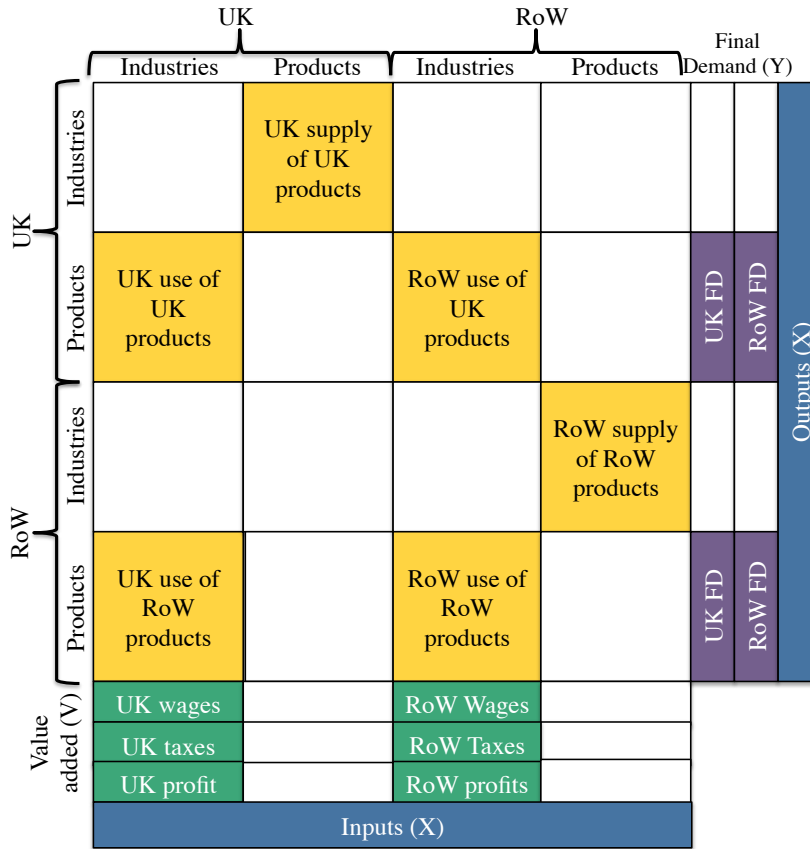
**Figure 5.1: Overview of methodology used in Chapter 5**

### *5.1.1. Model description and estimation of historical supply chain employment*

A static two-region input output model was used for this research. Input-output models are a system of linear equations that depict the distribution of an industry's product, both goods and services, throughout the economy, usually in monetary terms. Static MRIO models provide a snapshot of an economy at a particular point in time. When the production structure within these models is modified, the results reveal net changes in output and employment relative to the historical structure of the economy. These changes include direct employment impacts from a change in direct sector purchases (e.g. less new steel bought by the construction industry) and indirect impacts that affect employment higher up the supply chain (e.g. fewer jobs to mine metallurgical coal which would then be sold to the steel industry to make products used by the construction industry). There may also be employment impacts resulting from a change in household disposable income, (e.g. if car sharing reduces the costs of mobility, households will spend money on other goods and services and this can create jobs in other sectors). These are referred to as induced impacts and are one aspect of a potential rebound effect, explained in Section 2.4.1. Another aspect of the rebound effect which is not captured in a static MRIO framework is the impact of a change in product prices on consumption choices which could lead to both income and substitution effects. Sorrell (2007) reviewed over 500 studies on the evidence for rebound effects for energy efficiency initiatives and concluded that rebound effects vary widely between different technologies, sectors and income groups and cannot be quantified with much confidence. So although other top down modelling approaches can offer estimates of these rebound effects they require additional assumptions that can create further uncertainties.

The model used in this Chapter was developed at the University of Leeds and its construction is described in Scott et al. (2013). In the model, the global economy is split into two-regions, the 'United Kingdom' (UK) and 'Rest of World' (RoW). The model was selected because of the high resolution of the UK data, taken directly from the Office of National Statistics (ONS), for the years 1997-2011. The model splits the global economy into 106 sectors and products, aligning with the UK's 2-digit standard industrial classification (SIC) code. Most UK government-issued data is grouped according to a variant of these SIC codes. The common root classification means it is

easier to compare model data with other datasets issued by the ONS. RoW data was sourced from the Eora MRIO database described in Lenzen et al. (2013). The data was mapped onto the UK's 2 digit SIC code and converted to pounds sterling. The layout of the model for a single year is shown in Figure 5.2.



**Figure 5.2: Structure of Leeds University MRIO model for a single year, without employment extension.**

Yellow squares in the Supply and Use table (SUT) are 106x106 matrices containing non-zero values; non-coloured squares are 106x106 matrices containing zeros. In matrix notation, the supply and use table ( $Z$ ) can be written as:

$$Z = \begin{pmatrix} 0 & S^{uk} & 0 & 0 \\ U^{uk,uk} & 0 & U^{row,uk} & 0 \\ 0 & 0 & 0 & S^{row} \\ U^{uk,row} & 0 & U^{row,row} & 0 \end{pmatrix} \quad (5.1)$$

In the general notation,  $U^{sr}$  is a matrix of inputs into region  $s$ , from region  $r$ . Element  $u_{ij}^{sr}$  is the amount spent by each industry  $i$  in region  $s$  on product  $j$  from region  $r$ , also

referred to as ‘intermediate demand’. Similarly in the supply matrix  $\mathbf{S}^s$ , element  $s_{ij}^s$  details how much of product  $j$  is made by sector  $i$  in region  $s$ . The transposed vector of value added ( $\mathbf{V}'$ ) shows the amount each sector spends on non-physical inputs i.e. wages, taxation and profit written as:

$$\mathbf{V}' = (\mathbf{V}^{uk} \quad \mathbf{0} \quad \mathbf{V}^{row} \quad \mathbf{0}) \quad (5.2)$$

Each element,  $v_i^s$  shows how much is spent by sector  $i$  on non-physical inputs in region  $s$ . The vector of final demand  $\mathbf{Y}$  shows how much final consumers in each region spend on each product in each region.

$$\mathbf{Y} = (\mathbf{Y}^{uk} \quad \mathbf{Y}^{row}), \quad \mathbf{Y}^{uk} = \begin{pmatrix} 0 \\ \mathbf{Y}^{uk,uk} \\ 0 \\ \mathbf{Y}^{uk,row} \end{pmatrix}, \quad \mathbf{Y}^{row} = \begin{pmatrix} 0 \\ \mathbf{Y}^{row,uk} \\ 0 \\ \mathbf{Y}^{row,row} \end{pmatrix} \quad (5.3)$$

The general notation for element  $y_j^{sr}$  shows how much is spent on product  $j$  made in region  $r$  by final consumers in region  $s$ . A condition of the model is that the sum totals of all inputs (columns) were equal to the sum of all outputs (rows). Each element in SUT is divided by the total sum of the column ( $X_j^s$ ). This generates the direct requirements or ‘‘A’’ matrix containing elements  $a_{ij}^s = \frac{u_{ij}^s}{X_j^s}$ . The A matrix was converted into a Leontief inverse matrix using the equation:

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \quad (5.4)$$

$\mathbf{I}$  is the identify matrix the same size as  $\mathbf{A}$ . The Leontief matrix shows the total input requirements to deliver a unit of output, i.e. direct and all indirect inputs along the entire supply chain. An additional vector of labour intensity  $\mathbf{F}$  was included in the model and transposed ( $\mathbf{F}'$ ).

$$\mathbf{F}' = (\mathbf{F}^{uk} \quad \mathbf{0} \quad \mathbf{F}^{RoW} \quad \mathbf{0})$$

It is defined by elements  $f_j^s = \frac{m_j^s}{X_j^s}$  where  $m_j^s$  is the annual number of full time workers in sector  $j$  in region  $s$ , and  $X_j^s$  is the total value of output in sector  $j$  in region  $s$ . The matrix of direct and indirect employment to meet UK demand for products in a single year was calculated by the formula:

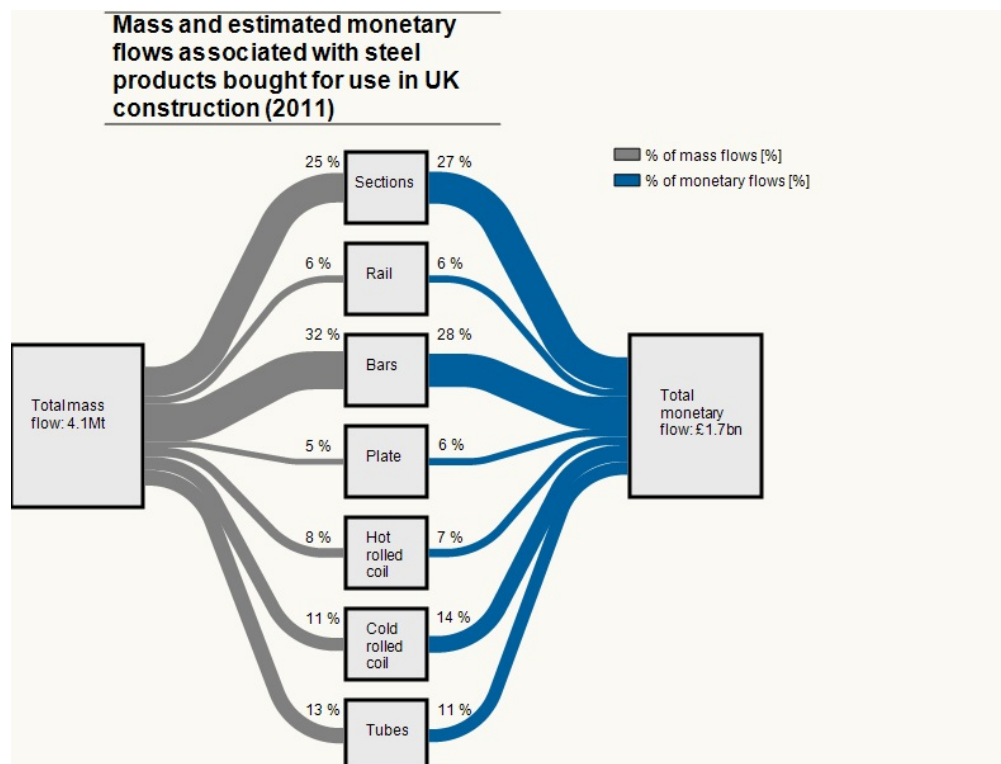
$$M = \hat{F} * L * \hat{Y}^{uk} \quad (5.5)$$

A ‘^’ denotes a square matrix with the vector values along the diagonal and zeros elsewhere. Formula (5.5) is used to calculate the direct and indirect UK and RoW employment associated with meeting UK demand for all products for all years between 1997-2011. In the IO literature, these are also referred to as ‘Type I’ multipliers (Miller & Blair, 2009).

### *5.1.2. Model preparation – product and sector disaggregation*

The two case studies under investigation in this chapter are: (1) increasing the number of car club users and (2) increasing the number of reused steel sections in construction projects. Figure 5.2 shows inter-sectoral monetary flows of payments between 106 sectors for 106 products. However, only certain sub-sectors and sub-products would be impacted by the introduction of these two material efficiency initiatives. Further disaggregation in the model is necessary to avoid over-estimating the change in monetary flows for each case study. For direct purchases between sectors and by final customers, the proportion of output attributable to a specific subsector was approximated using total sub-sector turnover as a proportion of total sector turnover, taken from the Annual Business Survey (ONS 2014a) for the year 2011. In the car-sharing case study for example, vehicles rental accounts for 47% of total household expenditure on ‘rental and leasing activities’. Indirect purchases between sectors were estimated using the value of steel sales to a particular sector as a proportion of total steel sales taken from ONS (2014b). An example of an indirect purchase would be steel purchased by fabricators which is then purchased by the construction sector. No equivalent information was available for international sub-sector turnover and sales so UK proportions were applied.

The reuse case study focuses solely on steel sections. Steel products are priced differently depending on the method of production and processing. To estimate the price of steel sections in the model, domestic and international steel mass flow data was taken from the ISSB (2008) and combined with relative historical steel product prices for the year 2011 (*MEPS, Platts, ISSB*). Figure 5.3 shows the estimated proportion of mass flows and direct and indirect expenditure attributable to different steel products bought by the construction sector in 2011.



**Figure 5.3: Sankey diagram converting mass flows of steel products bought by the construction sector in 2011 into equivalent monetary flows**

### 5.1.3. Interviews and literature review

Following model preparation detailed in section 5.1.2, twenty-four individuals were contacted and invited to participate in semi-structured interviews. These individuals were purposefully selected because of their expertise. Seventeen individuals agreed to be interviewed on the conditions of anonymity. Table 5.1 provides an overview of their relevant experience. Interviews took place either in person or via telephone and lasted around 1 hour.

**Table 5.1: Chapter 5 - Interviewee occupations and experience with car sharing or steel reuse.**

<b>Interview Type</b>	<b>Relevant experience?</b>	<b>Occupation or place of work</b>
Car Club	Yes	Industry association focused on shared mobility
Car Club	Yes	UK car club operator
Car Club	Yes	UK car club operator
Car Club	Yes	UK car club operator
Car club	Yes	UK car club operator
Car Club	Yes	Consultant to car clubs
Steel reuse	Yes	Architect
Steel reuse	Yes	Architect and material purchasing
Steel reuse	No	Engineering contractor
Steel reuse	Yes	Sustainability contractor
Steel reuse	Yes	Contractor involved with material purchasing decisions
Steel reuse	No	Steel fabricator
Steel reuse	No	Steel fabricator
Steel reuse	Yes	Steel fabricator
Steel reuse	Yes	Structural engineer and material purchasing
Steel reuse	Yes	Structural engineer and material purchasing
Steel reuse	No	Structural engineer and material purchasing

Interviewees were asked to consider how costs, sales volumes and labour requirements might change across different sectors in the supply chain in both case studies. Interviewees were asked to consider the scale of implementation that might be feasible between 2015 and 2020. Five years was assumed to be a realistic timeframe to potentially increase the number of car sharers and increase the number of reused steel sections in construction projects in the UK. Interviews were semi-structured to ensure important topics were covered but also to allow flexibility in pursuing new lines of enquiry as they arose. The pre-prepared interview questions are listed in Table 5.2. Fewer respondents in the reuse interviews had direct experience of reusing steel so questions were framed more hypothetically. Conversely, there are currently eight commercial car club operators in the UK. Car club interview questions were designed to elicit an understanding of different costs and labour requirements per car club member and car club vehicle.

**Table 5.2: Chapter 5- List of pre-prepared interview questions**

<b>Interview questions – car clubs</b>
• Approximately how many individuals work at your company/across all UK car club companies? What types of roles? Which roles are impacted by the number of car club members?
• How many vehicles are bought on average per car club member? How often are car club vehicles replaced?
• How are car club vehicles manufactured? Does this differ at all from private vehicle manufacturing?
• How are car club vehicles purchased?
• Who is responsible for vehicle maintenance? How frequently are car club vehicles checked?
• How are car club vehicles insured? How are insurance premiums calculated?
• What is the potential size of the UK car sharing market in 2020?
<b>Interview questions – steel reuse</b>
• Are you involved with material purchasing/sourcing decisions? How is this done? E.g. on a project-by-project basis or is there a coordinated company approach?
• How would you source reused steel sections for a project?
• Do you think a project with reused steel will require more or less labour? More or less material inputs? New capital equipment? Why?
• Would project costs be impacted by reusing steel? How? Why?
• Would the use of reused steel affect consumer demand for construction projects?
• What percentage of the yearly sectional steel stocks arising from demolition do you think could be suitable for structural reuse by 2020?

The collated interview responses are summarized in Table 5.3. The table includes an explanation of why monetary flows between sectors would change as a consequence of introducing each material efficiency strategy and provides an estimate of the maximum size of monetary flows that would be affected. For each supply chain change listed in Table 5.3, an additional review of academic, industry and government issued literature was conducted to corroborate and find quantitative estimates of the changes proposed. If no further evidence was found in the literature, the change was omitted from the modelling exercise. In the reuse case study for example, it was challenging to find additional information on search, haulage, cleaning, testing and storage costs for steel sections extracted from deconstruction sites so these were omitted from the modelling work. The modelling therefore only includes a partial assessment of supply chain employment impacts in the reuse case study. It is assumed that 10% of steel sections are reused, which is consistent with the reuse rates identified in Samson and Avery (2014) in the UK in 2000. In the car club case study, a low case of 100,000 members was assumed and a high case of 1 million members. This is upper case is considered credible



as in London alone there is an ambitious strategy outlined in Transport for London (2015) for 1 million car club users by 2025.

**Table 5.3: Summary of interview responses that show which inter-sector and inter-stakeholder monetary flows are anticipated to change with the introduction of each material efficiency strategy and what the maximum scale of change would be for the year 2011**

Purchasing sector (region)	Sector supplying goods and services (SIC code)	Region	Value of monetary flows in 2011 (£m)	Sub-sector impacted by reuse (SIC code)	Expected impact of material efficiency strategy (based on interview evidence)	Sub-sector turnover/Total sector turnover (ONS 2014a)	Maximum value impacted by reuse (£m)	Inclusion in modelling?
Construction (UK)	Construction (43)	UK	46111	Building projects (41.1)	Additional search costs to source reused steel sections	9%	3991	N
				Demolition (43.11)	Demolition teams sell more reused steel sections	0.2%	109	Y
Construction (UK)	Land transport services (49)	UK	1036	Freight transport by road (49.1)	Reused steel from deconstruction sites would be transported to steel fabricators	46%	481	N
Construction (UK)	Fabricated metal products (25)	UK	4258	Fabrication of metal structures (25.11)	Reused steel sections from deconstruction sites would be cleaned so condition is equivalent to new steel	20%	844	N
Construction (UK)	Architectural/engineering services (71)	UK	5258	Technical testing/analysis (71.1)	Steel from deconstruction sites would be tested & certified to confirm its material properties for reuse	9%	463	N
Construction (UK)	Warehousing/support services for transportation (52)	UK	75	Warehousing and storage (52.1)	Once certified, reused steel sections from deconstruction sites would need to be stored before being sold for future construction projects	25%	19	N
Construction (UK)	Manufacture of basic metals (24)	UK/RoW	181	Steel products (24.1-24.3)	Fewer new steel sections would be bought by the construction industry	100%	181	Y
<i>Total</i>			<b>56920</b>			<i>Total</i>	<b>6088</b>	

<b>Purchasing sector (region)</b>	<b>Sector supplying goods and services (SIC code)</b>	<b>Region</b>	<b>Value of monetary flows in 2011 (£m)</b>	<b>Sub-sector impacted by reuse (SIC code)</b>	<b>Expected impact of material efficiency strategy (based on interview evidence)</b>	<b>Sub-sector turnover/Total sector turnover (ONS 2014a)</b>	<b>Maximum value impacted by reuse (£m)</b>	<b>Modelled?</b>
Rental & leasing services (UK)	Manufacture of motor vehicles (29)	UK/RoW	500	Manufacture of motor vehicles (29.1)	More cars would be bought by rental and leasing companies to meet increased demand from car club members	24%	121	Y
Rental & leasing (UK)	Trade & repair services of motor vehicles (45)	UK/RoW	1,242	Sales of motor vehicles (45.11)	More cars would be bought by rental & leasing companies to meet the increased demand from car club members.	69%	854	Y
		UK		Repair & maintenance (45.2)	A larger car club fleet would mean higher expenditure on car repair & maintenance	15%	190	Y
Rental & leasing (UK)	Insurance & re-insurance (65)	UK	166	Non-life insurance (65.12)	A larger car club fleet would mean higher expenditure on car insurance.	30%	50	Y
Households (UK)	Rental & leasing activities (77)	UK	5,456	Rental & leasing motor vehicles (77.1)	Household expenditure on car rental would increase to reflect an increase in car club membership	47%	2,564	Y
Households (UK)	Manufacture of motor vehicles (29)	UK/RoW	16,587	Manufacture of motor vehicles (29.1)	Household expenditure on new cars would fall if car club membership defers private purchases	24%	4,044	Y
	Trade & repair services of motor vehicles	UK/RoW	20,976	Sales of motor vehicles	Household expenditure on second-hand cars would fall if car club memberships defers	69%	14,293	Y

(45)		(45.11)	private purchases		
		Repair & maintenance (45.2)	Household expenditure would fall if fewer cars are privately owned	15%	3,189
	48,459	Non-life insurance (65.12)	Household expenditure would fall if fewer cars are privately owned	30%	14,771
	<i>Total</i>	<b>93,384</b>		<i>Total</i>	<b>40,198</b>

#### 5.1.4 Modelling assumptions

The supply chain changes detailed in Table 5.3 were used to guide the modification of sector labour intensity, sales volumes and product prices in the MRIO model for the year 2011. Returning to the model description in Section 5.3.1, inter-sector monetary flows (intermediate demand) and payment by customers for finished goods and services (final demand) can be thought of as:

$$\begin{aligned}u_{ij}^{sr} &= Q_{ij} * P_j \\y_j^{sr} &= Q_{ij} * P_j\end{aligned}\tag{5.6}$$

To recall,  $u_{ij}^{sr}$  is intermediate demand and shows the amount spent by each industry  $i$  in region  $s$  on product  $j$  from region  $r$  and  $y_j^{sr}$  shows how much is spent on product  $j$  made in region  $r$  by customers as final demand in region  $s$ . This is equivalent to the quantity of product  $j$  purchased from sector  $i$  in region  $r$  ( $Q_{ij}$ ) multiplied by the price per unit of product  $j$  ( $P_j$ ). It is assumed that products are priced the same across regions. The interviews and literature review provided estimates of current product sales volumes and product prices and how these might change between certain sectors following the introduction of the material efficiency initiative. This enabled new estimates of intermediate and final demand that were calculated using the equations:

$$\begin{aligned}u_{ij}^{sr(new)} &= Q_{ij}^{(new)} * P_j^{(new)} \\y_j^{sr(new)} &= Q_{ij}^{(new)} * P_j^{(new)}\end{aligned}\tag{5.7}$$

**Table 5.4: List of changes made to the Input-Output table in the steel reuse case study**

Product/ service	Sector		Original physical flows	Original monetary flow in IO table			New Physical flows		New monetary flows in IO table		
	Supplier (region)	Customer (region)	Sales of steel sections (source)	Sales in 2011 (£m)	£/t steel section	Method (source)	Sales of steel sections	Explanation (source)	£/t steel section	Explanation (source)	Sales in 2011 (£m)
Deconstruction of buildings	Demolition (UK)	Construction (UK)	n/a	109	n/a	n/a	250Kt	Estimated total mass of steel sections that could be extracted in the UK if buildings are deconstructed instead of demolished (Ley et al., 2002)	135	Deconstruction costs more than demolition. Price/t from Geyer and Jackson (2004)	143
Reused steel sections	Demolition (UK)	Construction (UK), Fabricated metals (UK)	n/a	0	0	n/a	25Kt	Proportion of extracted steel sections that are suitable for reuse (interviews)	225	Assumed to be as least as much as the scrap price (letsrecycle.com) plus net cost of deconstruction over demolition.	6
New steel sections	Basic iron and steel (UK, RoW)	Construction (UK), Fabricated metals (UK)	1030Kt (ISSB, 2008)	464	450	See Fig. 5.3	1005Kt	25Kt of new steel sections are replaced by reused steel (interviews)	450	n/a	453

**Table 5.5: List of changes made to the Input-Output table in the car sharing case study**

Sector		Original physical flows	Original monetary flows in IO table			New physical flows		New monetary flows in IO table		
Product /service	Supplier (region)	Customer (region)	Annual sales (source)	Sales in 2011 (£m)	Price per unit	Method (source)	Sales (low; high)	Explanation (source)	Price per unit	Sales in 2011 (low; high) (£m)
Car club membership	Vehicle rental & leasing (UK)	Households (UK)	185,000 members <sup>(a)</sup>	305	£350/member	Av. usage per year <sup>(a)</sup> * av. member costs per year <sup>(c)</sup>	300,000; 1M members	Estimated membership by 2020 <sup>(d)</sup>	£350/member	345; 590
Private cars	Manufacture & sale of motor vehicles (UK, RoW)		2 M new car registrations per annum <sup>(b)</sup>	20,100	£10,050/car	Monetary sales ÷ physical sales	2 M; 1.94 M new car registrations	Considers cars club vehicles per member & private car displacement rate <sup>(a)</sup> & proportion of displaced cars that are new <sup>(e)</sup>	£10,050/car	20,096; 19,534
Private car	Insurance		31.4 M cars	18,840	£600/car		31.39 M;	Private vehicle	£600/	18,839;

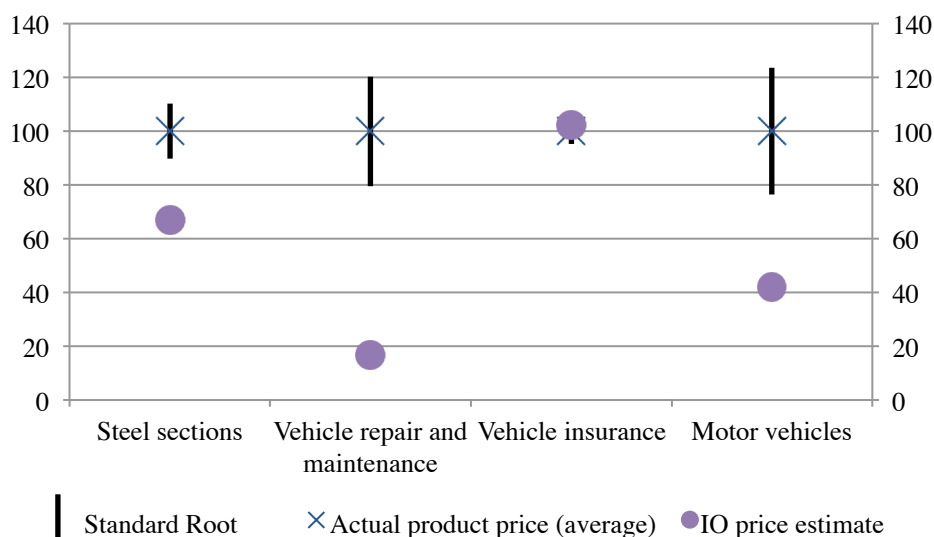
insurance (UK)		in UK fleet (b)				31.34 M cars in UK fleet	displacement rates <sup>(a)</sup>	car	18,806
Private car maintenance & repair	Maintenance & repair (UK)		3,120	£99/car				£99/car	3,108; 3,103

Sector			Original physical flows	Original monetary flows in IO table			New physical flows		New monetary flows in IO table	
Product /service	Supplier (region)	Customer (region)	Annual sales (source)	Sales in 2011 (£m)	Price per unit	Method (source)	Sales (low; high)	Explanation (source)	Price per unit	Sales in 2011 (low; high) (£m)
Car club vehicles	Manufacture & sale of motor vehicles (UK, RoW)	Rental & leasing sector	2,850 car club vehicles <sup>(a)</sup>	28	£10,050/car	Same price as private cars	4,615; 15,385 car club vehicles	Considers estimated membership in 2020 <sup>(d)</sup> and car club vehicles per member <sup>(a)</sup>	£10,050/car	45; 155
Car club vehicle insurance	Insurance (UK)			2	£600/car				£600/car	3; 9
Car club maintenance & repair	Maintenance & repair (UK)			0.3	£99/car				£99/car	0.5; 2

Sources: (a) Steer Gleave Davis, 2015; (b) SMMT, 2015; (c) Average annual membership costs of Zipcar, Drive Now, City Car Club & Go Wheels; (d) Industry interviews detailed in Section 5.1; (e) University of Buckingham, 2013.



Tables 5.4 and 5.5 list all of the changes made to the model in each case study. Product prices were estimated from combining mass flows and monetary flows detailed in Figure 5.3. These were compared to actual historical price data for the year 2011 taken from a number of sources. Figure 5.4 shows the MRIO price estimate as a proportion of actual product prices. Aside from vehicle insurance, most product prices in the model were underestimates.



**Figure 5.4: Estimated product prices used in the MRIO model shown as a percentage of actual historical product prices and the standard root.**

The divergence in estimated prices and historical prices may be due to a number of modelling assumptions. First, sub-sector sales to other sectors were apportioned using total sub-sector turnover as a proportion of total sector turnover. This proportion was assumed to be constant across all purchasing sectors. Second, it was challenging to accurately identify which sectors were supplying what sub-products, particularly if these were priced differently across sectors. Third only a limited number of sources were available to use to convert mass flows into equivalent monetary flows in the model. Data from the years 2004–2015 were used. In spite of these potential uncertainties, the estimates used to amend sales volumes, product prices and labour intensity were based on best available information and could be amended easily if further information became available. The new monetary flows between sectors detailed in Tables 5.4 and 5.5 were changed in the Input-Output table for the year 2011. Total sector spend was held constant by modifying the vector of value added in both case studies. For example, any money saved on material expenditure was assigned as

increased profits for the purchasing sector. In the reuse case study, total spend by final customers fell by around £20m in the low case and increased by £330m in the high case. These changes in total spend would lead to very small changes in induced employment and this calculation was omitted from the analysis. Equations 5.1 – 5.5 in Section 5.3.1 were then used to calculate the new direct and indirect employment to meet UK demand for products following an increase in the number of car club members ( $M^{car\ club}$ ) and reused of steel sections in UK construction projects ( $M^{reuse}$ ). Matrices showing the net change ( $N$ ) in labour requirements as a consequence of these two strategies were calculated by:

$$\begin{aligned} N^{re-use} &= M^{reuse} - M \\ N^{car\ club} &= M^{car\ club} - M \end{aligned} \tag{5.8}$$

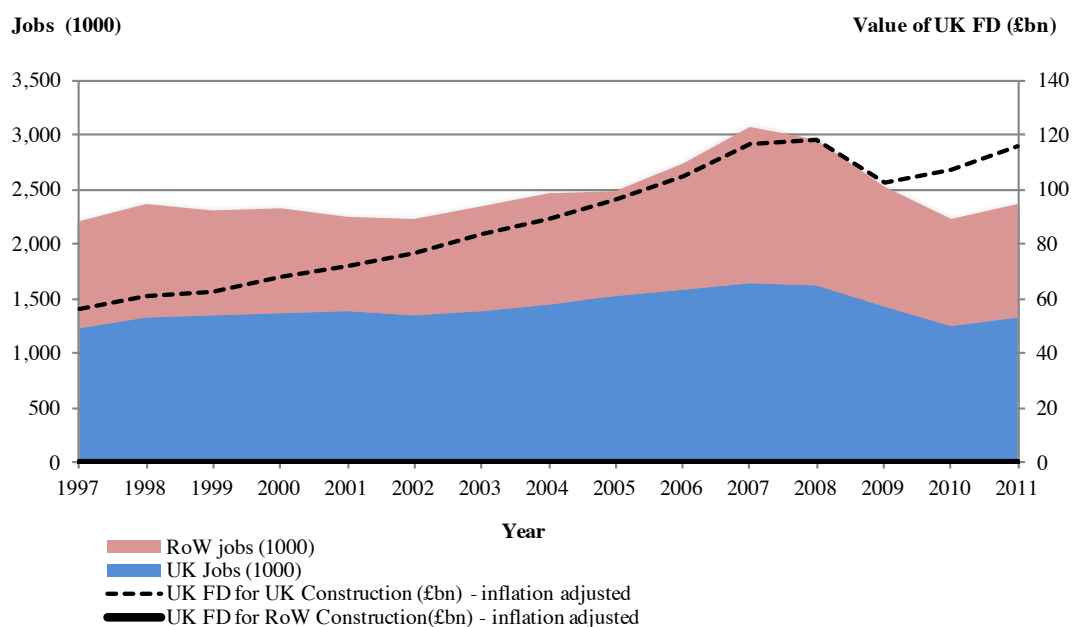
## *5.2. Employment impacts of material efficiency case studies*

This section presents the results of the multi-method approach described in Section 5.1. Section 5.2.1 shows historical supply chain employment for the UK construction and UK motor vehicle manufacturing sectors. Section 5.2.2 shows the net change in supply chain labour requirements for each material efficiency initiative.

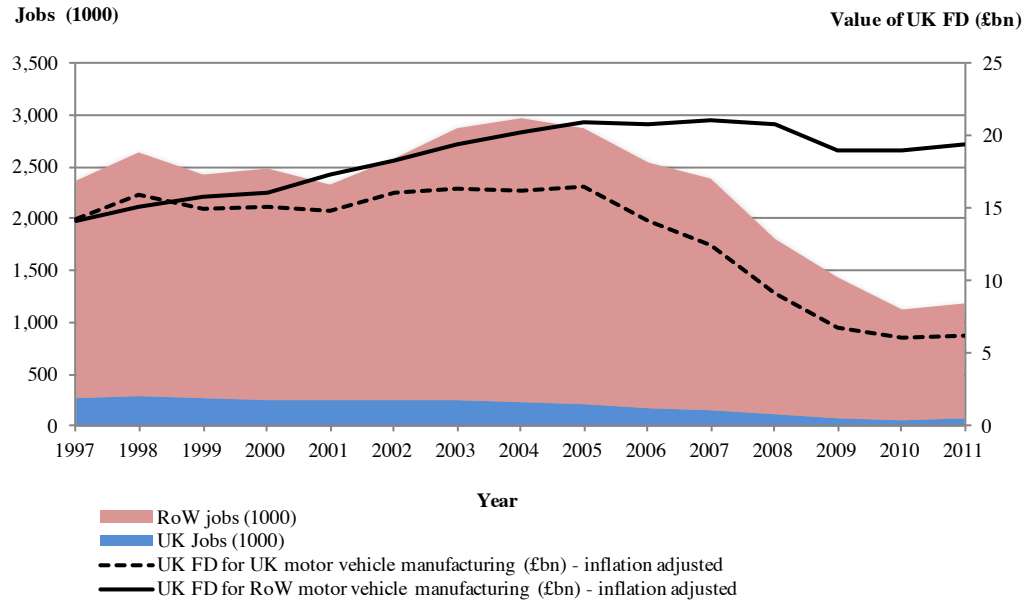
### *5.2.1. Historical supply chain employment trends*

Figures 5.5 and 5.6 show direct and indirect supply chain employment to meet UK final demand for construction and motor vehicle manufacturing. Figure 5.7 shows total UK employment in the motor vehicle manufacturing supply chain to meet UK and export demand for vehicles. These historical changes are useful for evaluating the relative size of change in employment in the two material efficiency case studies. Figure 5.5 shows UK final demand for construction increased at a constant rate of around 8% per annum between 1997 and 2011 except during the 2008–2010 recession. Approximately 60% of supply chain employment for construction is located in the UK. The division of supply chain employment between the UK and RoW remained constant from 1997 to 2004. From 2004 onwards, higher final demand created relatively more jobs abroad. Further analysis of the data shows RoW employment increased most in wood, glass, rubber,

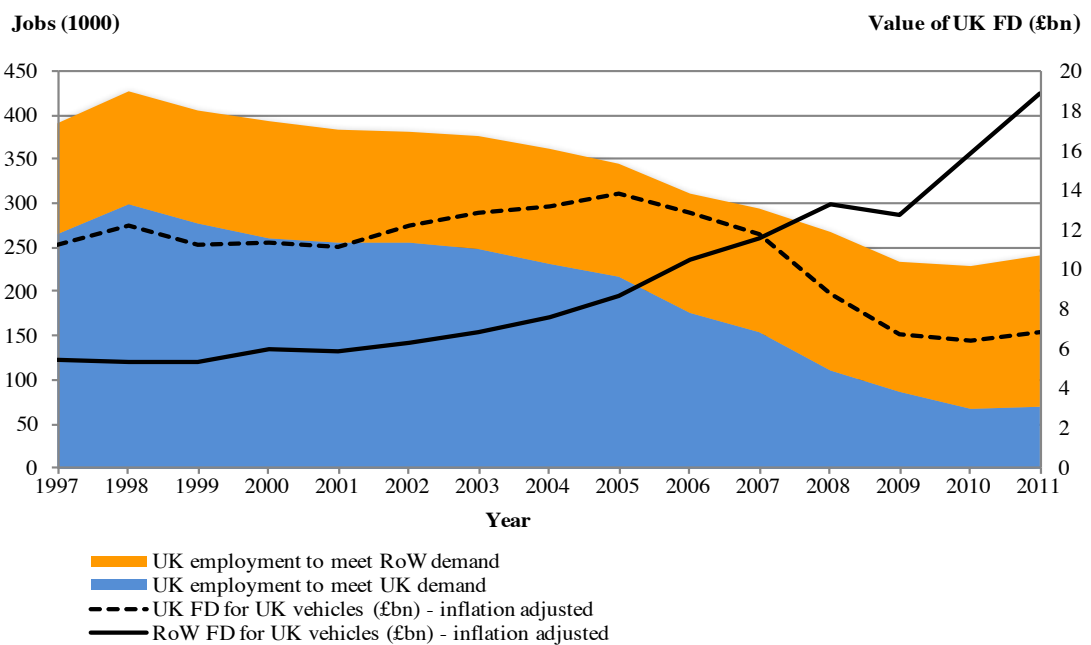
machinery and equipment manufacturing sectors. Domestic suppliers met around 99% of all UK final demand for construction. Conversely, Figure 5.6 shows that in 2011, UK motor vehicle manufacturers met only 25% of UK final demand for motor vehicles, down from 50% in 1997. Instead, UK manufacturers focused more on export markets, as is shown by the rise in ROW final demand for UK motor vehicles in Figure 5.7. Although the total value of UK and ROW final demand for UK motor vehicles was 50% higher in 2011 than 1997, total UK supply chain employment fell by around 100,000 jobs. This may have been due to increasing automation in the motor vehicle industry. Given the high reliance on motor vehicle imports in the UK, changes to UK final demand for vehicles, for example through increased car club membership, is unlikely to have a large impact on UK motor vehicle manufacturing employment. However, there will probably be impacts on sectors that provide complementary products and services associated with personal mobility.



**Figure 5.5: MRIO modelling results showing historical domestic and international supply chain employment to meet UK demand for construction between 1997 and 2011. Inclusion of the value of UK final demand over the same period.**



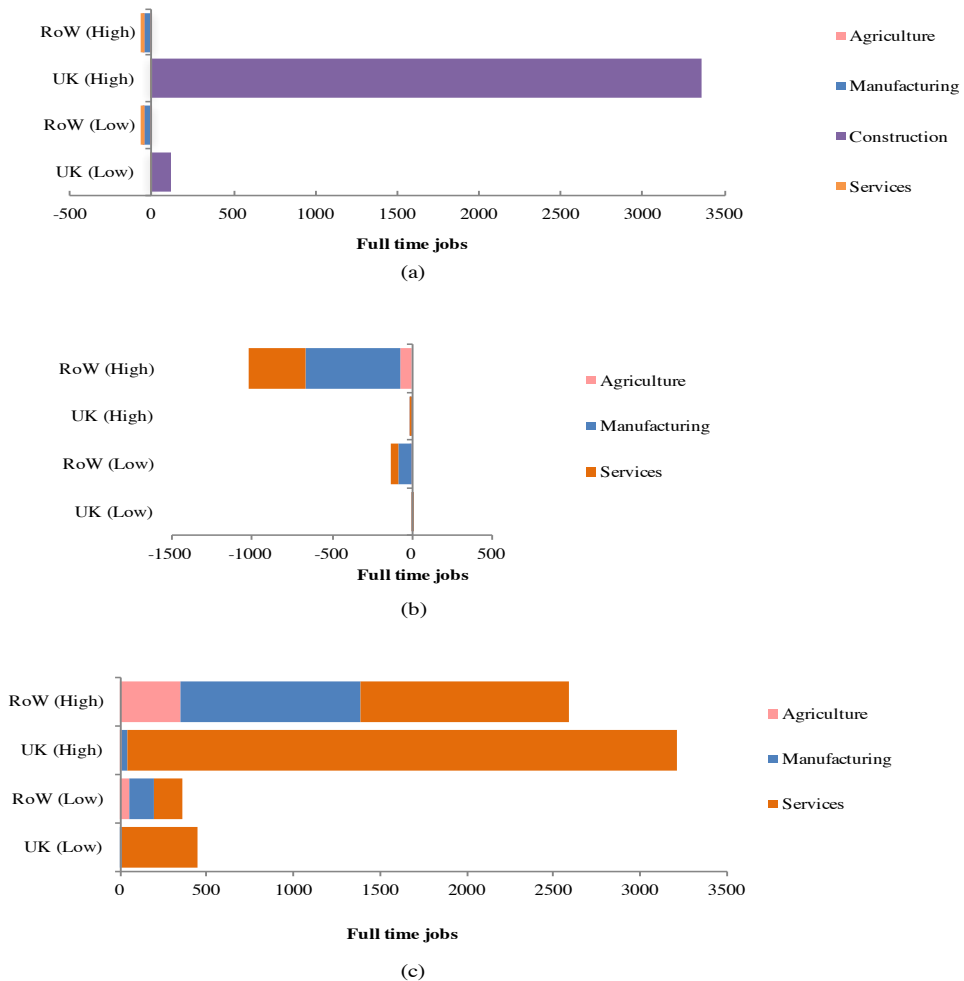
**Figure 5.6: MRIO modelling results showing historical domestic and international supply chain employment to meet UK demand for motor vehicles between 1997 and 2011. Inclusion of the value of UK final demand over the same period.**



**Figure 5.7: MRIO modelling results showing historical domestic and international UK motor vehicle manufacturing supply chain employment to meet UK and RoW demand between 1997 and 2011. Inclusion of the value of UK and RoW final demand over the same period.**

### 5.2.2. IO modelling estimates of potential supply chain employment impacts

The estimated employment impacts of material efficiency improvements from the two case studies are presented in Figure 5.8(a),(b),(c). Potential changes in employment are shown as the net changes in indirect and direct supply chain labour requirements for full time workers. Only three supply chains incurred non-negligible (>1000 full time employees) changes in labour requirements.



**Figure 5.8 (a) MRIO modelling results showing the net change in supply chain labour requirements for UK construction demanded in the UK as a consequence of increasing the amount of reused steel sections. Figure 5.8 (b) MRIO modelling results showing the net change in supply chain labour requirements for RoW vehicle manufacturing demanded in the UK as a consequence of increasing the number of car club members. Figure 5.8 (c) MRIO modelling results showing the net change in supply chain labour requirements for UK rental and leasing demanded in the UK as a consequence of increasing the number of car club members**

For the reuse of steel case study shown in Figure 5.8(a), the results show that:

- The change in employment is **negligible** in the *low case*
- **3,000 additional** full time UK construction workers would be employed in the *high case*

The increase in construction sector employment in the *high case* is due to the higher labour intensity of deconstruction compared to demolition in the high case scenario. However, the modelled change in construction sector employment was small relative to actual historical annual fluctuations in employment shown in Figure 5.5 and seasonal fluctuations reported by the ONS (2012). In 2012, all construction sector employment, including self-employment, varied by 70,000 workers. In the modelling exercise, the change in total domestic and international labour requirements in the fabricated metals sector was small, less than 35 workers in both the low and high cases. Although the modelling approach doesn't include any price changes and associated rebound effects, it is reasonable to assume that the additional time to deconstruct, clean and test steel sections might increase the cost of construction projects using reused steel. However, it is unclear how this would change over time, for example if an emerging market for reused steel experienced economies of scale. It is unlikely that the proposed rate of steel reuse in the modelling exercise would influence the price of new steel as this is largely driven by global supply trends. Further work could be conducted to see if the domestic market for steel scrap would be impacted by a fall in the supply of steel sections.

For the car club case study, the vehicle manufacturing supply chains in Figure 5.8(b), show that:

- The change in employment is **negligible** in the *low case*
- **500 fewer jobs** are needed in the RoW vehicle manufacturing supply chain in the *high case*
- There is **no change** to employment in the UK vehicle manufacturing supply chain in the *high case*.

These modelling results show that the UK motor vehicle manufacturing supply chain employment is fairly insulated from changes in UK demand for car sharing. This is because UK cars are predominantly exported.

For the car club case study, the rental and leasing supply chains in Figure 5.8(c), the show that:

- **500** more UK jobs are needed in the *low case* and **3200** in the *high case*.
- **Around half** of the new UK jobs are in the rental and leasing sector and retail and repair of vehicles sector.
- The decline in RoW employment in figure 5.8 (b) due to a fall in private vehicle purchases is more than offset by the increase in RoW employment from increased car sharing in figure 5.8 (c). Across the two supply chains, there is a net increase of **1500 full time jobs in the RoW**.

A key point to note is that the car club case study might actually increase the number of new vehicles purchased in the UK. Interviewees indicated that due to higher usage rates and customer perceptions around vehicle conditions, car club vehicles are replaced on average every 12-18 months. Private vehicle displacement rates of new vehicles would need to be sufficiently high to ensure that the high annual turnover of car club vehicles would still result in a net reduction in new vehicle purchase rather than a displacement from private to shared ownership. Again, the modelling results do not show how the UK might transition to a higher number of car sharers or any potential rebound effects. Of potential importance are the impact of increased car club members on the volume and prices of cars in the second hand market. Assuming all car club vehicles were retired after a year of use, the volume of 0–2 year-old cars in the second hand market could increase by around 2% based on data presented in University of Buckingham (2013). It is unclear if this would impact on prices of vehicles in the second- hand market. Further research is therefore required to gather evidence on these and other feedback mechanisms, which can be used to make informed assumptions in future modelling work.

This discussion has shown that a simple modelling exercise, such as this manipulation of a static IO model, can be suitable for estimating the employment impacts of material efficiency improvements via different strategies and across different supply chains. The simplicity of the model also contributes transparency and there are clear areas for further enquiry – either through more sophisticated modelling techniques or to investigate some of the findings, for example around the ‘goodness’ of the construction sector employment data or the risk of a net increase in vehicle purchases due to high replacement rates in car clubs. These findings may be just as relevant for policymakers

as the estimates on employment impacts and the simple modelling framework make them relatively easy to communicate and require less modelling expertise compared with more complex models, such as CGE or macroeconomic, which have more feedback mechanisms and underlying economic assumptions.

### *5.2.3. Limitations of the modelling results*

Kanemoto & Murray (2013) list a number of limitations associated with all MRIO studies. These include: a lack of distinction between products and industries, differences in sectoral classification across regions and a time lag between publishing MRIO tables. Hawkins et al. (2007) identify additional limitations as the absence of economies-of-scale and the assumption that the input structure for producing imports is the same as domestic industries. However, Muradov & Bayhaqi (2013) argue that these limitations are counteracted by a number of advantages of MRIO analysis, in particular its simplicity, accessibility and the use of nationally reported statistics, meaning the underlying modelling data is used consistently. Recognising these potential methodological challenges, there is a precedent for the analysis presented in this chapter. A number of other studies have used a static MRIO model to compare different states of the economy including Skelton and Allwood (2013b), Bordigoni et al. (2012) and Morgenstern et al. (2004).

There are also limitations specific to this study. Due to limited data availability, many proposed changes to the supply chain detailed in Table 5.3 could not be modelled or were estimated from a single source which reduces their reliability. For example, in the reuse case study, transportation, cleaning, certification, storage, specifying and sourcing of steel were all omitted from the analysis. It is reasonable to assume these all activities would be conducted in the UK, as transporting steel over longer distances would increase costs and reduce the incentive to select reused steel sections over new steel. The model does not include estimates on any potential new domestic jobs from these activities. The modelling work also omitted any potential employment impacts associated with reusing other materials in construction, since deconstruction could increase the salvageability of all materials. As only part of the changes to the supply chain could be modelled and induced impacts, from a change in household wealth, are omitted, the change in domestic labour requirements in the reuse case study is likely to be an underestimate. There are also uncertainties regarding the underlying the model data. van den Brink and Anagboso (2010) note that the employment in the construction



sector is challenging to accurately estimate as the ONS's method of data collection, on which the MRIO employment data is based, tends to underestimate the output of small businesses and around 40% of the construction sector are self-employed sole traders. For simplicity, the model also includes the assumption of no net change in supply chain costs. Even in the case of employment creation, total value added was held constant so any increase in the sector wage bill was offset by an equivalent reduction in taxation or profit. In reality this is highly unlikely and even if the net impact on sector costs were zero, firms within the sector would be impacted differently as they are non-homogenous. Due to the model structure, there is also the assumption that all labour requirements increases linearly with output, ignoring any productivity gains or economies of scale. While this might be true for some roles, in reality it does not hold for all sectors. Interviews with car club operators revealed that the labour requirement in many of their business functions were either unrelated or non-linearly related to the number of car club members. It should also be noted that interview responses are only useful for characterising current understanding of these two material efficiency strategies. There are additional uncertainties regarding how these strategies might be scaled up, which may not be fully reflected in the interview responses because of the lack of precedent. The chosen modelling approach is useful for providing a first indication of the likely scale and location of immediate changes in direct and indirect supply chain employment but there is a high degree of uncertainty regarding how these sectors may transition to more materially efficient practices and how prices and demand may evolve. It is for this reason that the results should be interpreted as 'potential supply chain employment impacts'.

### *5.3. Discussion*

To recall, the question outlined at the beginning of this chapter was:

***Q3: What would be the macroeconomic impacts of more efficient material use in the UK?***

The results in this Chapter shows that more efficient material use would lead to a modest increase in UK employment. The lack of feedback mechanisms in the model means these results should only be interpreted as the immediate, short-term impact.

The multi-method approach presented in this chapter has also demonstrated that many different assumptions need to be made which influence the modelling results including the rate, geographical spread and approach to implementing material efficiency strategies (for examples, see Table 2.2 in Section 2.1.7). These assumptions may not be immediately apparent to a policymaker, either because they don't understand some of the underlying economic theory (for example the assumptions of market clearance, zero profits and imperfect competition underpin CGE models), or because they could not know in advance what variables could influence the modelling results. Through the process of conducting this research and bearing in mind the different priorities and expertise of policymakers, academics and industry practitioners, this Chapter has also outlined some of the many uncertainties associated with accurately modelling future employment impacts of a change in material demand.

In addition to providing estimates on the employment impacts of material efficiency improvements in the UK, the transparent, multi-method approach used in this chapter outlines important considerations for policy development. First, the mode for implementing material efficiency strategies is extremely important. For example, as discussed in Section 2.1.5 of this thesis, car club are perceived to improve material efficiency because they encourage greater intensity of use. However, the interviews and modelling results show they could confound this assertion if they increase demand for new as opposed to second-hand vehicles. To ensure car clubs are truly materially efficient, car club vehicles would need to be replaced infrequently and displacement rates for private vehicles would need to be high. Second, there may be trade-offs associated with different modes of strategy implementation, which need to be understood and evaluated. Continuing with the example of car clubs, the potential for supply chain employment creation would depend on how the car club operates. Car clubs that rely more on technology platforms to rent out car club vehicles, often the case with peer-to-peer car sharing, would create fewer job opportunities than those operators who rent out vehicles using call centres. However, peer-to-peer car sharing would be more materially efficient as no new vehicles are manufactured for use in the car sharing fleet. Finally, policymakers need to give further consideration to the likely evolution of supply chain costs and any rebound effects. For example, the reuse case study showed potential employment creation would be concentrated in the construction sector because of the assumption that all buildings in the UK were deconstructed rather than demolished. Increased deconstruction costs would increase overall project costs, which

might incentivise cost-cutting in other areas e.g. switching new steel for reused steel. These secondary impacts are not modeled in this chapter as one of the described limitations to the modelling is the assumption that supply chain costs are held constant. Skelton and Allwood (2013b) show that there is little incentive to introduce material efficiency strategies along the supply chain because labour costs are relatively higher than material costs. Therefore, there is likely to be little incentive to increase labour costs further by employing more deconstruction workers to salvage steel. There are also technical limits to the substitutability of the two factors of production. Even if labour was relatively cheaper than steel, there would be a limit to how much reusable steel could be salvaged from construction sites. If more people were employed to deconstruct buildings there would eventually be diminishing marginal returns on additional units of labour. Steel is also cheap relative to the total value of a building. Allwood and Cullen (2012) estimate that the steel purchased to manufacture a 7-storey office block accounts for only 3% of the total building costs. Even during times of high or volatile prices, as discussed in Chapter 3 after the 2007-2009 economic downturn, the sheer number of workers involved in designing, constructing, surveying, decorating, managing etc. a building project far outweigh the material costs. As a result, the construction sector may prioritise cost-cutting activities in other areas aside from material efficiency.

This chapter has shown, through a transparent approach to case study development, that both the modelling process and modelling outputs can provide important insights to inform policy development. Further academic research on this topic is suggested in Chapter 6.

# 6. Conclusions

This multidisciplinary thesis has explored a number of questions that help to explain why there may be unrealised technical opportunities for implementing material efficiency innovations related to steel use in the UK. Chapter 3 focused on understanding what socio-technical factors guide the process of designing and manufacturing vehicles in the UK. These factors were then applied as a conceptual framework to understand what features of the UK automotive industry's operating context are contributing to current upward trends in material throughput. Chapter 4 applied Kingdon's (1995) Multiple Streams Framework to evaluate features of the UK's policy and political landscape that explain why material efficiency solutions are currently a limited part of the UK policy agenda to reduce GhG emissions from cars. Finally, Chapter 5 presented a transparent multi-method approach for developing case studies for inclusion in a static multi-region input-output model to evaluate the employment impacts of individual material efficiency strategies. This Chapter concludes this thesis by outlining the contribution to knowledge from this research (Section 6.1) and suggesting activities for industry practitioners, policy entrepreneurs and academic researchers that could support further implementation of material efficiency innovations related to steel use in the UK (Sections 6.2-6.4).

## 6. 1. Contribution to knowledge

This thesis made the following contributions to knowledge in response to the research questions identified in Chapter 1.

*Q1: Why are there unrealised opportunities to implement material efficiency improvements in UK industry?*

Industry uses material as an input to production. In the automotive sector, the efficiency of material use is an outcome of the decisions and actions taken during the vehicle design and manufacturing process. A novel contribution from Chapter 3 is the theory that in the UK this process is guided by six connected socio-technical factors, namely: (1) customer preferences; (2) market positioning; (3) techno-economic feasibility; (4) supply chain feasibility; (5) regulation and (6) organisational attributes. These factors were identified through an iterative process of data collection (semi-structured interviews with twelve experts working in the UK automotive supply chain) and data analysis involving coding and grounded theory development, substantiation and refinement. These factors were then used as a conceptual framework to characterise the UK automotive industry's operating context and examine what features contribute to current upward trends in material throughput. Material throughput was shown to depend on vehicle throughput and vehicle material intensity. A number of conclusions were reached which respond to (*Q1*).

- Decisions and actions taken by the automotive industry that impact on material use are embedded within a complex design and manufacturing process involving thousands of individuals. These individuals have competing organisational priorities and their actions will be guided by longstanding routines, relationships and expertise informed by previous experience. The opportunity to reduce the material intensity of vehicles as a way of reducing GhG emissions from cars is evaluated by this network of actors alongside other socio-commercial considerations. Current trends in vehicle material intensity indicate that in the UK automotive industry these other considerations supersede any perceived potential benefits from more efficient use of materials.
- Many features of the industry's current operating context disadvantage practices that involve optimising the material efficiency of component parts in each model through lightweight design or materials. For example, more time would be

required to design and test each component and there may be reduced purchasing and manufacturing economies-of-scale if component designs are not transferable across models.

- The industry's current business model, favouring high vehicle throughput, is very mature and there is longstanding investment in expertise and capital. Reorientation to alternative business models and forms of value capture based around lower vehicle throughput and longer life vehicles would require complex business model innovation and/or product innovation. Chapter 3 provided evidence that this transition may be perceived by the automotive industry as both costly and risky. This can act as a deterrent to innovation.

### *Q2 - Why are few material efficiency policies implemented in the UK?*

Chapter 4 of this thesis applied Kingdon's (1995) Multiple Streams Framework (MSF) to explain why material efficiency remains a small part of the UK policy agenda to reduce GhG emissions from cars. Data from semi-structured interviews with policy entrepreneurs internal and external to the UK government were triangulated with other policy documents to develop, refine and substantiate the discussion in Section 4.2. A number of features of the recent UK political and policy landscape are observed in response to (Q2):

- Current UK climate policy regulation is focused on reducing domestic GhG emissions only. Figure 1.1. shows that in 2007 only 5% of all steel that ended up in UK cars was produced in the UK. There are no regulatory provisions to reduce emissions generated from international material production, including steel, to meet UK demand. The regulatory focus on domestic GhG emissions also means that inefficient material use is currently only perceived as a public problem insofar as it increases in-use vehicle emissions, which explains some policy support for lightweight vehicle design and car clubs.
- UK policymakers appear to have little capacity or interest in expanding the policy agenda to consider full lifecycle GhG emissions from cars which would favour all, rather than some, material efficiency strategies. Estimating lifecycle emissions and how they could be reduced through material efficiency improvements was viewed by interviewees as technically challenging and uncertain. The organisational structure in central government also favours a sectoral, rather than product lifecycle, approach to GhG emissions policy in the

UK. This can constrain policymaker's perspective on material efficiency opportunities and may mean that supply chain, producer-consumer or whole economy opportunities are overlooked.

- Material efficiency is not a commonly understood term by individuals shaping policies to reduce GhG emissions from cars in the UK. There is a lack of real-world and modelling evidence that material efficiency solutions could deliver cost-effective reductions in GhG emissions with economic co-benefits. These are identified as important evaluative criteria for UK policymakers when considering different policy and technical solutions to reduce GhG emissions.
- There appears to be decreasing political interest in improving the efficiency of resource use, including materials, in the UK. In the short-term, much political and public attention will be focused on the UK's departure from the EU. It is currently unclear if this will present a window of opportunity to redefine the UK vehicle GhG emissions policy, which is guided by EU regulation, to include material efficiency solutions.
- A small number of policy entrepreneurs outside of government and the UK automotive industry are promoting material efficiency solutions in the sector but they appear to have disparate priorities and are disadvantaged by fewer resources and less access to policymakers. This can limit their effectiveness.

*Q3: What would be the macroeconomic impacts of more efficient material use in the UK?*

Chapter 5 of this thesis presented a transparent approach for developing case studies for use in Multi-Regional Input-Output modelling exercises that examine the employment impacts of material efficiency improvements. The case studies explored were (1) increasing the number of reused steel sections in the construction industry and (2) increasing the number of car club users. The multi-method approach involved: interviews with industry experts to identify probable changes to the supply chain due to each case studies and potential scale of deployment; a literature review to corroborate and refine these proposed changes, augmentation of detailed steel price data to translate monetary units in the MRIO model into physical units and integration of MRIO data with other government issued data sets to inform further model disaggregation. A conclusion from this modelling exercise is that the initial, immediate consequences of these actions would not adversely affect employment prospects in the UK. In the car

sharing case study jobs would be created in the UK rental and leasing sector and in the retail and repair of vehicles sector. Since vehicles manufactured in the UK are predominantly exported, the UK motor vehicle manufacturing supply chain is fairly insulated from changes in demand for private vehicle ownership due to car sharing. There is a risk that car sharing actually increases demand for new vehicles if car club membership does not lead to high displacement of private vehicle ownership and if the car club vehicle fleet is replaced frequently. Employment in the UK construction sector increases in the steel reuse case study because deconstructing rather than demolishing buildings is labour intensive. Domestic labour is substituted for imported steel. However, due to data limitations, not all features of the reuse case study could be modelled so the results should be viewed only as a partial estimate.

Other contributions to knowledge come from the process of developing and modelling these two case studies. These insights are just as relevant for policymakers considering the policy interventions as they highlight potential variabilities and uncertainties with modelling results.

- Material efficiency innovations can be implemented in a variety of ways. Each mode of implementation may have distinct macro-level impacts and there may be trade-offs between impacts. In the car club case study, for example, employment creation would be higher if car club members joined a commercial car club that relies on operators who rent out vehicles from a call centre. However, peer-to-peer car sharing may be more materially efficient if existing, rather than newly purchased, vehicles become car club vehicles. Trade-offs can be best understood if there is a high degree of resolution when developing material efficiency case studies for use in modelling studies as each material efficiency strategy could be implemented in a variety of ways.
- The iterative process of verifying and modifying case study assumptions may be more time consuming but creates greater clarity on how particular modelling assumptions, innovation types and modes of implementation were chosen and why. This allows policymakers to understand the likely band of uncertainty in which policies need to be developed.



Chapter 1.5 of this thesis outlined a much broader question that builds on Q1-3 but goes beyond the case study of material efficiency in the UK. To tackle climate change and other complex social, environmental and economic issues, it is critical to reflect on:

***How could good research ideas, from engineering or otherwise, be developed into strategies to encourage take up by industry practitioners and policymakers?***

A number of conclusions can be developed from conducting this PhD research, which partly responds to this overarching question.

- Interdisciplinary research between engineers and social scientists can help to align technical solutions with motivations, priorities and operating context of the individuals engaged in reducing GhG emissions.
- Collaboration between engineers and social scientists is necessary but can be challenging because of the differences in underlying research philosophy. Engineering research tends to be more positivist and factual. For example, Allwood and Cullen (2012) show through a series of case studies that there is the technical potential to improve the efficiency of material use. However, this research is also value-laden as the authors conclude that the efficiency of material use should be improved to reduce GhG emissions. Another engineer who doesn't value the environment so highly might conclude that if material efficiency improvements are too costly then there shouldn't be any strategies introduced. The interpretivist philosophy underpinning much of the research in the social sciences more explicitly considers these differences in underlying values. The qualitative analytical tools in the social sciences are also well suited to investigating if the same technical solutions are perceived differently by different individuals.
- Combining insights from different social sciences can provide the building blocks of a strategy to encourage the uptake of new ideas. For example, Chapter 2.3.1 shows that industry practitioners and policymakers experience bounded rationality and capacity constraints. Chapter 2.2.2 shows that once a particular attitude or behaviour has been established they can be difficult to change due to system stability. Therefore good research ideas need to be promoted by a community of individuals (Chapter 4.2.4) in a way that leads to consistent understanding (Chapter 4.2.2), during timely windows of opportunity (Chapter 2.3.1). These new ideas may appear to compete with existing socio-commercial

priorities within industry (Chapter 3.3) or be misaligned with prevailing political norms (Chapter 4.2.3) or policy cycles (4.2.1). The anecdotal evidence in this thesis shows that having a good idea is requisite but not necessarily sufficient to bring about widespread real world change.

- While the six engineering strategies for material efficiency were the starting point for this thesis. An alternative approach would have been to use the operating context of the policymaker or industry practitioner as a starting point for the analysis and match this up to technical emissions reduction solutions, which would include material efficiency among others, with their operational priorities or values.

In spite of these challenges, industry practitioners, policymakers and academics could all take action to encourage the uptake of material efficiency improvements. This is explored in chapters 6.2-6.4. Many of the suggestions outlined are specific to steel but would have wider applicability to other materials.

## *6.2. Implications for industry practitioners*

The research in this thesis has mainly focused on the automotive industry. The discussion in this section are again specific to this industry but may also be of interest to practitioners in other industries where material efficiency opportunities are unrealised. Chapter 3 of this thesis showed that industry practitioners in the automotive industry interact with a network of actors in a broader socio-technical system that they also help to shape. The automotive industry's operating context, characterised by six socio-technical factors, could be purposefully altered by industry practitioners with the intention of reversing the current upward trend in material throughput. Examples of this could include:

- Influencing customer preferences for smaller vehicles through advertising campaigns. Autotrader (2016) reports that UK vehicle manufacturers collectively spent approximately £1.5bn on vehicle advertising, indicating that the automotive industry is experienced in, and sees the value of, shaping customer preferences.
- Investment in novel materially efficient products and processes, such as those listed in Table 2.3, to improve their future techno-economic feasibility.

- Developing supply chain capabilities to deliver more materially efficient component designs. As discussed in Sako (2004), the automotive industry has a history of developing their supplier capabilities to deliver joint benefits including: cost reduction, inventory reduction and quality improvement.

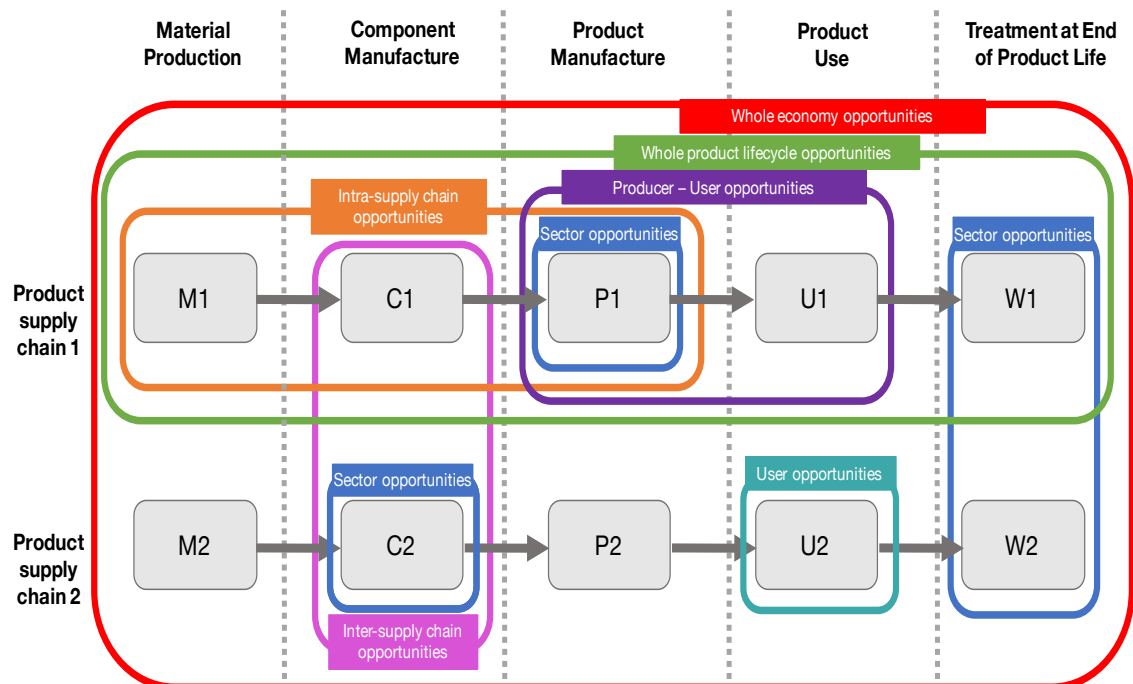
This thesis has highlighted many reasons why these individual actions might be unsuccessful in changing current trends in material demand due to system stability. Wells and Niewenhuis (2010), along with other socio-technical studies detailed in Section 2.2, outlined numerous sources of stability in the automotive industry, which favours the status quo. Chapter 3 also showed that that decisions around material use will be informed by many other considerations, not limited to the technical potential for material efficiency improvements.

A key implication for industry practitioners, therefore, is to be mindful of the opportunities for material efficiency improvements presented by emerging niche innovations and to be mindful of macro-level developments that could destabilize existing regimes. Industry commentators McKinsey & Company (2016) and PwC (2016) outline a number of niche innovations that may experience wider proliferation in the near term including: electrified vehicles; autonomous vehicles; additive manufacturing and on-demand mobility services. These innovations and new market entrants were discussed by many individuals who participated in interviews for Chapter 3 of this thesis. One commented that the UK automotive industry is “*probably in the greatest state of flux it has been since I entered the industry 25 years ago. There’s an awful lot of change happening at a rate which is unprecedented*”. Each of these innovations could mean vehicles are designed for different purpose or manufactured and used a different way, which could impact on vehicle material intensity and throughput. It is, however, challenging to anticipate the timing, acceptability and diffusion rates of these niche innovations.

### 6.3. Implications for policy entrepreneurs

Numerous actions could be taken by policy entrepreneurs inside and outside of government that might lead to further policy support for the implementation of material efficiency improvements in the UK automotive industry. These suggested actions may also be of interest to policy entrepreneurs who are working to promote material efficiency solutions for other materials, products and supply chains.

Chapter 5 outlined that the current organisational structure within government favours a sectoral approach to developing policies to reduce GhG emissions from cars and there is a focus on reducing emissions that originate in the UK. This favours light-weighting and increasing the intensity of vehicle use. Figure 6.1 shows how a sector level approach to identifying material efficiency opportunities is unlikely to be exhaustive. Figure 6.1 is a simplified schematic of two product supply chains. Each grey rectangle represents a different stakeholder involved in either manufacturing, using or treating a product at the end of its life. The letter in each grey rectangle denotes the type of stakeholder and the number in each grey rectangle denotes the product supply chain. For example C1 refers to all component manufacturers supplying parts to Product 1 manufacturers. Figure 6.1. shows there may be opportunities for material efficiency improvements through many different configurations of stakeholder collaboration.



**Figure 6.1. A systems approach for identifying material efficiency opportunities**

Many examples of these interactions could be conceived and this thesis has provided examples of these opportunities being realised by some companies in the UK.

- **Sector level opportunities** – e.g. reduction of product dimensions
- **Inter-supply chain opportunities** – e.g. industrial symbiosis by processing offcuts from a production line in one sector for use as an input in another.
- **Intra-supply chain opportunities** – e.g. lightweight design of component parts
- **Producer – user opportunities** – e.g. supply of product maintenance services to support product longevity
- **User opportunities** – e.g. keep products for longer, use products more intensively, share products
- **Whole product lifecycle opportunities** - e.g. design products for disassembly and material extraction
- **Whole economy opportunities** – e.g. a combination of designing products for disassembly and material extraction and supplying reusable materials as inputs to new product supply chains without re-melting.

Organisational restructuring within government may be required to ensure that all categories of material efficiency opportunities, that could help reduce GhG emissions throughout a product's lifespan, are not overlooked by policymakers working in sectoral silos. Further consideration should also be given to thematic overlap between different policy teams and departments. For example, policies around the treatment of vehicles at End-of-Life are currently within the remit of the waste team at the Department of Environment, Food and Rural Affairs. However, the steel reuse case study outlined in Chapter 5 has shown that if more reusable material can be extracted at the end of a product's life, there is the opportunity to displace virgin material production which is usually more emissions-intensive. Connections between resource, waste and climate change impacts need to be fully understood by UK policymakers. The recent merger between the Department of Energy and Climate Change and the Department of Business Innovation and Skills may present an opportunity for organisational restructuring and facilitate cross-Whitehall collaboration.

Public sector innovation funding may also need to be reviewed to ensure support is available for all three categories of innovation, process, product and organisational, that

deliver material efficiency improvements throughout a car's life. The Automotive Council's (AC, 2013) strategy document states that the current intention in government and industry is to support process and product innovation only. The Innovation and Technology team in the Automotive Sector division at the newly created Department for Business, Energy and Industrial Strategy is responsible for delivering funding for these two types of innovation. This includes the creation, jointly with industry, of a £1bn Advanced Propulsion Centre to support the development of new supply chains for low carbon vehicles over 10 years. This Centre supports the commercialization of innovative technologies, including lightweight designs and materials. It is relatively more challenging to identify funding sources for organizational innovation that could deliver material efficiency improvements. One example is a competition brief issued by Innovate UK (2016), the UK's Innovation Agency. The brief referenced material efficiency and was open to projects that delivered innovation in a manufacturing system, technology, process or business models. However, the total amount of funding available was only £5m and projects needed to demonstrate cross-sector applicability.

One option to expand funding to support organizational innovation that delivers material efficiency improvements is the creation of a new Catapult Centre. There are currently seven Catapult Centres, which aim to develop the UK's innovation capabilities by connecting businesses with the UK's research and academic communities. They are focused on developing innovations that are at Technology Readiness Levels 4-6. Technology Readiness Levels is an approach for evaluating the maturity of technology and identifying what action is required to encourage further maturation. Levels 4-6 signal that an innovation needs to be validated in a lab and external environment prior to commercialisation. The creation of a Material Efficiency Catapult Centre, which includes organisational innovation, builds on the suggestion made in Allwood (2016) for a Steel Catapult Centre. The author identifies Port Talbot as an appropriate site for trialling out new technologies and processes that can deliver upcycling of scrap steel and supply chain integration with downstream sectors that process steel. A Material Efficiency Catapult Centre, with more funding opportunities from Innovate UK, could help industry redefine how value is created from their material inputs, how value is delivered to customers and what approaches could be taken to make this process more materially efficient throughout a product's lifespan. Trialling out different modes of implementing material efficiency innovations would help

industry to: evaluate between options; identify potential challenges to achieving scale and identify what aspects of their current business model might be incompatible.

If the creation of a new Catapult Centre is viewed as too ambitious or resource-intensive, another option would be for policymakers to focus their efforts on sharing information about opportunities to implement material efficiency innovations in industry. UK policy precedents show that this could be delivered in a number of ways. However, following the recommendation in HMT (2008), any historical policy precedents should undergo a comprehensive evaluation to ensure that lessons learned are fed back into the decision-making process. First, there could be a network of government-funded consultants who assess plant-level or supply chain opportunities for material efficiency improvements, much like the assessments offered in the 2012-2015 Green Deal to improve the energy efficiency of the UK housing stock. A second option could be the creation of a new social enterprise, partly funded by the government, that is focused on sharing information on material efficiency opportunities for both industry and consumers. A similar service is provided by the Energy Savings Trust for energy efficiency savings. A final suggestion, which is informed by the 2003-2013 National Industrial Symbiosis Programme, is the creation a national network of industry representatives to share ideas about how to implement material efficiency innovations, within industry and across supply chains. It is possible that a window of opportunity may soon emerge for policy entrepreneurs to stimulate interest in these suggestions. The UK Government's recent Industrial Strategy Green Paper includes the assertion that *"increasing the efficiency of material use across the whole supply chain can deliver huge cost savings and improve the productivity of UK businesses"*. The Government's stated intention is to *"explore opportunities to reduce raw material demand and waste in our energy and resource systems...to promote well functioning markets for secondary materials, and new disruptive business models that challenge inefficient practice"*. The Industrial Strategy offers little clarity about how this could be achieved, which may present an opportunity for entrepreneurs to put forward some of the suggestions made in this Section.

If, after the Industrial Strategy public consultation process, it emerges that there is little political ambition or finance available to support material efficiency innovations, policy entrepreneurs could focus their efforts on internal communications. Chapter 5 showed that UK policymakers had low levels of awareness of the six material efficiency

strategies outlined in Allwood et al. (2012). Entrepreneurs in government could aim to create a clearer understanding about material efficiency solutions among their colleagues. For example, through face-to-face presentations and discussion or through written material that is circulated electronically. Lorenzoni and Benson (2014) show that discourse in institutions affects idea emergence and has previously helped normalise climate policy solutions in the UK.

Chapter 5 highlighted that a small and disparate community of policy entrepreneurs outside of government are promoting material efficiency solutions as an option to reduce GhG emissions. One recommendation is that these individuals collaborate with other entrepreneurs who are motivated more by other sustainability objectives, such as resource efficiency and the circular economy. Pralle (2006) suggests that redefining solutions, linking them to broader issues and sharing ownership could expand their appeal. Policy entrepreneurs outside of government could also ‘venue shop’, as discussed in Baumgartner and Jones (1993), to find the policy forum where they could have the most impact. Chapter 5 showed that level of political discourse around material efficiency has been high-level and non-technical and policymakers in central government interpreted the concept in different ways. Discussions on material efficiency solutions may be better suited to more technical policy forums in the UK, such as Chatham House, or events hosted by stakeholders in the automotive industry that are frequented by policymakers. Entrepreneurs could also try and raise public awareness of the GhG emissions impact, and broader sustainability impacts, associated with inefficient material use. Alternatively, they could focus on individual material efficiency solutions. This may entail: communicating the benefits of more materially efficient products; helping customers distinguish between more and less materially efficient products and providing information on how to use, and dispose of, products in a more materially efficient way.



## 6.4. *Future research agenda*

Academic research can support further industry and policy implementation of material efficiency opportunities in the UK. A number of topics for further investigation can be identified from the findings presented in Chapters 3-5 and the suggestions outlined in Sections 6.2 and 6.3.

The six socio-technical factors presented in Chapter 3 need to be tested and refined further to evaluate their applicability in different sectors and regions. This could include a direct replication of the study method outlined in Chapter 3. If these factors are found to be applicable in different industries and regions they could be used to compare and contrast operating contexts and identify favourable operating conditions for implementing material efficiency innovations. During this fieldwork further consideration could be given to: the stability or variability of each factor over time; whether there is an order of importance to the factors or whether they need to be considered collectively; whether these factors are comprehensive and critically, whether and how these factors interact. Testing and refining the factors could also involve further desk-based research. A number of studies from different disciplines have considered individual factors in great detail. ‘Customer preferences’, for example, are investigated in studies found in marketing, psychology and management journals. For examples, see Simonson (2005), Wakefield & Blodgett (1999) and Almquist & Lee (2009), respectively. A systematic evaluation of this multidisciplinary literature base would help identify any transferable insights that could help expand and refine these factors and connections between them. This process may also provide new ideas about methods to measure and test these factors or on different ways in which they could be applied. Returning to the example of ‘Customer Preferences’, Chrzan and Golovashkina (2006) measure the importance of various product attributes using six different methods and show that the choice of method can impact customer satisfaction results. In Section 3.4.1 one industry interviewee opined that if the vehicle weight was reduced by removing features such as electric seats, “*customer satisfaction would drop because they’ve become accustomed to having extra features*”. Future research could focus on testing this assertion using the different methods outlined in Chrzan and Golovashkina (2006) to identify which features contribute least to customer satisfaction. Once identified those features could potentially be removed to improve vehicle material intensity while minimising the impact on a customer’s experience.

Section 6.2 explored the concept of socio-technical transitions, which is informed by a diverse literature base including evolutionary economics, sociology of technology and neo-institutional theory. Future research could investigate how the transition to a more materially efficient socio-technical system of vehicle design and manufacture might be managed. This could build on the research by Smith et al. (2005) who explore options for exerting pressure on a socio-technical system to stimulate change, and for developing adaptive capacity to facilitate change.

Chapter 4 showed that the MSF is a suitable model for explaining why material efficiency is a limited part of the UK policy agenda to reduce emissions from cars. This research could be expanded on in two ways. First, by combining the MSF with other models of the policy process or theories from the social sciences to increase its explanatory power. Second, to use the MSF in an ex-post comparison of different policy and political contexts to understand what contributed to the introduction of material efficiency policies in other sectors and regions. The studies detailed in Section 2.3.2 might provide some initial ideas on theories that are complementary to the MSF. Institutional theory, for example, is employed in Buhr (2012) to explore how institutional entrepreneurs contribute to an institution's receptiveness to change. This might stimulate further ideas, beyond those in Section 6.3, on how entrepreneurs within government could help create a policy window and expand the climate policy agenda to include material efficiency solutions. Future research that applies the MSF for comparative purposes could begin with the policies detailed in Section 1.5. This includes a National Material Efficiency Programme in Finland, a proposed change in value-added-tax in Sweden and Scotland's Resource Efficiency Strategy.

Chapter 4 also highlighted what information would be useful for policymakers evaluating material efficiency solutions, but is currently unavailable. Collating this information, and developing appropriate indicators from it, could be an area of future academic research. This could include studies that: examine material and emissions flows through different sectors of the economy (for example see Serrenho et al., 2015), examine the efficiency with which this material is being used (for example see Serrenho and Allwood., 2016), identify realistic targets for material efficiency improvements for different materials and products (for example see Allwood et al., 2012) and benchmark these targets against current industry practices. Evidence is also needed on the potential

challenges, costs and impacts of implementing material efficiency improvements at the sector, supply chain, regional and national level. This information would help ensure material efficiency solutions are evaluated consistently alongside other GhG mitigation solutions. These insights could be gathered from both real-world and modelling case studies.

The multi-method approach to case study development detailed in Chapter 5 could be applied to other types of models to evaluate the macroeconomic impacts of material efficiency improvements. Dynamic and static input-output models use have the same underlying structure so the approach could easily be replicated. A dynamic model would show the employment impacts of material efficiency over a longer time horizon and enable an exploration of the potential impacts on material stocks. Further research could examine if there are any transferable insights on how to transparently model material efficiency case studies in models with a different underlying structure, such as computer-generated equilibrium and macro-econometric models. Estimating the macroeconomic impacts of material efficiency improvements across a range of model types would enable policymakers to make more informed judgements regarding the extent of the uncertainty in each modelling study.

Finally, the lessons outlined at the end of Chapter 6.1 around how to encourage the uptake of good ideas among policymakers and industry practitioners could be a topic of further study or, at the very least, used as a set of guidelines for conducting interdisciplinary research. There appears to be some recognition from academia that a narrow, single-discipline focus on decarbonisation ‘*avoid many crucial real-world elements for accelerated transitions*’ (Geels et al., 2017). Fortunately, the methods outlined in this thesis are easily replicable to investigate other solutions that could reduce GhG emissions in other sectors and world regions. The challenge for future research may therefore lie with identifying open-minded academics who are willing to collaborate and communicate with others outside of their discipline and the academic community.

This future research agenda should motivate and facilitate further implementation of policies and industry initiatives that lead to material efficiency improvements. The problem of climate change is too significant for potential material efficiency solutions to be overlooked.

# References

- Allwood, J.M. et al., 2010. Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050. *Environmental Science and Technology*. 44, 1888-1894. DOI:10.1021/es902909k
- Allwood, J.M. et al., 2011. Material Efficiency: A White Paper. *Resources, Conservation and Recycling*. 55(3) 362-381. DOI:10.1016/j.resconrec.2010.11.002
- Allwood J.M. et al., 2012. *Sustainable Materials: With Both Eyes Open*, UIT: Cambridge, UK.
- Allwood, J. M., 2013. Transitions to Material Efficiency in the UK Steel Economy. *Philosophical Transactions of the Royal Society Series A*. 371: 20110577. DOI:10.1098/rsta.2011.0577
- Allwood, J.M. et al., 2013. Material Efficiency: Providing Material Services with Less Material Production. *Philosophical Transactions of the Royal Society Series A* 371: 20120496 DOI: 0.1098/rsta.2012.0496
- Allwood, J.M. 2016. *A Bright Future for UK Steel: Strategy for Innovation and Leadership Through Up-cycling and Integration*. Department of Engineering, University of Cambridge, UK.
- Almquist, E., Lee, B., 2009. What Do Customers Really Want? *Harvard Business Review*. April, 2009.
- American Chemistry Council (ACC), 2015. *Plastics and Polymer Composites in Light Vehicles*. Washington USA
- Autotrader, 2016. *The Automotive Market Today. Market Overview*. Available at: <http://ar2016.autotrader.co.uk/assets/pdf/auto-trader-ar2016-market-overview.pdf>
- Bajzelj, B. et al., 2013. Designing Climate Change Mitigation Plans that Add Up. *Environmental Science & Technology*. 47(4), 8062-8069. DOI:10.1021/es400399h
- Baker, R., 2002. Energy policy: The problem of public perception. In Bent R. et al., (Eds.) *Energy: Science, Policy, and the Pursuit of Sustainability*. Island Press: Washington DC.
- Barrett, J., Scott, K., 2012. Link Between Climate Change Mitigation and Resource Efficiency: A UK Case Study. *Global Environmental Change*. 22, 299-307. DOI:10.1016/j.gloenvcha.2011.11.003
- Baumgartner, F.R., Jones, B., 1993. *Agendas and Instability in American Politics*. University of Chicago Press: Chicago, USA.
- Beeson. M., Stone, D., 2013. The Changing Fortunes of a Policy Entrepreneur: The Case of Ross Garnaut. *Australian Journal of Political Science*. 48(1),1-14. DOI:10.1016/j.vetpar.2011.11.049
- Bernard, H. R., Ryan, G. W. 2010. *Analysing Qualitative Data – Systematic Approaches*. Sage Publications Ltd. London, UK
- Birkland, T., 2010. *An Introduction to the Policy Process: Theories Concepts and Models of Public Policy Making*. Routledge Publishing: UK
- Bleischwitz, R. et al. 2009. *Sustainable Growth and Resource Productivity: Economic and Global Policy Issues*. Greenleaf Publishing: Sheffield, UK.
- Bleischwitz, R. 2010. International economics of resource productivity –

- Relevance, measurement, empirical trends, innovation, resource policies. *International Economics and Economic Policy*. 7, 227-244. DOI 10.1007/s10368-010-0170-z
- Blumstein, C. et al., 1980. Overcoming Social and Institutional Barriers to Energy Conservation. *Energy*. 5(4), 355-371.
- Boeije, H. (2010). *Analysis in Qualitative Research*. Sage Publications Ltd. London, UK.
- Bohringer, C., Rutherford, T. 2015. The circular economy – an economic impact assessment. Report to SUNIZA.
- Bordigoni, M. et al., 2012. Role of Embodied Energy in the European Manufacturing Industry: Application to Short-term Impacts of a Carbon Tax. *Energy Policy*. 41, 335–350, DOI:10.1016/j.enpol.2012.01.011.
- Bowen, G.A., 2009. Document Analysis as a Qualitative Research Method. *Qualitative Research Journal*. 9(2),27-40. DOI:10.3316/QRJ0902027.
- Braun, V., Clarke, V. 2006. Using Thematic Analysis in Psychology. *Qualitative Research in Psychology*. 3(2), 77-101. DOI:10.1191/1478088706qp063oa
- Brunner, S., 2008. Understanding Policy Change: Multiple Streams and Emissions Trading in Germany. *Global Environmental Change*. 18(3),501-507. DOI:10.1016/j.gloenvcha.2008.05.003
- Buhr, K., 2012. The Inclusion of Aviation in the EU Emissions Trading Scheme: Temporal Conditions for Institutional Entrepreneurship. *Organization Studies*. 33(11),1565-1587. DOI:10.1177/0170840612463324
- Cairney, P., Jones, M.D., 2016. Kingdon’s Multiple Streams Approach: What Is the Empirical Impact of this Universal Theory? *Policy Studies Journal*. 44(1), 37-58. DOI:10.1111/psj.12111
- Cambridge Econometrics & Bio Intelligence Service, 2014. Study on Modelling of the Economic and Environmental Impacts of Raw Material Consumption.. Technical report 2478. European Commission. Brussels, Belgium
- Capstick, S.B. et al., 2015. Public Perceptions of Climate Change in Britain Following the Winter 2013/2014 Flooding. *Working Paper 15-01*, Cardiff University, Cardiff, UK.
- Carpenter, A., 2012. *CO<sub>2</sub> Abatement in the Iron and Steel Industry*. IEA Clean Coal Centre. London, UK.
- Carruth, M.A. et al., 2011. The Technical Potential for Reducing Metal Requirements Through Lightweight Product Design. *Resources Conservation and Recycling*. 57, 48-60. DOI:10.1016/j.resconrec.2011.09.018
- Carruth, M.A., Allwood, J.M. 2013. A Novel Process for Transforming Sheet Metal Blanks: Ridged Die Forming. *CIRP Annals - Manufacturing Technology*. 62, 267-270. ISSN 0007-8506
- Carter, N., Jacobs, M., 2013. Explaining Radical Policy Change: The Case of Climate Change and Energy Policy Under the British Labour Government 2006-2010. *Public Administration*. 92(1),125-141. DOI:10.1111/padm.12046
- Catulli, M., 2010. Abbey Steel: Conquering the Steel Recycling Market. In *“Business to Business Marketing: Relationships, Networks and Strategies”*. Ellis, N. (Ed.). Oxford University Publishing; Oxford, UK.
- Cervero, R., 2003. City CarShare: First-Year Travel Demand Impacts. *Journal of the Transportation Research Board*. 1839, 159-166. DOI:10.3141/1839-18
- Chance, T., 2009. Towards Sustainable Residential Communities; The Beddington Zero Energy Development (BedZED) and Beyond. *Environment & Urbanization*. 21(2), 527–544, DOI:10.1177/09562478093D3o9w0n0lo7a.

- Cleveland, C. J., Ruth, M., 1999. Indicators of Dematerialization and the Materials Intensity of Use. *Journal of Industrial Ecology*. 2(3), 15–50.  
DOI:10.1162/jiec.1998.2.3.15
- Cheah, L.W., 2010. *Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S.* PhD thesis, Massachusetts Institute of Technology, Boston, USA
- Chrzan, K., Golovashkina, N., 2006. An Empirical Test of Six Stated Importance Measures. *International Journal of Market Research*. 48(6),
- Climate Change Act (CCA), 2008. HMSO. London, UK
- Coelho, A., De Brito, J., 2011. Economic Analysis of Conventional Versus Selective Demolition—a Case Study. *Resources, Conservation & Recycling*. 55, 382–392, DOI:10.1016/j.resconrec.2010.11.003.
- Collantes, G., Sperling, D., 2008. The Origin of California's Zero Emission Vehicle Mandate. *Transportation Research Part A: Policy and Practice*. 42(10),1302-1313. DOI:10.1016/j.tra.2008.05.007
- Cooper, S. et al., 2016. A Multi-Method Approach for Analysing the Potential Employment Impacts of Material Efficiency. *Resources, Conservation & Recycling*. 109, 54-66. DOI:10.1016/j.resconrec.2015.11.014
- Cooper, S. et al., (*under review*). Socio-technical Factors Influencing Current Trends in Material Throughput in the UK Automotive Industry. *Journal of Cleaner Production*.
- Cooper, S. et al., (*under review*). Why are Material Efficiency Solutions a Limited Part of the Climate Policy Agenda? An Application of the Multiple Streams Framework to UK Policy on CO<sub>2</sub> Emissions from Cars. *Environmental Policy and Governance*.
- Cooper, D., Allwood, J.M., 2012. Reusing Steel and Aluminum Components at End of Product Life. *Environmental Science & Technology*, 46(18), 10334–40. DOI:10.1021/es301093a
- Cooper, D. et al., 2014. Component Level Strategies for Exploiting the Lifespan of Steel in Products. *Resources, Conservation & Recycling*. 84, 24–34. DOI:10.1016/j.resconrec.2013.11.014
- Corbin, J.M., Strauss, A., 1990. Grounded Theory Research: Procedures, Canons, and Evaluative Criteria. *Qualitative Sociology*. 13(1), 3-21.  
DOI:10.1007/BF00988593
- Cullen, J.M. et al., 2012. Mapping the Global Flow of Steel: from Steelmaking to End-Use Goods. *Environmental, Science & Technology*. 46,13048-13055. DOI: 10.1021/es302433p
- Cullen, J.M., Allwood, J.M. (2010) Theoretical Efficiency Limits for Energy Conversion Devices. *Energy*. 35(5), 2059-2069.  
DOI:10.1016/j.energy.2010.01.024
- D'Este, P. et al., 2012. What Hampers Innovation? Revealed Barriers Versus Deterring Barriers. *Research Policy*, 41(2), 482-488.  
DOI:10.1016/j.respol.2011.09.008
- Dantata, N., et al., 2005. An Analysis of Cost and Duration for Deconstruction and Demolition of Residential Buildings in Massachusetts. *Resources, Conservation & Recycling*. 44(1), 1–15. DOI:10.1016/j.resconrec.2004.09.001.
- Dehning, P. et al., 2017. Factors Influencing the Energy Intensity of Automotive Manufacturing Plants. *Journal of Cleaner Production*. 142(4), 2305-2314.  
DOI:10.1016/j.jclepro.2016.11.046
- Dennis, K., Urry, J., 2009. *After the Car*. Polity: Cambridge, UK.

- Densley-Tingley, D., Davison, B., 2011. Design for deconstruction and material reuse. *Proceedings of the Institute for Civil Engineering - Energy*. 164(4), 195–220, DOI:10.1680/ener.2011.164.4.195.
- Densley-Tingley, D. et al., (*accepted*). Understanding and Overcoming the Barriers to Structural Steel Reuse, a UK Perspective. *Journal of Cleaner Production*.
- Department for Business, Energy and Industrial Strategy (BEIS). 2016. Final UK Greenhouse Gas Emissions National Statistics: 1990-2014.
- Department for Transport (DfT), 2014a. National Travel Survey Factsheets. Car Travel Factsheet 2014. Department for Transport (DfT), London, UK.
- Department for Transport (DfT), 2014b. Vehicle Licensing Statistics. Department for Transport (DfT), London, UK.
- Department for Transport (DfT). 2016a. Licensed Vehicles by Body Type: Great Britain and United Kingdom. Table VEH0102. London, UK
- Department for Transport (DfT). 2016b. National Travel Survey 2015. London, UK
- Distelkamp, M., Meyer, M. 2014 Report About Resource Reduction Cost Curves for Material Consumption in Different Member States and Sectors. POLFREE Deliverable 1.4, Osnabrück.
- Economic and Social Council (ECOSOC). 1996. Committee on New and Renewable Sources of Energy and on Energy for Development. Second Session. United Nations. New York, 12 - 23 February 1996.
- Ellen MacArthur Foundation, 2013. Towards the Circular Economy Vol.1: an economic and business rationale for an accelerated transition. Isle of Wight, UK.
- European Commission (EC), 2003. Directive 2002/96/EC on Waste Electrical and Electronic Equipment (WEEE). Brussels, Belgium
- European Commission (EC), 2008. Directive 2008/98/EC on Waste and Repealing Certain Directive. Brussels, Belgium
- European Commission (EC), 2009. Setting Emission Performance Standards for New Passenger Cars as part of the Community's Integrated Approach to Reduce CO<sub>2</sub> Emissions from Light-duty Vehicles. Regulation No 443/2009. Brussels, Belgium.
- European Commission (EC), 2011. Roadmap to a Resource Efficient Europe. COM/2011/0571. Brussels, Belgium
- European Commission (EC), 2014. Assessment of scenarios and options towards a resource efficient Europe: an analysis for the European built environment. European Commission. Brussels, Belgium.
- European Commission (EC). 2015. Closing the Loop - An EU Action Plan for the Circular Economy. COM/2015/0614. Brussels, Belgium.
- European Environment Agency (EEA), 2016. More from Less - Material Resource Efficiency in Europe. 2015 Overview of Policies, Instruments and Targets in 32 Countries. 10/2016. Copenhagen, Denmark.
- Flachenecker, F., Rentschler, J., 2015. Investments in Resource Efficiency - Costs and Benefits, Investment Barriers and Intervention Measures. A Report prepared for the European Bank for Reconstruction and Development (EBRD). London, UK
- Geels, F.W., 2012. A Socio-Technical Analysis of Low-Carbon Transitions: Introducing the Multi-Level Perspective into Transport Studies. *Journal of Transport Geography*. 24, 471-482. DOI:10.1016/j.jtrangeo.2012.01.021
- Geels, F.W., Kemp, R., 2007. Dynamics in Socio-Technical Systems: Typology of Change Processes and Contrasting Case Studies. *Technology in Society*. 29(4) 441-455. DOI:10.1016/j.techsoc.2007.08.009
- Geels, F.W., 2002. Technological Transitions as Evolutionary Reconfiguration

- Processes: a Multi-level Perspective and a Case-study. *Resources Policy*. 31 (8/9), 1257–1274
- Geels, F.W., 2005. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles. *Technology Analysis and Strategic Management*. 17(4), 445-476.
- Geels, F.W., Sovacool, B.K., Schwanen, T., Sorrell, S. 2017. Sociotechnical transitions for deep decarbonization. *Science*. 357 (6357). 1242-1244. doi: 10.1126/science.aao3760
- Geyer, R., Jackson, T., 2004. Supply Loops and their Constraints: The Industrial Ecology of Recycling and Reuse. *Californian Management Review*. 46(2), 55–73.
- Giddens A. 2009. *The Politics of Climate Change*. Polity Press
- Gillard, R. Gouldson, A., Paavola, J. Van Alstine, J. 2016. Transformational Responses to Climate Change: Beyond a Systems Perspective of Social Change in Mitigation and Adaptation. *WIREs Climate Change*. 7, 251-265. . doi: 10.1002/wcc.38
- Gieseckam, J., 2015. The Contribution to UK Climate Mitigation Targets from Reducing Embodied Carbon in the Construction Sector. Unpublished Doctoral Thesis. University of Leeds, UK.
- Gorgolewski, M., 2008. Designing with Reused Building Components: Some Challenges. *Building Research & Information*. 36 (2), 175–188. DOI:10.1080/09613210701559499.
- Gray, D.E., 2013. *Doing Research in the Real World* (Third Edition). Sage Publications Ltd. London, UK.
- Guy, B., McLendon, S., 2000. *Building Deconstruction: Reuse and Recycling of Building Materials*. Powell Center for Construction and Environment, University of Florida, USA.
- Hagerman, S. et al., 2015. Expert Views on Biodiversity Conservation in an Era of Climate Change. *Global Environmental Change*. 20(1), 192-207. DOI:10.1016/j.gloenvcha.2009.10.005
- Hawkins, T. et al., 2007. A Mixed-Unit Input-Output Model for Environmental Life-Cycle Assessment and Material Flow Analysis. *Environmental Science and Technology*. 41(3), 1024-1031. DOI:10.1021/es060871u
- Her Majesty's Stationery Office (HMSO, 1994). *Sustainable Development: The UK Strategy*. London, UK.
- Her Majesty's Treasury (HMT). 2011. *Green Book - Appraisal and Evaluation in Central Government*. London, UK
- Hermansen E.A.T., 2015. Policy Window Entrepreneurship: The Backstage of the World's Largest REDD+ Initiative. *Environmental Politics*. 24(6):932-950. DOI:10.1080/09644016.2015.1063887
- Holweg, M. et al., 2013. *Growing the Automotive Supply Chain. The Road Forward*. A report for the Automotive Council UK.
- Horton, P.M., 2016. *Reducing Sheet Metal Yield Losses in the Automotive Industry*. Unpublished First Year Report for PhD. Department of Engineering. University of Cambridge, UK.
- Hsu, C.C., Sandford, B. A., 2007. The Delphi Technique: Making Sense of Consensus. *Practical Assessment Research & Evaluation*. 12(10), 1-8
- Incropera, F.P., 2015. *Climate Change: A Wicked Problem: Complexity and Uncertainty at the Intersection of Science, Economics, Politics and Human Behaviour*. Cambridge University Press. New York, USA.
- Innovate UK, 2016. *Competition Brief: Manufacturing and Materials*. London, UK.



- International Council on Clean Transportation (ICCT), 2016. European Vehicle Market Statistics - The European Vehicle Market Statistics Pocketbook. Available at: <http://eupocketbook.theicct.org> (accessed 01/09/2016)
- International Energy Agency (IEA), 2008. Energy Technology Perspectives: Scenarios & Strategies to 2050. Paris, France
- International Energy Agency (IEA), 2015. World Energy Outlook. Paris, France
- International Organisation of Motor Vehicle Manufacturers (OICA), 2016. Production Statistics. Available at: <http://www.oica.net/category/production-statistics/> (accessed 10/08/16)
- International Steel Statistics Bureau (ISSB), 2008. International Steel Statistics. London, UK.
- Intergovernmental Panel on Climate Change (IPCC). 2014. Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Janda, K.B., Topouzi M., 2015. Telling Tales: Using Stories to Remake Energy Policy. *Building Research & Information*. 43(4), 516-533. DOI:10.1080/09613218.2015.1020217
- Jevons, W. S., 1865/1965. In: Flux, A.W. (Ed.), The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines, 3rd edition 1905. Augustus M. Kelley, New York.
- Jones M.D. et al., 2016. A River Runs Through It: A Multiple Streams Meta-Review. *Policy Studies Journal*. 44(1),13-36. DOI: 10.1111/psj.12115
- Kanemoto, K., Murray, J., 2013. What is MRIO? MRIO Benefits & Limitations. In: Murray, J., Lenzen, M. (Eds.), *The Sustainability Practitioner's Guide to Multi-Regional Input-Output Analysis*. Common Ground; Illinois, USA
- Keskitalo, E. et al., 2016. Agenda-Setting on the Environment: The Development of Climate Change Adaptation as an Issue in European States. *Environmental Policy and Governance*. 22(6), 381-394. DOI:10.1002/eet.1579
- Kingdon JW. 1995. Agendas, Alternatives and Public Policies. HarperCollins: New York, USA.
- Khagram, S., Nicholas, K.A., MacMynowski Bever, D., Warren, J. 2010. Thinking about knowing: conceptual foundations for interdisciplinary environmental research. *Environmental Conservation*. 34 (4), 388-397. DOI:10.1017/S0376892910000809.
- Krosnick, J. et al., 2006. The Origins and Consequences of Democratic Citizens' Policy Agendas: A Study of Popular Concern about Global Warming. *Climatic Change*. 77(1), 7-43. DOI:10.1007/s10584-006-9068-8
- Lasswell, H. 1956. *The Decision Process: Seven Categories of Functional Analysis*. University of Maryland Press: Maryland, USA.
- Lenzen, M., et al., 2013. Building Eora: A Global Multi-Region Input-Output Database at High Country and Sector Resolution. *Economic Systems Research*. 25(1), 20-49, DOI:/10.1080/09535314.2013.769938.
- Ley, J., et al., 2002. Material Flow Analysis of the UK Steel Construction Sector. *Proceedings Steel in Sustainable Construction: IISI World Conference*
- Lifset, R., Eckelman, M. 2013. Material Efficiency in a Multi-Material World. *Philosophical Transactions of the Royal Society Series*. 371:20120002. DOI:10.1098/rsta.2012.0002
- Litman, T., 2009. *Transportation Cost Benefit Analysis: Techniques, Estimations and Implications*. Victoria Transport Policy Unit:Victoria, Canada.

- Loorbach, D., Rotmans, J. 2010. The Practice of Transition Management: Examples and Lessons from Four Distinct Cases. *Futures*, 42(3), 237-246. DOI: /10.1016/j.futures.2009.11.009
- Lorenzoni, I., Benson, D., 2014. Radical Institutional Change in Environmental Governance: Explaining the Origins of the UK Climate Change Act 2008 through Discursive and Streams Perspectives. *Global Environmental Change*. 29,10-21. DOI:10.1016/j.gloenvcha.2014.07.011
- McKinsey & Company, 2012. *Advanced Industries: Lightweight, Heavy Impact*. McKinsey & Company, 2016. *Disruptive Trends That Will Transform the Auto Industry*.
- Meyer, B. et al., 2007. Material Efficiency and Economic-Environmental Sustainability. Results of Simulations for Germany with the Model PANTA RHEI. *Ecological Economics*. 63, 192-200. DOI:10.1016/j.ecolecon.2006.10.017
- Meyer, B. et al., 2012. Modelling Green Growth and Resource Efficiency: New Results. *Mineral Economics*. 24, 145–154. DOI:10.1007/s13563-011-0008-3
- Milford, R. et al., 2013. Assessing the Potential of Yield Improvements, through Process Scrap Reduction, for Energy and CO<sub>2</sub> Abatement in the Steel and Aluminium Sectors. *Resources, Conservation and Recycling*. 55, 1185-1195. DOI:10.1016/j.resconrec.2011.05.021
- Milford, R. et al., 2013. The Roles of Energy and Material Efficiency in Meeting Steel Industry CO<sub>2</sub> Targets. *Environmental Science & Technology*. 47(7), 3455-3462. DOI:10.1021/es3031424
- Miller, R., Blair, P., 2009. *Input–Output Analysis—Foundations and Extensions*. Cambridge University Press, Cambridge, UK.
- Mirasgredis, S. et al., 2014. A Methodological Framework for Assessing the Employment Effects Associated with Energy Efficiency Interventions in Buildings. *Energy and Buildings*. 82, 275-286. DOI:10.1016/j.enbuild.2014.07.027
- Moloney, S. et al., 2010. Transitioning to Low Carbon Communities—from Behaviour Change to Systemic Change: Lessons from Australia. *Energy Policy*. 38, 7614-7623. DOI:10.1016/j.enpol.2009.06.058
- Mont, O., 2002. Clarifying the Concept of Product System Service. *Journal of Cleaner Production*. 10(3), 237-245
- Morgenstern, R., et al., 2004. The Near-Term Impacts of Carbon Mitigation Policies on Manufacturing Industries. *Energy Policy*. 32(16), 1825–1841. DOI: 10.1016/j.enpol.2004.07.001
- Moynihan, M. Allwood, J.M., 2014. Utilization of Structural Steel in Buildings. *Proceedings of the Royal Society A*. 470: 20140170. DOI:10.1098/rspa.2014.0170
- Muradov, K., Bayhaqi, A., 2013. How MRIO Can Help APEC to Address its Environmental Objectives. In: Murray, J., Lenzen, M. (Eds.), *The Sustainability Practitioner's Guide to Multi-Regional Input-Output Analysis*. Common Ground; Illinois, USA.
- Nathani, C. 2009. Analysing the Economic Impacts of a Material Efficiency Strategy. In Sangwon, S. (Ed.). *Handbook of Input-Output Economics in Industrial Ecology*. Springer, Netherlands.
- Natural Scotland. 2013. Safeguarding Scotland's Resources - Blueprint for a More Resource Efficient and Circular Economy. Edinburgh, UK
- Nieuwenhuis, P., 2014. Sustainable Automobility; *Understanding the Car as a Natural System*. Edward Elgar publishing; Cheltenham, UK.

- Organization for Economic Cooperation and Development (OECD), 2005. *Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data*, 3rd Edition. Paris, France
- Office for Low Emissions Vehicles (OLEV). 2013. Driving the Future Today. A Strategy for Ultra-Low Emission Vehicles in the UK. London, UK.
- Office for National Statistics (ONS), 2012a. Family Spending 2012 Edition. Table A1. Components of Household Expenditure. London, UK
- Office for National Statistics (ONS), 2012b. EMP14: Employees and Self-Employed by industry. London, UK
- Office for National Statistics (ONS), 2014a. Annual Business Survey, 2013. Final Results. London, UK.
- Office for National Statistics (ONS), 2014b. UK Manufacturers Sales by Product (PRODCOM) for 2013. London, UK.
- Office for National Statistics (ONS). 2016. Material consumption in the United Kingdom, 2000 to 2013. London, UK
- Oguchi M. Fuse, M., 2015. Regional and Longitudinal Estimation of Product Lifespan Distribution: A Case Study for Automobiles and a Simplified Estimation Method. *Environment, Science & Technology*. 49 (3),1738–1743. DOI:10.1021/es505245q
- Orange, R. 2016. “Waste Not Want Not: Sweden to Give Tax Breaks for repairs”. Available at: <https://www.theguardian.com/world/2016/sep/19/waste-not-want-not-sweden-tax-breaks-repairs>. [accessed 20.12.2016]
- Orsato R., Wells, P., 2007. U-turn: The Rise and Demise of the Automobile Industry. *Journal of Cleaner Production*. 15(11), 994-1006. DOI:10.1016/j.jclepro.2006.05.019
- Orsato, R., 2004. The Ecological Modernization of Organizational Fields: A Framework for Analysis. In Sharma S., Starik, M. (Eds.) *Stakeholders, the Environment and Society*. Edward Elgar Publishing; Cheltenham, UK,
- Pajunen, N. et al., 2012. Drivers and Barriers of Effective Industrial Material Use. *Minerals Engineering*. 29, 39-46. DOI:10.1016/j.mineng.2011.12.008
- Palm, J., Thollander, P. 2010. An Interdisciplinary Perspective on Industrial Energy Efficiency. *Applied Energy*. 87, 3255-3261. DOI:10.1016/j.apenergy.2010.04.019
- Parag, Y., Eyre, N., 2010. Barriers to Personal Carbon Trading in the Policy Arena. *Climate Policy*. 10, 353-368. DOI:10.3763/cpol.2009.0009
- Parker, J. et al., 2011. What Can We Learn from Car Sharing Experiences in the UK? *Proceedings of the Institution of Civil Engineers: Transport*. 164(3), 181-188.
- Pfaff, M., Sartorius, C., 2015. Economy-wide Rebound Effects for Non-Energetic Raw Materials. *Ecological Economics*. 118, 132–139. DOI:10.1016/j.ecolecon.2015.07.016 0921-8009/
- Pongiglione, M., Calderini, C., 2014. Material Savings Through Structural Steel Reuse: A Case Study in Genoa. *Resources, Conservation and Recycling*. 86, 87–92, DOI:10.1016/j.resconrec.2014.02.0
- Porter, M. E., 1985. *The Competitive Advantage: Creating and Sustaining Superior Performance*. Free Press; New York, USA.
- Pralle, S., 2006. *Branching Out, Digging*. In: *Environmental Advocacy and Agenda Setting*. Georgetown University Press; Washington DC, USA
- Prettenthaler, F.E., Steininger, K.W. 1999. From Ownership to Service Use Lifestyle: the Potential of Car Sharing. *Ecological Economics*. 28,443–453. DOI:10.1016/S0921-8009(98)00109-8

- Prime Minister's Office, 2016. *PM announces major research boost to make Britain the go-to place for innovators and investors*. Press Release.
- PWC, 2016. *Auto Industry Trends - Automakers and Suppliers Can No Longer Sit Out the Industry's Transformation*. London, UK
- Reddy, B.S., 2013. Barriers and Drivers to Energy Efficiency – A New Taxonomical Approach. *Energy Conservation & Management*. 74, 403–16. DOI:10.1016/j.enconman.2013.06.040
- Rockström, J., et al., 2009. A Safe Operating Space for Humanity. *Nature*. 461, 472–475. DOI:10.1038/461472a
- Rohracher, H. 2001. Managing the Technological Transition to Sustainable Construction of Buildings: A Socio-Technical Perspective. *Technology Analysis & Strategic Management*. 13(1), 137-150. DOI:1080/09537320120040491
- Sabatier, P.A., Jenkins-Smith H.C., 1993. *Policy Change and Learning: An Advocacy Coalition Approach*. Westview Press; Colorado, USA.
- Sabatier, P.A., 2007. The Need for Better Theories. In Sabatier, P.A. (Ed.) *Theories of the Policy Process*. Westview Press; Colorado, USA.
- Sansom, M., Avery, N., 2014. Reuse and Recycling Rates of UK Steel Demolition Arisings. *Proceedings of the Institute of Civil Engineers - Sustainability*. 167, 89–94. DOI:10.1680/ensu.13.00026
- Sako, M., 2004. Supplier development at Honda, Nissan and Toyota: comparative case studies of organizational capability enhancement. *Industrial and Corporate Change*. 13(2), 281-308. DOI:10.1093/icc/dth012
- Scott, K. et al., 2013. *Estimating Emissions Associated with Future UK Consumption Patterns*. A report for the UK Committee on Climate Change; London, UK.
- Serrenho, A.C., Allwood, J.M., 2016. Material Stock Demographics: Cars in Great Britain. *Environmental Science and Technology*. 50(6),3002–3009. DOI:10.1021/acs.est.5b05012
- Serrenho, A.C. et al., 2015. The Influence of UK Emissions Reduction Targets on the Emissions of the Global Steel Industry. *Resources, Conservation and Recycling*. 107, 174-184. DOI:10.1016/j.resconrec.2016.01.001
- Shahbazi, S., 2015. *Material Efficiency Management in Manufacturing*. Mälardalen University Press Licentiate Theses No. 210.
- Shahbazi, S. et al., 2016. Material Efficiency in Manufacturing: Swedish Evidence on Potential, Barriers and Strategies. *Journal of Cleaner Production*. 127, 438-450. DOI:10.1016/j.jclepro.2016.03.143
- Shultmann, F. 2005 *Deconstruction and Material Reuse—an International Overview*. Report 2—Deconstruction in Germany. CIB Publication 300
- Simonson, I., 2005. Determinants of Customers' Responses to Customized Offers: Conceptual framework and Research Propositions. *Journal of Marketing*. 69(1), 32-45.
- Skelton, A.C.H., Allwood, J.M. 2013a. Product-Life Trade-Offs: What if Products Fail Early? *Environment, Science and Technology*. 47(3), 1719–28. DOI:10.1021/es3034022
- Skelton, A.C.H., Allwood, J.M. 2013b. The Incentives for Supply Chain Collaboration to Improve Material Efficiency in the Use of Steel: An Analysis using Input Output Techniques. *Ecological Economics*. 89, 33-42. DOI:10.1016/j.ecolecon.2013.01.021
- Smith, A. et al., 2005. The Governance of Sustainable Socio-Technical Transitions. *Research Policy*. 34, 1491-1510. DOI:10.1016/j.respol.2005.07.005

- Society of Motor Manufacturers and Traders (SMMT). 2016. *Motor Industry Facts 2015*. London, UK.
- Soderholm, P., Tilton, J.E., 2012. Material Efficiency: An Economic Perspective. *Resources, Conservation and Recycling*. 61. 75-82.  
DOI:10.1016/j.resconrec.2012.01.003
- Sorrell, S. 2011. Barriers to Industrial Energy Efficiency – A Literature Review. UNIDO Working Paper 10/2011. Vienna, Austria
- Sorrell, S. et al., 2004. *The Economics of Energy Efficiency – Barriers to Cost Effective Investment*. Edward Elgar Publishing; Cheltenham, UK.
- Sorrell, S., 2007. *The Rebound Effect: An Assessment of the Evidence for Economy-Wide Energy Savings from Improved Energy Efficiency*. A Report Produced by the Sussex Energy Group for the Technology and Policy Assessment Function of the UK Energy Research Centre. Sussex, UK.
- Stahel, W. 2016. The Circular Economy. *Nature*. 531, 435-438.  
DOI:10.1038/531435a
- Steer Davis Gleave (SDG), 2015. Carplus Annual Survey 2014/2015 (London, Scotland, England & Wales. London, UK.
- Steer Davis Gleave (SDG), 2016. Carplus Annual Survey 2015/2016 (London, Scotland, England & Wales. London, UK
- Steinhilber, S. et al., 2013. Socio-Technical Inertia: Understanding the Barriers to Electric Vehicles. *Energy Policy*. 60, 531-550.  
DOI:10.1016/j.enpol.2013.04.076
- Storch, S., Winkel, G., 2013. Coupling Climate Change and Forest Policy: A Multiple Streams Analysis of Two German Case Studies. *Forest Policy and Economics*. 36, 14-26. DOI:10.1016/j.forpol.2013.01.009
- Transport & Environment. 2013. *Mind the Gap! Why Official Car Fuel Economy Figures Don't Match up to Reality*. Brussels, Belgium.
- Transport for London (TFL), 2015. *A Car Club Strategy for London Growing Car Clubs to Support London's Transport Future*. Transport for London, London, UK.
- UN Framework Convention on Climate Change (UNFCCC), 2009. Copenhagen Accord. FCCC/CP/2009/11/Add.1
- UN Framework Convention on Climate Change (UNFCCC), 2015. Paris Agreement. Decision 1/CP.21
- United Nations Environmental Programme (UNEP) 2007. *Buildings and Climate Change: Status, Challenges, and Opportunities*. Marrakesh, Morocco.
- University of Buckingham, 2013. *The Used Car Market Report 2013*. A Report for the BCA. London, UK.
- Urry, J., 2004. The 'System' of Automobility. *Theory Culture & Society*. 21(4/5) 25-39. DOI:10.1177/0263276404046059
- van den Brink, Y., Anagboso, M., 2010. Understanding the Divergence Between Output and Employment in the UK Construction Industry. *Economic & Labour Market Review*. 4 (3), 42–51. DOI: 10.1057/elmr.2010.36
- Wakefield, K.L., Blodgett, J.G., 1999. Customer Response to Intangible and Tangible Service Factors. *Psychology and Marketing*. 16(1), 51-68. DOI: 0.1002/(SICI)1520-6793(199901).
- Walz, R., 2011. Employment and Structural Impacts of Material Efficiency Strategies: Results from Five Case Studies. *Journal of Cleaner Production*. 19(8), 805–815. DOI:10.1016/j.jclepro.2010.06.023.
- Weber, L. 1997. Some Reflections on Barriers to the Efficient Use of Energy. *Energy Policy*. 25(10), 833-835.

- Wells, P.E., 2010. *The Automotive Industry in an Era of Eco-Austerity: Creating an Industry as if the Planet Mattered*. Edward Elgar Publishing; Cheltenham, UK.
- Wells, P.E., Nieuwenhuis, P., 2012. Transition failure: Understanding Continuity in the Automotive Industry. *Technological Forecasting and Social Change*. 79(9) 1681-1692. DOI:10.1016/j.techfore.2012.06.008
- Wells, P.E., Xenias, D., 2015. From 'Freedom of the Open Road' to 'Cocooning': Understanding Resistance to Change in Personal Private Automobility. *Environmental Innovations and Societal Transitions*. 16, 106-119. DOI:10.1016/j.eist.2015.02.001
- Witik, R.A. et al., 2011. Assessing the Lifecycle Costs and Environmental Performance of Lightweight Materials in Automobile Applications. *Composites Part A: Applied Science and Manufacturing*. 42,1694–1709. DOI:10.1016/j.compositesa.2011.07.024
- Winning, M., Calzadilla, A., Bleischwitz, R., Nechifor, V. 20017. Towards a circular economy: insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel. *International Economics & Economic Policy*. 14(3), 383-407. DOI:10.1007/s10368-017-0385-3
- World Steel, 2014. *Steel's Contribution to a Low Carbon Future and Climate Resilient Societies*. Brussels, Belgium.
- World Steel, 2016. *Steel Statistical Yearbook 2016*. Brussels, Belgium
- WorldAutoSteel, 2015. *Automotive Mass Benchmarking: A New Paradigm*. Ohio, USA.
- Worrell, E. et al., 2010. *Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry*. Ernest Orlando Lawrence Berkley National Laboratory. LBNL-4779E
- Yellishetty, M. et al., 2010. Iron Ore and Steel Production Trends and Material Flows in the World: Is this Really Sustainable? *Resources, Conservation and Recycling*. 54(12), 1084-1094. DOI:10.1016/j.resconrec.2010.03.003
- You, H. et al., 2006. Development of Customer Satisfaction Models for Automotive Interior Materials. *International Journal of Industrial Ergonomics*. 36(4) 323–330. DOI:10.1016/j.ergon.2005.12.007
- Yusuf, J. et al., 2016. The Sea is Rising... but not onto the Policy Agenda: A Multiple Streams Approach to Understanding Sea Level Rise Policies. *Environment and Planning C: Government and Policy*.34(2), 228-243. DOI:10.1177/0263774X15614457
- Zahariadis N. 2007. Multiple Streams Framework – Structure, Limitations Prospects. In Sabatier, P.A.(Ed.) *Theories of the Policy Process*. Westview Press: Colorado, USA.
- Zervas, E., 2010. Analysis of the CO2 Emissions and of the Other Characteristics of the European Market of New Passenger Cars. 1. Analysis of General Data and Analysis per Country. *Energy Policy* 38(10), 5413–5425 DOI:10.1016/j.enpol.2010.02.008

## Websites

[www.zipcar.co.uk/london/check-rates](http://www.zipcar.co.uk/london/check-rates) [Accessed 16/06/15]  
[www.citycarclub.co.uk/about/what-does-it-cost](http://www.citycarclub.co.uk/about/what-does-it-cost) [Accessed 16/06/15]  
[www.uk.drive-now.com/#!/rates](http://www.uk.drive-now.com/#!/rates) [Accessed 16/06/15]  
[www.co-wheels.org.uk/pricing](http://www.co-wheels.org.uk/pricing) [Accessed 16/06/15]  
[www.www.steelbb.com](http://www.www.steelbb.com) [Accessed 16/06/15]  
[www.meps.co.uk](http://www.meps.co.uk) [Accessed 16/06/15]  
[www.letsrecycle.com/prices/metals/](http://www.letsrecycle.com/prices/metals/) [Accessed 16/06/15]  
[www.parkers.co.uk](http://www.parkers.co.uk) [Accessed 16/06/15]  
[www.worldsteel.org](http://www.worldsteel.org) [Accessed 16/06/15]  
[www.iea-coal.org.uk](http://www.iea-coal.org.uk) [Accessed 16/06/15]  
[www.european-aluminium.eu](http://www.european-aluminium.eu) [Accessed 16/06/15]  
[www.world-aluminium.org](http://www.world-aluminium.org) [Accessed 16/06/15]  
[www.reinforcedplastics.com](http://www.reinforcedplastics.com) [Accessed 16/06/15]  
[www.carbonfiber.gr.jp](http://www.carbonfiber.gr.jp) [Accessed 16/06/15]  
[www.euroncap.com/en/about-euro-ncap/](http://www.euroncap.com/en/about-euro-ncap/) [accessed 04/01/2017]  
[www.gov.uk/government/organisations/hm-treasury/about](http://www.gov.uk/government/organisations/hm-treasury/about) [Accessed 10/01/2017]  
[www.steelbenchmarker.com](http://www.steelbenchmarker.com) [Accessed 07/10/2017]