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Chapter

What can the stock-flow-service nexus offer to corporate environmental sustainability?

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Abstract:

The stock-flow-service nexus approach is used to analyse the interactions that occur between energy/material flows, material stock and energy/material services. The latter identify the functions that energy and materials contribute to society. In this chapter, we employ this nexus to a corporate setting in order to evaluate environmental performance. Using a Colombian bus rapid transit operator as a case study, we apply five nexus indicators to evaluate the efficiency of one unit of vehicle stock, fuel and waste relative to distance travelled, as a proxy for service delivery. During the 11-year period studied (2001 to 2011), the bus company's fuel efficiency increased by 5%, going from 1.851 to 1.948 km/kg. Stock efficiency improved 35%, going from $5.7x10^4$ to $7.6x10^4$ km/bus. The interquartile range of stock evolution, which refers to the variance between the first and third quartile of the total distance travelled by each bus, reduced from 40,426 to 22,070 km. This demonstrates improved fleet management practices. However, this progress came at the cost of increased waste generation. In fact, service provision per unit of waste outflow (as measured by stock degradation efficiency) decreased 47%, going from 65 to 34 km/kg. Similarly, the annual fraction of waste relative to a unit of vehicle stock went from 10% to 25%. These opposing trends highlight the difficulty of improving overall environmental performance. In light of this situation, we discuss the considerable value and challenges of using a nexus perspective as part of an integrated management system and as the basis of corporate decision making in general.

Keywords:

Energy service, material service, mobility-as-a-service, resource efficiency, sustainable materials, sustainable transport

1. Introduction

Internationally recognised management systems, such as ISO 9001 or ISO 14001, are formal mechanisms that companies frequently use to improve their corporate image and performance (Whitelaw 2012). The aim of ISO 9001 compliance is to provide products and services that fulfil consumer needs and applicable statutory and regulatory requirements (ISO 2015a). ISO 14001, meanwhile, drives improved environmental performance at the organisational level (ISO 2015b). Meeting ISO standards requires a commitment to "continuous improvement" so that the management system becomes an integral component of long-term company operations, as opposed to a "tick box" formality. In the first few years following certification, it is relatively easy to quantifiably demonstrate progress as the company, its sub-contractors, suppliers, shareholders and customers come together to identify low-hanging fruit. However, as the management system matures it becomes increasingly difficult to meaningfully influence performance in ways that notably improve the primary activity (e.g. providing a public transport service) (Barrett et al. 1998; Boiral 2011; Boiral et al. 2018). Sensing diminishing returns, those leading the management system may begin to suggest changes that move attention and resources away from the main business function and focus and onto secondary, or even tertiary concerns (e.g. using recycled printer paper when printing is not part of the company's core processes) (Steger et al. 2017). If left unchecked, the resulting system can become overly cumbersome and difficult to manage. It is likely to introduce unnecessary costs and complexity for minimal gain, as change increasingly becomes introduced for change sake (Gunningham and Sinclair 1999). Key resources may also get pulled from the running of the business to the running of the management system, which brings into question the purpose of being certified in the first place (Liyin et al. 2006; Weidema 2010; Reis et al. 2018).

In this chapter, we propose a stock-flow-service nexus approach as a potential solution to the plateaus experienced by the leaders of mature corporate management systems. This nexus captures the relationship between specific combinations of energy and material flows, material stocks and energy/material services (Haberl et al. 2017). Energy and material services are two interconnected concepts that consider the non-economic purpose behind the development of a business offering from a customer or societal viewpoint rather than the product or offering in its own right (Carmona et al. 2017). This perspective enables a business to consider operational effectiveness and resource efficiency using units that measure a person's ability to undertake a given activity or experience a certain state. It does not emphasise energy and materials savings per se, which, in any case, may do little to drive meaningful change. In this regard, energy and material services can be used to support an organisational level re-framing of resource input and product/service output. The concept can also be employed as an integral component of a resource management strategy directed towards the Brundtland (1987) definition of sustainable development.

The move away from a traditional product or service perspective to an energy and material service perspective opens up a systems-based understanding of resource use. By considering both energy and material aspects of resource consumption and accumulation, in order to achieve non-monetary end goals, this nexus provides a more complete picture of environmental sustainability and resource efficiency (Wiedenhofer et al. 2019). This chapter thus identifies and evaluates the strengths and weaknesses of adopting a stock-flow-service nexus approach at the corporate level. The usefulness of the nexus is tested via a case study of the energy flows, material flows and stocks, and transport service provided by a bus fleet in Bogota, Colombia. The innovative aspects are (1) a demonstration of the connection between stock and flows and the service they provide to the average user of an urban bus service; (2) the identification of the benefits and potential shortcomings of the stock-flow-service nexus and its associated indicators, when applied to an integrated management system developed in a corporate sustainability setting; (3) a proposal of continuous improvement initiatives that could be employed by those organisations that have reached a plateau in their environmental performance.

2. Conceptual Framework

2.1. Energy and material services

Energy and material services in a general sense can, according to Fell (2017) and Whiting et al., (2020), be defined as those functions that energy and materials contribute to personal or societal activity with the purpose of obtaining or facilitating desired end goals or states, regardless of whether or not a particular flow or stock is supplied by the market. Where, the term "function" refers to a specific characteristic which enables a person or group of people to do something (e.g. experience the mobility that transport offers) and does not refer to material properties or technical attributes such as steel's tensile strength in a chassis or a motor's RPM.

Energy and materials are not typically desired in and of their own right or necessarily perceived to be critical to human wellbeing (Day et al. 2016). However, because they support food production, maintain and expand material stocks, including residential buildings and road infrastructure, and provide services such as thermal comfort and mobility, it is useful to follow the energy or material production chain into services. This is especially the case if services, as an intermediate step between material production/consumption and wellbeing have the potential to improve society as a whole (Brand-Correa and Steinberger 2017; Kalt et al. 2019; Whiting et al. 2020).

The energy/material service concept allows for a distinction between material consumption or accumulation that contributes to a societal function measurable in physical units (such as passenger-km) and resource consumption or accumulation that only supports social status, financial wealth, or leads to obsolete stock or waste. It is a concept that can be applied in a specific sense to several circumstances and applications. Examples include historical socioeconomic analysis, wellbeing, philosophically leaning investigations into economic activity and the re-evaluation of corporate practices. In the case of the latter, end goals or desired states can be understood as a company's strategic objectives *beyond* financial wealth creation or economic stability.

When the energy/material services concept is used in corporate settings, it can give legitimacy to a whole range of business initiatives, including those aligned with a "triple bottom line" perspective. The latter is a common corporate practice for evaluating performance and business value in social and environmental terms, in addition to economic ones (Bocken et al. 2014). The energy/material services concept also facilitates a strategic re-think of how energy and materials are thought of, valued and used. In particular, it breaks the paradigm of seeing materials as products and emphasises the purpose behind their manufacture and a company's raison d'être. In this regard, the energy and material service concept (and its associated tools) has the potential to support financial sustainability when the units considered align with a company's primary business activity. Resource savings in this area of operation will optimise and support those functions which are integral to the corporation's continued success. This is because they are most likely to serve customers and various other stakeholders instead of subsidiary actions, which often take away resources and management focus but have a limited positive impact (and sometimes a negative one) on a company's ability to achieve its fundamental purposes.

2.2. Stock-flow-service nexus

Energy and materials are two sides of the same coin (Krausmann et al. 2016). Energy production, distribution and use involves material infrastructure, while material extraction and processing require a substantial energy input. In turn, specific combination of energy flows, material flows and stock and the interaction between them creates specific types of energy and material services, including heating, lighting and transport. Adequate provision of these services then offers numerous societal benefits, both material and immaterial (Haberl et al. 2017).

Stocks, which include buildings, vehicles, machinery and electronic devices, are those materials that typically stay in the socioeconomic system for at least a full calendar year. Given their longer use phase (relative to flows, which are consumed within one calendar year), stocks fulfil many functions in the economic system (Pauliuk and Müller 2014; Weisz et al. 2015). In fact, they form the physical basis for production and consumption and are integral to the provision of societal services and the generation of financial wealth (Fishman et al. 2014; Krausmann et al. 2017). For example, between 1960 and 2018, approximately 20 percent of Latin American economic output flows went into the construction and maintenance of material stocks (World Bank 2019). Material stocks are extremely relevant to resource accounting given that their maintenance and expansion relies heavily on diverse flow types at considerable quantities. In 2010, the material flow destined to support stock levels (52 percent) was greater than the annual energy, food and material flows for dissipative uses combined (Krausmann et al. 2017; Krausmann et al. 2018).

An articulated bus, like the ones featured in this case study (Volvo, B10M) requires 5.2 to 7.5 tonne of steel, around 1.5 tonne of iron, between 0.2 and 1.6 tonnes of aluminium, 400 kg of rubber, and around 100 to 530 kg of plastics and other metals such as copper and lead (Simonsen 2012). Other materials used, albeit in more minute quantities include cerium (IV) oxide for the wind screens, to block the UV light, and for catalytic converters. While often ignored, the sheer quantities of the different chemical elements involved means that decisions linked to stock have considerable ramifications for corporate environmental management systems, plans, processes and overall performance.

Energy flows activate stock but do not offer service provision without material consumption (e.g. both fuel and vehicle stock combine to provide transport and later they become air emissions and solid waste). It is also important to note that the nature and quantity of both energy and material flows are heavily influenced by material stock. Fuel consumption, for example, is determined by both a user's desire to travel (the service they require) and vehicle design (the nature of the stock, including its aerodynamics, weight etc). In this respect, it becomes clear that there is a corporate benefit to being able to quantifiably analyse the complex relationships between energy and material flows and material stocks and how exactly they come together to provide services.

One way to analyse the physical complexity of the socioeconomic system is through the "Stock-Flow-Service Nexus" approach (Figure 1) (Müller 2006; Haberl et al. 2017). In addition, Carmona et al., (2020) propose six nexus indicators: "stock efficiency", "flow efficiency", "stock degradation efficiency", "stock maintenance rate", "stock expansion rate" and "specific embodied impact". These indicators take into consideration inflow, stock and outflows, from either a production or consumption perspective, and should be used to quantify various interactions (stock-flow, stock-service or flow-service). Furthermore, if one only follows the trend of stock efficiency without taking into consideration the stock maintenance and stock expansion rates, one might be led to believe that a service is improving at the expense of a shortage of stock, when in fact this is not the case.

Figure 1. A Stock-Flow-Service Nexus scheme

If a company wishes to analyse their activity from a service nexus perspective, they would need to undertake an allocation procedure in order to determine which fraction of stock/flow contributes to different services. The material service provided by some products is easier to calculate than others. For example, smartphone use can be split up and assigned according to minutes or computer power devoted to a specific task (service). Another way to do it, especially when you have multi and simultaneous services, is by applying allocation or weighting procedures. This something that already forms part of the LCA methodology when practitioners consider environmental externalities linked to transport, for example (Ally and Pryor 2007). The difference is that a service perspective focuses on positive outputs rather than any detrimental impacts that are not captured by more common metrics such as GDP (as is purpose behind extended LCAs developed by Guinee et al., 2010; Weidema, 2018; Wulf et al., 2017).

A nexus approach can pinpoint exactly where an inefficiency occurs, the trade-off between stocks, flows and service and consequently the potential for overall efficiency gains. It also can provide insight into the obstacles that may be faced when trying to achieve strategic goals. The results derived from the stock-flow-service nexus in a corporate setting can thus direct/support "stock optimisation", a concept Carmona et al. (2017) define as the most appropriate selection of materials, and their use, relative to an agreed set of criteria. The latter could be established for the achievement of environmental goals or in order to fulfil client requirements. In this respect, a company may use the nexus approach to assess current stock levels, to ascertain how stocks are being employed (or not) and whether (and to what degree) their corporate actions support societal needs.

Whilst a nexus approach can be used to evaluate the relationship between flows/stocks and a number of energy and material services and service units, a single material service unit does not, and cannot, capture all relevant aspects of service provision. Kilometres, for example, quantify distance travelled but are not indicative of the average user's qualitative experience. Without proper context, especially if other units are not used in conjunction, results can be misleading. A high number of kilometres is not necessarily a good thing because whilst it may mean that the transport network is large, allowing a person to travel further, it could equally signify that the network is inefficient at taking a person from one point to another because it uses a convoluted rather than a direct route, which captures more potential users but increases everyone's travel time. Larger distances will also increase CO_2 emissions and will lead to more vehicle wear and tear over a shorter timeframe. In other words, a bigger service network is not always better. In fact, one could argue that, in terms of distance, a transport service of the highest quality enables a person to travel fewer kilometres and still achieve their end goal. Thus, one should interpret service units with caution, especially in the absence of a comprehensive literature/data review and contextual analysis.

3. Case Study

3.1. Bogota's BRT System

This chapter explores the operation of Bogota's bus rapid transit (BRT) from 2001 to 2011. A BRT is a terrestrial mass transport system that operates on specifically designated trunk lines, where all other forms of transport are excluded and ticket sale offices and stations unique to the BRT are found along route. In this respect, a BRT, with its articulated buses, resembles and essentially emulates the performance and amenities of a metro or rail system but at a much lower cost (Wright and Hook 2007; Hensher and Golob 2008).

During the period studied, Bogota's BRT system was run by Transmilenio (TM), the transport management entity, and various sub-contracted trunk and feeder operators, fare and user information operators and the governmental institution in charge of infrastructural development. All bus services that fell under the umbrella of TM were provided by different sub-contracted companies operating within the private sector. All sub-contracted activities were explicitly defined in concession contracts. All policies and practices were audited by TM.

Bogota's BRT was developed in phases (Figure 2). In Phase I (2000-2002) the system spanned 42 km across five trunk lines operated by four private companies. In Phase II (2003-2006), it spread 84 km across eight trunk lines, operated by the four original companies and three new sub-contractors. These figures, following the completion of Phase III in 2012, have since increased to 112.9 km across 11 trunk lines run by 10 companies (including the seven previous ones) (Transmilenio 2017; Transmilenio 2019). Bogota's BRT was, and as of 2019, remains Colombia's most expansive form of public transport. It is the third busiest BRT in the world with 658 million annual trips (BRTdata.org 2019). This represents a six-fold increase on the trips taken in 2001 and a 36 percent increase from those taken in 2011 (Transmilenio 2017; BRTdata.org 2019). There were 2.4 million trips taken on an average weekday in 2018 (Transmilenio 2019).

Heightened consumer demand for BRT services has occurred due to populational increases (by more than a million when one compares the 2005 and 2016 censuses) and the conversion of centralised residential buildings into commercial ones, which has caused more people to re-locate into Bogota's suburbs, thus forcing them to commute (DANE 2018; SDP 2018).

Figure 2. Transmilenio development phases. Source: Adapted from Cervero and Dai (2014)

The growing demand for BRT has led to overcrowding at stations and in transit. At the same time, maintenance and operational efficiency have declined, as the replacement fleets requested in 2011 only entered into circulation in 2019 (Hidalgo 2019). Consequently, there is no business case for increasing the number of trips made by users. However, there is a case for using a nexus approach to consider efficiency from a service perspective, in addition to a typical environmental analysis that considers where energy or material flow savings can be made.

Some potential stumbling blocks, especially those associated with unidimensional analysis can be avoided if service is measured using a whole range of parameters and units, such as safety, comfort and punctuality, in addition to distance. When measuring the latter, the nexus approach could be used by a public transport operator to highlight where the number of kilometres starts to detrimentally affect service quality. When reflecting on health and safety, one could consider the diminishing returns on the fatality rate for each additional kg of air emission reduction-related vehicle components. Thus, whilst we recognise the role of various metrics in evaluating service provision, for the simplicity required in a proof of concept, we restrict this present case study to kilometres, as a proxy for passenger mobility. This unit was selected because aside from representing the primary function of a bus company, TM paid its sub-contracted trunk line operators (between 2001 and 2011) on the basis of the number of the kilometres logged by their bus fleet, independently of how many people used the service. The onboard distance was also selected because it was measured by odometers and GPS devices and the resulting data was independently audited by members of the United Nation's *Clean Development Mechanism* (CDM) scheme (UNFCCC 2015).

3.2 The Bus Company

Given the considerable size of Bogota's BRT, this case study's scope is restricted to just one of the trunk operators, which we will refer to as the "bus company". The bus company's fleet was constituted by 191 articulated buses of either type Euro II, Euro III or Euro IV, named in reference to European environmental norms. In addition to these vehicles, the company also owned a collection of offices and workshops where administration, maintenance and management took place. In this chapter, we focus solely on the Euro II buses. These buses formed the bulk of the bus company's fleet (125 out of 191) and constitute the majority of data available on company performance between 2001 and 2011.

The bus company was managed under an integrated management system (IMS) framework. The purpose behind the management system was to develop appropriate policies and achieve the resulting corporate strategies and goals relative to the service quality parameters presented in Table 1. The company had consolidated the quality management system by 2003 and established its environmental management system by 2005. The IMS was planned under a "plan, do, verify, act" scheme with reference to international standard norms including ISO 9001:2008 and ISO 14001:2004. The environmental aspects presented in Table 2 were formally identified by analysing process inputs and outputs, chemical use and environmental incidents.

Table 1. The parameters used by the subcontracted bus company to multi-dimensionally evaluate service provision. Source: bus company

Service parameters	Variable
Safety	Maintenance cost at the accident rate
	The percentage of programmed drivers with a maximum of four and half hours driving shifts
	Bus replacement due to brake or driving failures
Opportunity	Fulfilment of the programmed number of kilometres
	Fulfilment of programmed bus timetable
Cleanliness	In-house cleaning fines
	Non-conformities in cleaning processes
Continuity	Breakdowns
Conformity	Fines sent by TM due to contractual non-compliance
User satisfaction	Customer satisfaction survey results
	Complaints per kilometre of service

Table 2: Significant environmental aspects during fleet operation. Source: as identified by the bus company

Environmental Aspect	Environmental Effect	Environmental Impact	Situation
Planned reserved bus distance travelled ---------------- Vehicle acceleration, braking and gear changes	Fuel consumption	Reduction in non-renewable resources	Normal
	Particulate matter and exhaust gas emission	Air pollution Visual pollution	Normal
Hazardous substance use (paint, solvents, oils, greases, diesel, coolant, aerosols) ----------- Part cleaning ----------- Resource use for the washing and cleaning of buses and associated installations	Hazardous chemical consumption	Nature resource reduction	Normal
		Quality modification of waterbodies or soil	Normal
	Hazardous waste generation (coated materials, packaging and surplus of used oils, fuels, paints, coolants and thinner)	Air pollution, reduction in soil and soil quality	Normal
Substance transfer (paints, solvents, cleaning supplies, coolant, oils, fuels) -------------------	Risk of spills/leaks	Water pollution and soil contamination. Reduction in water body quality	Abnormal

The breakdown of vehicle systems due to road based impacts with objects or crashes ------------ Electronic system failure ------------ Terrorist acts	Risk of fire and/or explosion	Air pollution or soil contamination	Abnormal / Emergency

In 2007, the bus company established, as part of its IMS, a set of policies and practices that could be considered as a rudimentary example of nexus thinking from a service perspective. This approach was adopted when the bus company realised that they were mismanaging fleet mileage. The rationale behind this action was to ensure effective and standardised use of the bus fleet by guaranteeing that each bus met the projected distance travelled (as contractually stipulated). The business case was the prevention of unnecessary vehicle scrapping, reduced maintenance time and the lower costs associated with further procurement of spare parts and, potentially, individual buses. The company's goals were achieved via a stock optimisation model (based on lineal programming) that projected various scrapping scenarios relative to expected daily kilometres, running costs and maintenance activities for each individual bus. The main indicator used to measure the success of the intervention was "Attainment of Projected Distance for the Selected Scenario". The result was that no bus was scrapped due to travelling beyond legal limits, although there were some unexpected consequences, including increased fuel costs.

4. Method

In this case study, the stock-flow-service nexus approach is used to assess the degree at which flows and stocks were influenced by fleet mileage in the business as usual scenario (2001-2007) and upon enacting the stock optimisation strategy (2008-2011). Five indicators are employed to verify the added value in approaching sustainability issues from a service nexus perspective.

4.1 Quantifying Energy/Material Flows, Stocks and Services

The data presented in this case study is obtained from the following primary sources: TM and the subcontracted bus fleet operator. The raw data, which correspond to empirical processes, were internationally verified and validated by the United Nations. The obtained results represent a snapshot of company operations and not a theoretical model based on estimations and/or assumptions. In this respect, it is important to note that these results are specific to the operating conditions (selection of vehicle, percentage of biofuel mix, maintenance frequency and the origin/destination matrix etc) of a particular bus company during the period studied.

The primary input, at 97 to 99 percent of the total energy consumption, was diesel fuel. This is normal given that it represents 74 percent of the energy units employed in the mobilisation of passengers travelling on Latin American public transport (Carmona and Ocampo 2014). What is atypical is the fact that biofuel was added to the diesel, when Colombia passed the resolution *182142 of* 2007, which enforced a five percent addition of biofuel into the conventional fuels used by diesel motors. This legislation established the technical quality of the fuel's specifications. It also led to the development of B5 fuel, a name chosen in reference to the percentage needed. In 2012, this legislation was superseded by one that required a seven percent biofuel addition to diesel, the implications of which lie beyond the scope of this chapter. The bus company's fuel consumption was registered daily at service stations via the *i-button* system, which served as an inventory control. This real time system registered and stored information on fuel supply type and quantity and distance travelled, amongst others. This data was audited under the United Nation's CDM project.

Non-fuel materials inflows (e.g. lubricants, greases and coolants) were not considered within the scope of the study, since the fleet in question didn't increase, and such flows only become relevant when stock expands (or contracts). Whilst higher volumes of material inputs were used during the maintenance phase, they did not directly impact service provision and were adequately captured in the outputs, in the form of waste. The latter are categorised as “conventional waste” and “hazardous waste”. Waste streams include oil, air filters, oil filters, contaminated material, batteries, mud, used thinner, scrap metal, coolant, fluorescent tubes, used tyres, rubber, broken/replaced glass, acrylic, electronic waste, plastics, aluminium, polystyrene and PET.

Stocks refer solely to Euro II buses and do not encompass other vehicles types, buildings or other forms of infrastructure or machinery that supported the bus company’s operations. Mobility as a service was measured in kilometres and captured in a legally fitted tachograph, a device which records distance covered, vehicle speed, vehicle operation time, driving time, work disruptions and rest periods.

4.2 Stock-Flow-Service Efficiency Indicators

Table 3 summarises the indicators used in this BRT case study to express various aspects of the stock-flow-service nexus. The *stock efficiency* indicator (Eq. 1) identifies the impact of stock size on service provision. It can be used to demonstrate the significance of material accumulation and, consequently, may drive corporate policy, practice and procurement decisions. It can also identify where service units need to be adjusted so to maintain or improve service efficiency. In a transport case study, this indicator provides insights into how vehicle size and design influence service delivery. For example, it can reveal whether the current bus fleet is large enough (or not) relative to the number of kilometres of service requested by the public transport authority. The *flow efficiency* indicator (Eq. 3) highlights how product innovation and/or user interaction affect resource consumption and service provision. It can be used to re-draw public transport policies linked to sustainable fuel transitions because it is when considering *stock efficiency* relative to *flow efficiency*, that the trade-off between flows and stocks becomes apparent. The *stock degradation efficiency* indicator (Eq. 5) states the level of physical depreciation that occurs during service delivery. It can help identify whether waste is being generated due to preventive maintenance activities or due to poor road conditions or driver error.

The *stock maintenance rate* (Eq. 7) depicts the minimum amount of material flow that is required to maintain/upgrade stock (rather than expand it). It provides insights into stock component longevity and thus helps decisionmakers to anticipate future procurement for new buses or spare parts, for example. While out of the scope of this chapter, an additional resource interaction can be captured through the *specific embodied impact* indicator. This identifies the amount of inputs or outputs associated with a flow or stock. One can use it to determine how much CO_2 is released from fuel consumption, stock production and maintenance.

Finally, the *interquartile range of stock evolution* (IQR – Eq. 9) represents the statistical dispersion (the spread of the middle half of the data) between the first and third quartiles relative to specific stock characteristics, such as year of registration, kilometres, etc. It can identify the intensity or frequency at which an individual bus provides a service. In this case study, ensuring that all buses were employed to the same degree prevented vehicle scrapping and unnecessary re-investment in new buses, which represented a considerable financial and environmental cost.

Table 3. Stock-flow-service indicators

Indicator	Description	General Equations	Case study application
Stock efficiency	The amount of stock required to provide a unit of service	$\frac{S}{M_{Stock}}$ (1)	$\frac{Service\ (km/year)}{Stock\ (number\ of\ buses)}$ (2)

Stock degradation efficiency	The amount of stock that degrades (worn out/made obsolete) to provide a unit of service	$\frac{S}{M_{Outflow}}$ (3)	$\frac{Service\ (km)}{Waste\ outflow\ (tonne)}$ (4)
Flow efficiency	The amount of inflow that is directly consumed to provide a unit of service	$\frac{S}{M_{Inflow(consumables)}}$ (5)	$\frac{Service\ (km)}{Fuel\ (kg)}$ (6)
Stock maintenance rate	Fraction of material required to maintain stock at a specified level	$\frac{M_{Outflow}}{M_{Stock}}$ (7)	$\frac{Steel\ ouflow\ (tonne/year)}{Steel\ stock\ (number\ of\ buses)}$ (8)
Interquartile range (IQR) of stock evolution	Distance between first and third quartile of the different elements that constitute the stock	$Q3 - Q1$ (9)	$Q3\ kilometre\ distance - Q1\ kilometre\ distance$ (10)

Note: Where, S: Material service, M_{Stock}: Material stock, M_{Inflow}: Annual material inflow (depending on the equation it may be a consumable or a durable), $M_{Outflow}$: Annual material outflow, Qn: quartile n

5. Results and analysis

5.1. Flow, Stock and Service Trends

Figure 3a shows that the service provided by the Euro II fleet varied between 7 and 11 million km/year, with the maximum annual distance covered by the bus company's fleet in 2004. This peak occurred as the BRT network expanded, prior to newly contracted operators being able to fully adapt to their new role. A five percent decline between 2004 and 2006 followed as the new operators began running at full capacity. This new dynamic gave TM the opportunity to re-design bus routes and re-assign them across all operators, according to their fleet capacity. In 2007 the bus company purchased newer vehicles (Euro III and IV), subsequent to an amendment to the service contract. This resulted in a reduction in route assignments for the older buses within the fleet. In 2011, for example, the Euro II vehicles were responsible for only 60 percent of the total kilometres travelled. As one might expect, Figure 3b shows a strong correlation between service and fuel consumption and thus the most intense diesel use (5,758 tonnes) occurred in 2004. At the same time, Euro II bus stock (Figure 3c) remained constant with only one bus being scrapped due to a traffic incident. Figure 3d presents an absolute increase in waste production because with an aging stock (and even if the number of vehicles remains constant and the service reduces) there is an increasing number of energy and material flows associated with maintenance activities.

Figure 3. Service, flows and stock variables from 2001-2011. A: Service in km. B: Inflow as tonnes of fuel consumption. C: Stock as bus units. D: Outflows as tonnes of wastes.

5.2 Trends in Nexus Indicators

Relative to 2006 (2.046 km/kg), Figure 4a presents a 10.5 percent fuel efficiency increase from the 1.851 km/kg baseline registered in 2001. This incremental improvement resulted from improved fuel injection procedures and control measures designed to keep the percentage of kilometres driven by reserved service buses (those running from point A to B, but not operating a public service) to less than two percent of the total. From 2007 onwards fuel efficiency reduced, falling to 1.948 km/kg by 2011. This happened for two reasons. The main one was the introduction of B5 diesel, which was of poor quality due to the unexpected presence of solids that were not removed in the production process. These solids negatively affected the injector system and reduced combustion engine efficiency. It also had detrimental environmental effects because it increased the opacity of exhaust gases (Carmona and Ocampo 2014). The second reason was an inability to maintain reserved service bus kilometres at two percent following TM's route re-designs. By 2011, such kilometres had reached seven percent of the total.

Figure 4b shows the yearly distance travelled by the average bus. In 2001, the stock efficiency was 57,000 kilometres per bus. This number increased to 76,000 kilometres per bus by 2011.

Given that stock remained almost the same, any fluctuations occurred due to changes in service provision - in the sense that stock efficiency increased in direct proportion to kilometres travelled. The same held true for the stock maintenance rate, which was only affected by the quantity of waste generated (Figure 4c). For the latter and taking into consideration that each bus weighed 9 tonnes, the weight equivalent of 10 percent of the fleet stock was required in 2001 to maintain/support bus operations. This increased to 25 percent by 2011.

In summary, the company's action plans regarding improved operational efficiency were countered and masked by various external factors including TM's expansion of trunk lines, and route re-design plus the legally enforced use of poor quality biodiesel. Internal factors, particularly those linked to increased vehicle deterioration due to aging, also contributed to the problem. Consequently, although improvements were made, they simply prevented overall performance from worsening.

Figure 4. Nexus indicator performance 2001-2011. A: Fuel efficiency. B: Stock efficiency. C: Stock maintenance rate. D: Stock degradation efficiency.

Stock degradation efficiency went from 65 km/kg in 2001 to 34 km/kg by 2011 (Figure 4d). Figure 5 presents the stock degradation efficiency for each waste stream. Waste quantities of used oil, which was replaced every 7,500 to 10,000 km, is coupled to service provision, meaning that the more a bus travelled, the more waste oil was produced. Other waste streams were influenced by maintenance cycles (e.g. engine and injection system repairs, battery and tyre replacements), hence the peaks. Waste was also produced in the corrective maintenance activities that followed accidents. Outflows derived from the latter were constituted by contaminated materials, thinner and cardboard, and produced an irregular peaked pattern. It is important to note that only one bus suffered irreparable damage following an accident (in 2003). This event was removed from the data as it was an outlier that produced 18 tonnes of additional outflow. The quantity of waste per bus increased as the fleet aged, due to a higher demand for vehicle maintenance. In 2011, 36 waste steams were generated. The most common were used oil (27%), scrap metal (17%), used tyres (9%) and mud (9%). Some 56 percent of the waste's total weight was sent for recycling.

Figure 5. Stock degradation efficiency for each waste stream

5.2.1 Stock optimisation

Figure 6 presents the results of the stock optimisation scenario, as measured by the IQR. The optimal scenario is a low IQR because it means that the distance travelled among the fleet was uniform. The high IQR values registered at the beginning of BRT operations followed by their rapid decline and stabilisation were an expected part of the learning curve. Between 2001 and 2006, the distance travelled by any one particular bus was not monitored relative to others in the fleet. Consequently, some buses were used at a much higher frequency than others. Those with the least mileage were driven only during peak hours whilst those used the most were seldom parked. If this practice had continued, some buses would have reached the legal limit of a million kilometres and would have been scrapped. This would have rendered the company unable to provide the agreed upon level of service during the peak period, without investment in new vehicles. In response to this imbalance, an optimisation strategy was launched in 2007. The impact of the strategy can be seen in the IQR's decline between 2009 and 2011; however, it did not automatically transform into better results in terms of fuel efficiency, stock efficiency or stock degradation efficiency (as seen in Figure 4). This highlights one of the challenges of improving environmental performance, when, as is often the case in an integrated management system, it does not rely on a single action but instead encompasses various complex interactions (not all of which are captured by the stock-flow-service nexus).

Figure 6. Interquartile range (IQR) of stock evolution. Note: dashed line represents the starting year for the implementation of the stock optimisation strategy.

5.2.2. Normalisation of indicators

To better understand the evolution of stock-flow-service nexus, each interaction (i.e. service-flow, service-stock, flow-stock) was normalised to 2001. An efficient scenario is one where all the efficiency indicators increase through time whilst the maintenance rate and IQR decrease. As Figure 7 shows, and as explained in the previous subsections, the bus company's stock efficiency and fuel efficiency were not optimal because there was no significant improvement. In addition, those indicators linked to waste (i.e. the stock degradation efficiency and the stock maintenance rates) demonstrate poorer performance. To mitigate the issues identified by these indicators, the company would have had to develop partnerships with suppliers or establish waste management strategies that either extended product lifespan (e.g. by using a lubricant that needed to be substituted every 15,000 rather than 10,000 km) or which would have led to higher recoverability rates. The lowest level of fluctuation was in fuel consumption. However, in financial terms, given that fuel costs represented 35 percent of the company's budget, a one percent decrease in efficiency would had led to a 0.4 percent increase in expenditure (which is equivalent to the annual cost of the urea required by the Selective Catalytic Reduction for NOx reduction purposes in the Euro IV fleet).

Figure 7. Nexus indicators normalisation. (*) dashed line represents the starting year for the implementation of the stock optimisation strategy

6. Discussion and concluding remarks

Through the efficiency indicators explored in this chapter, we have demonstrated that the stock-flow-service nexus approach can be used to quantify the extent at which flows relative to stocks, flows relative to service and stocks relative to service mobilise a bus fleet. In 2011, the bus company required 0.51 kg of diesel fuel and $1.3x10^2$ units of vehicle stock to provide 1 km of service. In turn, this 1 km of service led to the degradation/loss and replacement of $2.9x10^2$ kg of material flows to ensure stock functionality at the expected standard. This kind of information gets overlooked if a company does not consider the role of stock accumulation, overemphasises fuel efficiency and ignores services units.

The nexus approach allows for a better understanding of where, and to what extent, a company's physical assets are contributing to strategic goals, such as the optimisation of in-use fleet (as identified by the IQR) and waste reduction (which is captured by the stock maintenance rate). The nexus can also help corporate decisionmakers weigh up whether it is best to invest in fuel efficiency, stock efficiency, waste reduction or find a balance between the three. Quantifying interactions between stock (e.g. the vehicle chassis) and material flows (e.g. tyre tread) may also support future procurement strategies, where, for example, a slightly more expensive but well-designed vehicle can be argued for on the basis of fuel and lubricant savings. This is particularly useful when service and operation are affected because certain components must be replaced at a given number of kilometres or at certain levels of wear and tear. It is especially beneficial when a company is having to replace parts prior to a bus manufacturer's specified max number of kilometres. The service nexus approach can also support a more solid understanding of operational dynamics, which may permit a more accurate prediction of fleet or spare parts replacement, thus decreasing the amount of time a vehicle stays in the garage. This perspective also has the potential to provide further evidence for addressing driver behaviour, if that is the root cause for shorter than expected vehicle or part lifecycles or if it represents the only financially viable way to increase profitability and/or improve user experience.

Via the stock efficiency indicator, a management team can identify where material accumulation could provide more services. This may lead to a better allocation of resources, where, for example, parked buses are used for driver training so that new buses are not bought explicitly for that purpose or office spaces are co-shared. In terms of waste management, decisionmakers could use the nexus to justify vehicle lifetime extension via the conversion of buses into temporary offices, mobile libraries or museums, or driver classrooms. The nexus approach could also help companies to establish evidence-based targets. For example, it can identify which waste outflows are coupled with kilometres and which ones are associated with corrective maintenance due to road accidents or low-quality spare parts. With this knowledge, one can propose a reasonable waste reduction target that aligns with data rather than policies that respond solely to public sentiments and marketing goals.

In short, once a company reaches a product-focused performance plateau, the stock-flow-service nexus can offer a nuanced perspective that changes the way corporate leaders and executive boards consider resources and wastes. This is particularly the case if they are not aware of the importance of material stocks, how they drive flows (and vice versa) and, by extension, help to determine service quality. The service nexus could also be used to ascertain the sustainability of a transition from conventional to electric/hybrid vehicles. This is because it can identify the extent at which stock efficiency and fuel efficiency are affected by changes in the material composition of the vehicle. According to Grütter (2014), a 12-metre electric bus that is able to travel 200 km between charging cycles contains a battery weighing around three tonnes. This mass increase will, due to axle-weight restrictions, reduce the number of passengers allowed to embark on any one trip. A move towards electrified bus fleets is therefore something that needs to be carefully considered on transport systems as busy as Bogota's BRT.

There are various challenges that would need to be overcome before the nexus approach, the concept of material services and its associated indicators are widely accepted. There may be reluctance among key stakeholders to use yet another measuring stick because of the cost and effort involved. In addition, there often needs to be overwhelming evidence that the metric matters to a company and its shareholders or a government and members of the public. Another challenge is the integration of the various aspects (safety, continuity, cleanliness, user satisfaction, accessibility, etc.) that contribute to mobility as a service, given that they are measured using different units, which do not necessary lend themselves to material allocation. For example, how should one link vehicle stock to cleanliness? Neither is it clear how or to what extent steel supports hygiene. In addition, when evaluating multicriteria performance, it can be difficult to prioritise actions, even if a weighting method is applied. Weighting can be a subjective exercise and may reflect corporate interests and not those of the customers a company is supposedly serving. Such issues need to be fully considered if one is to make the most of the advantages that a nexus perspective offers.

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7. References

Ally, J., and T. Pryor. 2007. Life-cycle assessment of diesel, natural gas and hydrogen fuel cell bus transportation systems. *Journal of Power Sources* 170: 401–411.

Barrett, P., M. Sexton, and M. Curado. 1998. Sustainability through integration. In *Proceedings, CIB World Building Congress 1998, Symposium D, Gävle, Sweden*, 1767–76.

Bocken, N. M., S. W. Short, P. Rana, and S. Evans. 2014. A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production* 65: 42–56.

Boiral, O. 2011. Managing with ISO systems: lessons from practice. *Long Range Planning* 44: 197–220.

Boiral, O., L. Guillaumie, I. Heras-Saizarbitoria, and C. V. Tayo Tene. 2018. Adoption and outcomes of ISO 14001: a systematic review. *International Journal of Management Reviews* 20: 411–432.

Brand-Correa, L. I., and J. K. Steinberger. 2017. A Framework for Decoupling Human Need Satisfaction From Energy Use. *Ecological Economics* 141: 43–52.

BRTdata.org. 2019. Annual demand (passengers per year).

Brundtland, G. H. 1987. *Report of the World Commission on environment and development: "Our common future."* New York, NY, USA: United Nations.

Carmona, L. G., and A. I. Ocampo. 2014. An Evaluation of the Environmental Performance of Bus Rapid Transit and the Contribution to Public Policy in Emerging Cities Using Bogota as a Case Study. In *Health, Violence, Environment & Human Development in Developing Countries*, ed. A. Cotte Poveda and C. I. Pardo Martinez, 107–145. New York, US: Nova Science Publishers Inc.

Carmona, L. G., K. Whiting, A. Carrasco, T. Sousa, and T. Domingos. 2017. Material Services with Both Eyes Wide Open. *Sustainability* 9: 1508.

Carmona, L. G., K. Whiting, H. Haberl, and T. Sousa. 2020. The use of steel in the United Kingdom's transport sector: a material stock-flow-service nexus case study. *Journal of Industrial Ecology*: In review.

Cervero, R., and D. Dai. 2014. BRT TOD: Leveraging transit oriented development with bus rapid transit investments. *Transport Policy* 36: 127–138.

DANE. 2018. *Informe comité nacional de expertos para la evaluación del censo nacional de población y vivienda de Colombia 2018 (in Spanish)*. Bogotá, Colombia: Departamento Administrativo Nacional de Estadística.

Day, R., G. Walker, and N. Simcock. 2016. Conceptualising energy use and energy poverty using a capabilities framework. *Energy Policy* 93: 255–264.

Fell, M. J. 2017. Energy services: A conceptual review. *Energy Research & Social Science* 27: 129–140.

Fishman, T., H. Schandl, H. Tanikawa, P. Walker, and F. Krausmann. 2014. Accounting for the material stock of nations. *Journal of Industrial Ecology* 18: 407–420.

Grütter, J. 2014. *Real world performance of hybrid and electric buses*. Grütter Consulting.

Guinee, J. B., R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall, and T. Rydberg. 2010. *Life cycle assessment: past, present, and future*. ACS Publications.

Gunningham, N., and D. Sinclair. 1999. Environment management systems, regulation and the pulp and paper industry: ISO 14001 in practice. *Environmental and Planning Law Journal* 16: 5–24.

Haberl, H., D. Wiedenhofer, K. H. Erb, C. Görg, and F. Krausmann. 2017. The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum. *Sustainability* 9: 1047.

Hensher, D. A., and T. F. Golob. 2008. Bus rapid transit systems: a comparative assessment. *Transportation* 35: 501–518.

Hidalgo, D. 2019. Celebrating 18 Years of TransMilenio: Growing Pains and What Lies Ahead for Bogotá's BRT. *The City Fix.*

ISO. 2015a. *ISO 9001:2015 Quality management systems: Requirements*. Geneva, Switzerland: International Organization for Standardization.

ISO. 2015b. *ISO 14001:2015 Environmental Management Systems: Requirements with Guidance for Use*. Geneva, Switzerland: Intenational Organization for Standardization.

Kalt, G., D. Wiedenhofer, C. Görg, and H. Haberl. 2019. Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade. *Energy Research & Social Science* 53: 47–58.

Krausmann, F., H. Weisz, and N. Eisenmenger. 2016. Transitions in sociometabolic regimes throughout human history. In *Social Ecology: Society-Nature Relations across Time and Space*, ed. H. Haberl, M. Fischer-Kowalski, F. Krausmann, and V. Winiwarter, 63–92. Cham, Switzerland: Springer.

Krausmann, F., D. Wiedenhofer, C. Lauk, W. Haas, H. Tanikawa, T. Fishman, A. Miatto, H. Schandl, et al. 2017. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences* 114: 1880–1885.

Krausmann, F., C. Lauk, W. Haas, and D. Wiedenhofer. 2018. From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. *Global Environmental Change* 52: 131–140.

Liyin, S., Y. Hong, and A. Griffith. 2006. Improving environmental performance by means of empowerment of contractors. *Management of environmental quality: an international journal* 17: 242–257.

Müller, D. B. 2006. Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecological Economics* 59: 142–156.

Pauliuk, S., and D. B. Müller. 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. *Global Environmental Change* 24: 132–142.

Reis, A. V., F. de O. Neves, S. E. Hikichi, E. G. Salgado, and L. A. Beijo. 2018. Is ISO 14001 certification really good to the company? a critical analysis. *Production* 28.

SDP. 2018. *Análisis demográfico y proyecciones poblacionales de Bogotá (in Spanish)*. Bogotá, Colombia: Alcaldía Mayor de Bogotá, Secretaría Distrital de Planeación.

Simonsen, M. 2012. *Energi- og utslippsvirkninger av produksjon av Volvo 8500 busser (in Norwegian)*. Sogndal, Noruega: Vestlandsforsking.

Steger, U., L. Wei, and F. Zhaoben. 2017. *Greening Chinese Business: Barriers, Trends and Opportunities for Environmental Management*. 2nd ed. Abingdon, UK: Routledge.

Transmilenio. 2017. Estadísticas de oferta y demanda del Sistema Integrado de Transporte Público - SITP - Octubre 2016 (in Spanish).

Transmilenio. 2019. Historia de TransMilenio (in Spanish).

UNFCCC. 2015. *AM0031: Large-scale Methodology, Bus rapid transit projects, Version 06.0, Sectoral scope(s): 07*. Rio de Janeiro, Brasil and New York, US: United Nations Framework Convention on Climate Change.

Weidema, B. P. 2010. Environmental training for the food industry. In *Environmental Assessment and Management in the Food Industry*, 356–373. Oxford, UK: Elsevier.

Weidema, B. P. 2018. The social footprint—a practical approach to comprehensive and consistent social LCA. *The International Journal of Life Cycle Assessment* 23: 700–709.

Weisz, H., S. Suh, and T. E. Graedel. 2015. Industrial Ecology: The role of manufactured capital in sustainability. *Proceedings of the National Academy of Sciences* 112: 6260–6264.

Whitelaw, K. 2012. *ISO 14001 environmental systems handbook*. Oxford, UK: Elsevier.

Whiting, K., L. G. Carmona, L. I. Brand-Correa, and E. Simpson. 2020. Illumination as a material service: A comparison between Ancient Rome and early 19th century London. *Ecological Economics* 169C: 106502.

Wiedenhofer, D., T. Fishman, C. Lauk, W. Haas, and F. Krausmann. 2019. Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting: Concepts, Modelling, and Global Application for 1900–2050. *Ecological Economics* 156: 121–133.

World Bank. 2019. Gross fixed capital formation in % of GDP.

Wright, L., and W. Hook. 2007. *Bus rapid transit planning guide*. New York, US: Institute for Transportation & Development Policy.

Wulf, C., P. Zapp, A. Schreiber, J. Marx, and H. Schlör. 2017. Lessons learned from a life cycle sustainability assessment of rare earth permanent magnets. *Journal of Industrial Ecology* 21: 1578–1590.

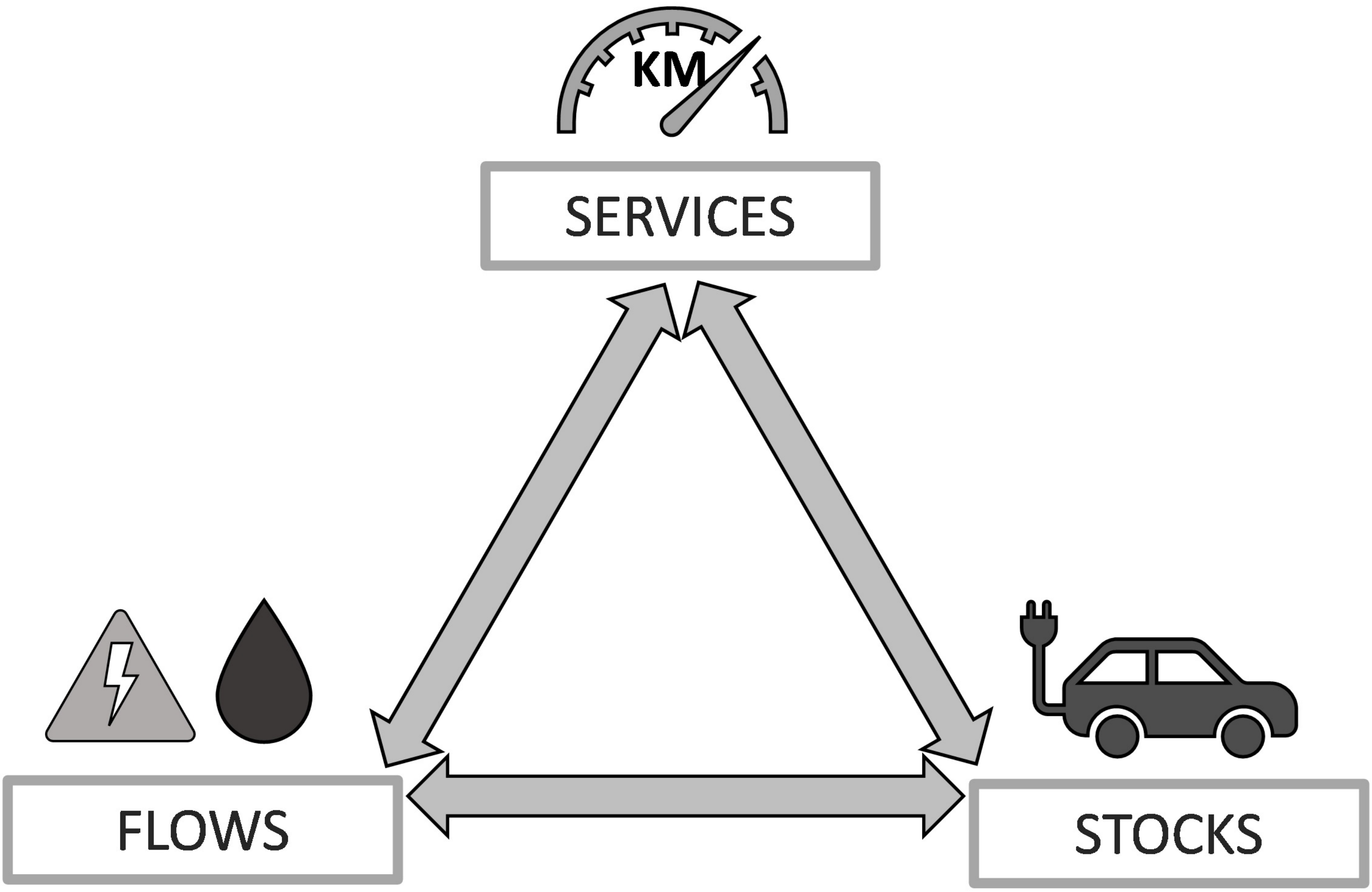

Figure 1. A Stock-Flow-Service Nexus scheme

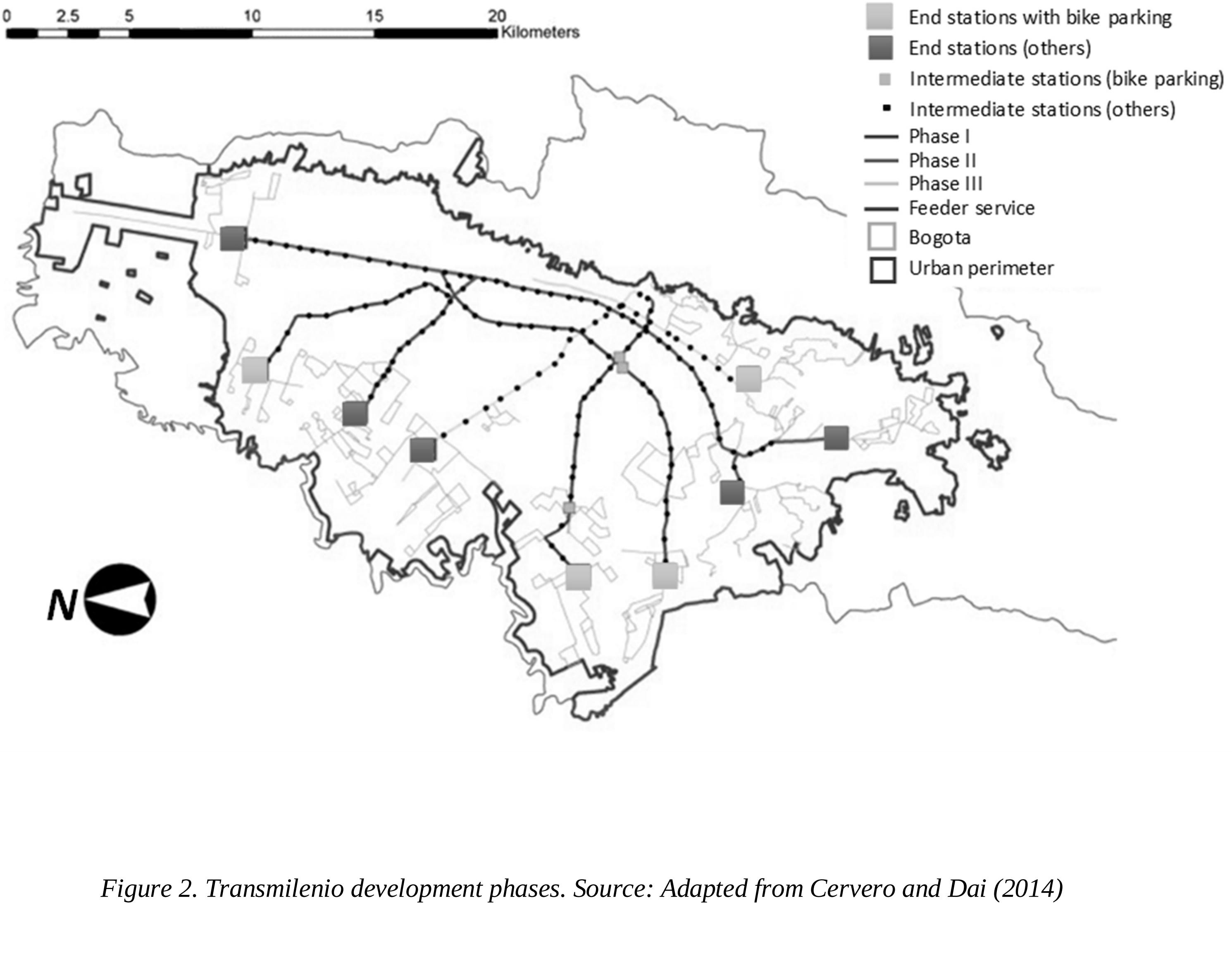

Figure 2. Transmilenio development phases. Source: Adapted from Cervero and Dai (2014)

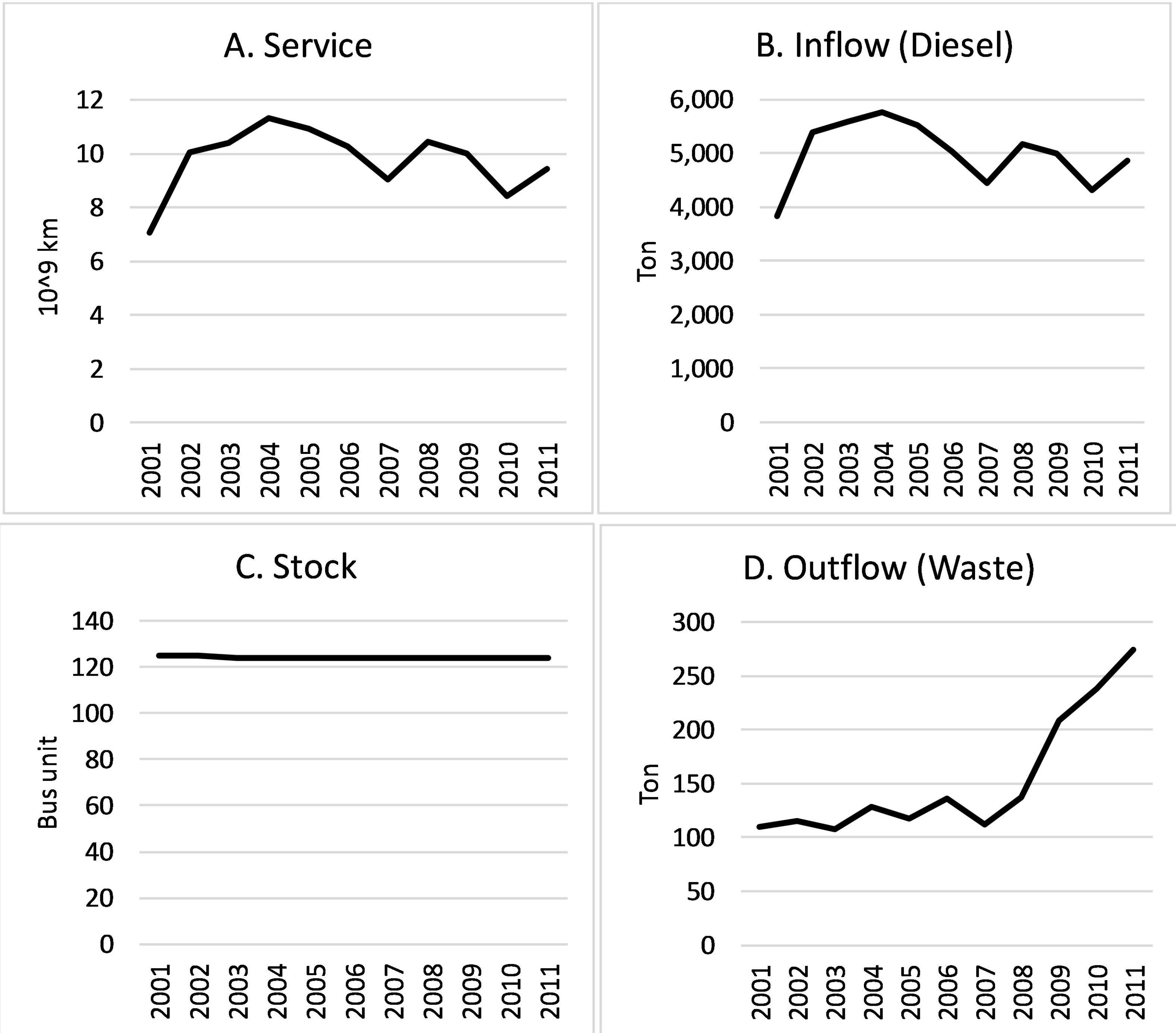

Figure 3. Service, flows and stock variables from 2001-2011. A: Service in km. B: Inflow as tonnes of fuel consumption. C: Stock as bus units. D: Outflows as tonnes of wastes.

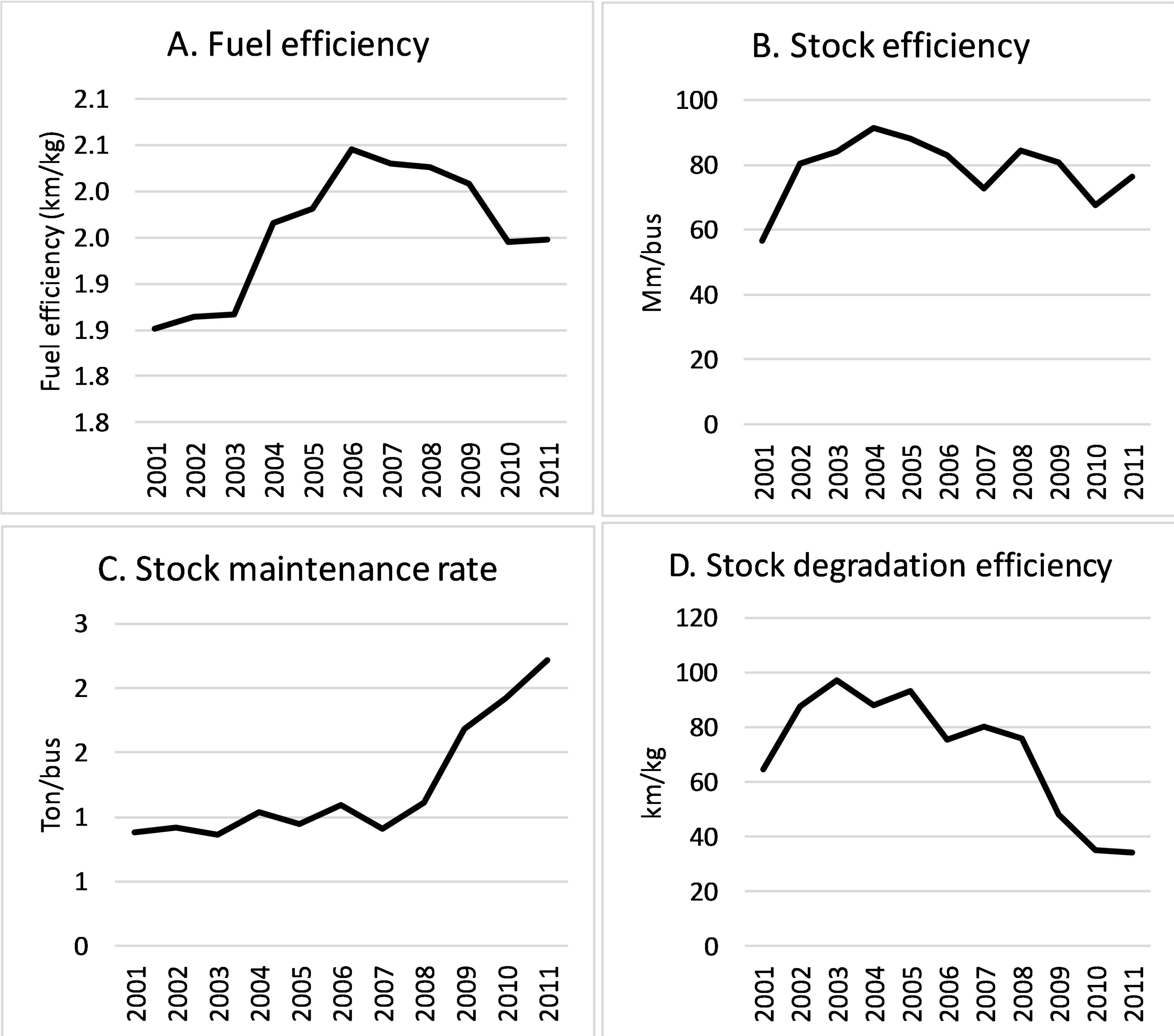

Figure 4. Nexus indicator performance 2001-2011. A: Fuel efficiency. B: Stock efficiency. C: Stock maintenance rate. D: Stock degradation efficiency.

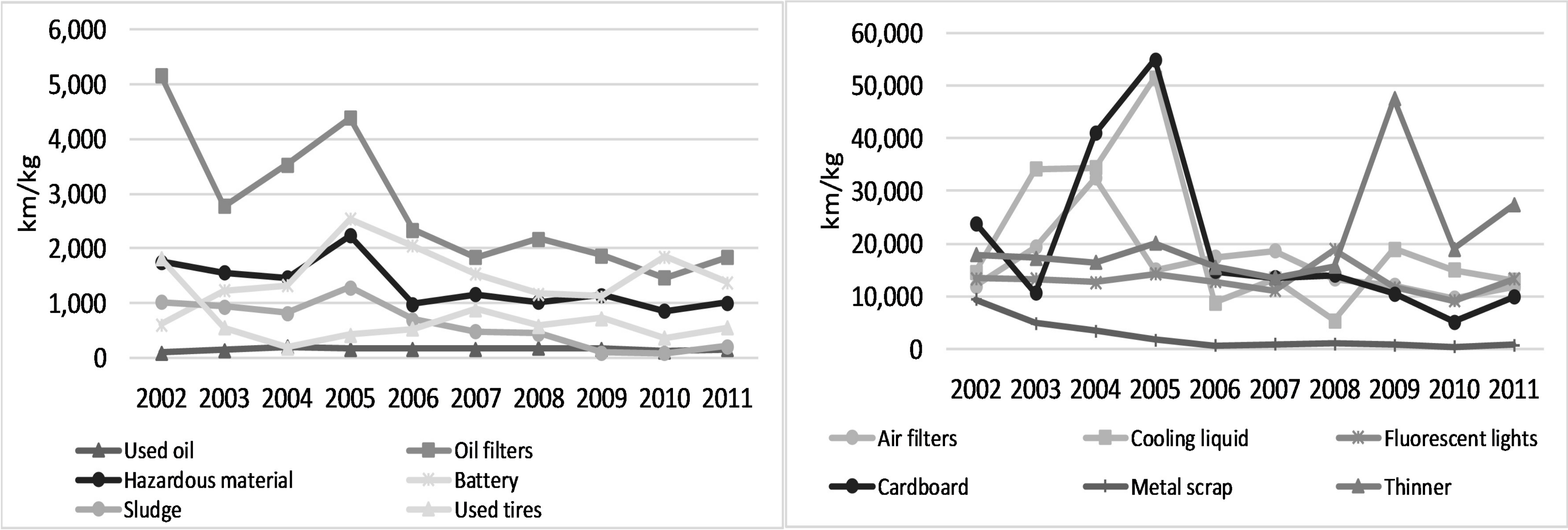

Figure 5. Stock degradation efficiency for each waste stream

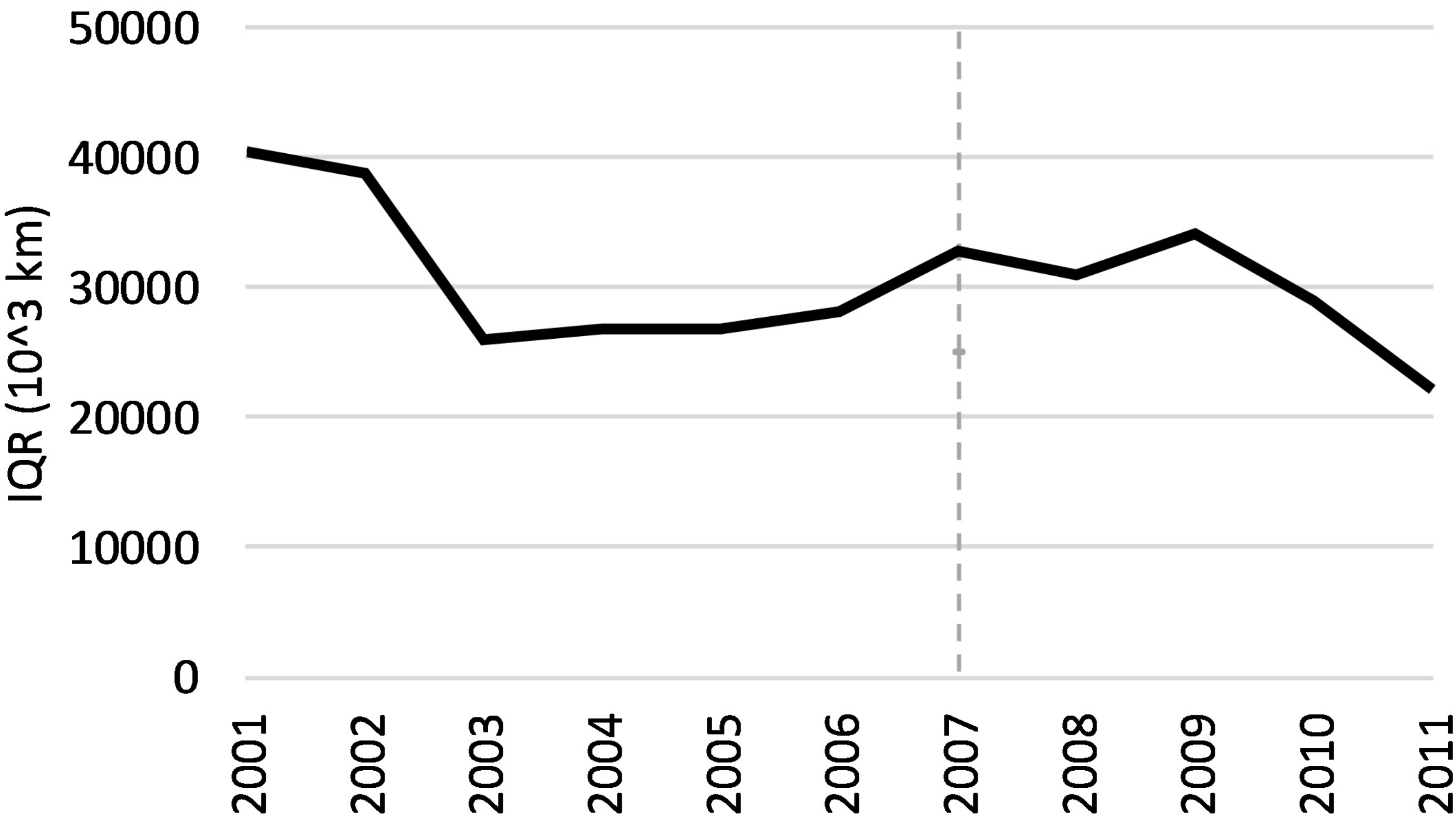

Figure 6. Interquartile range (IQR) of stock evolution. Note: dashed line represents the starting year for the implementation of the stock optimisation strategy.

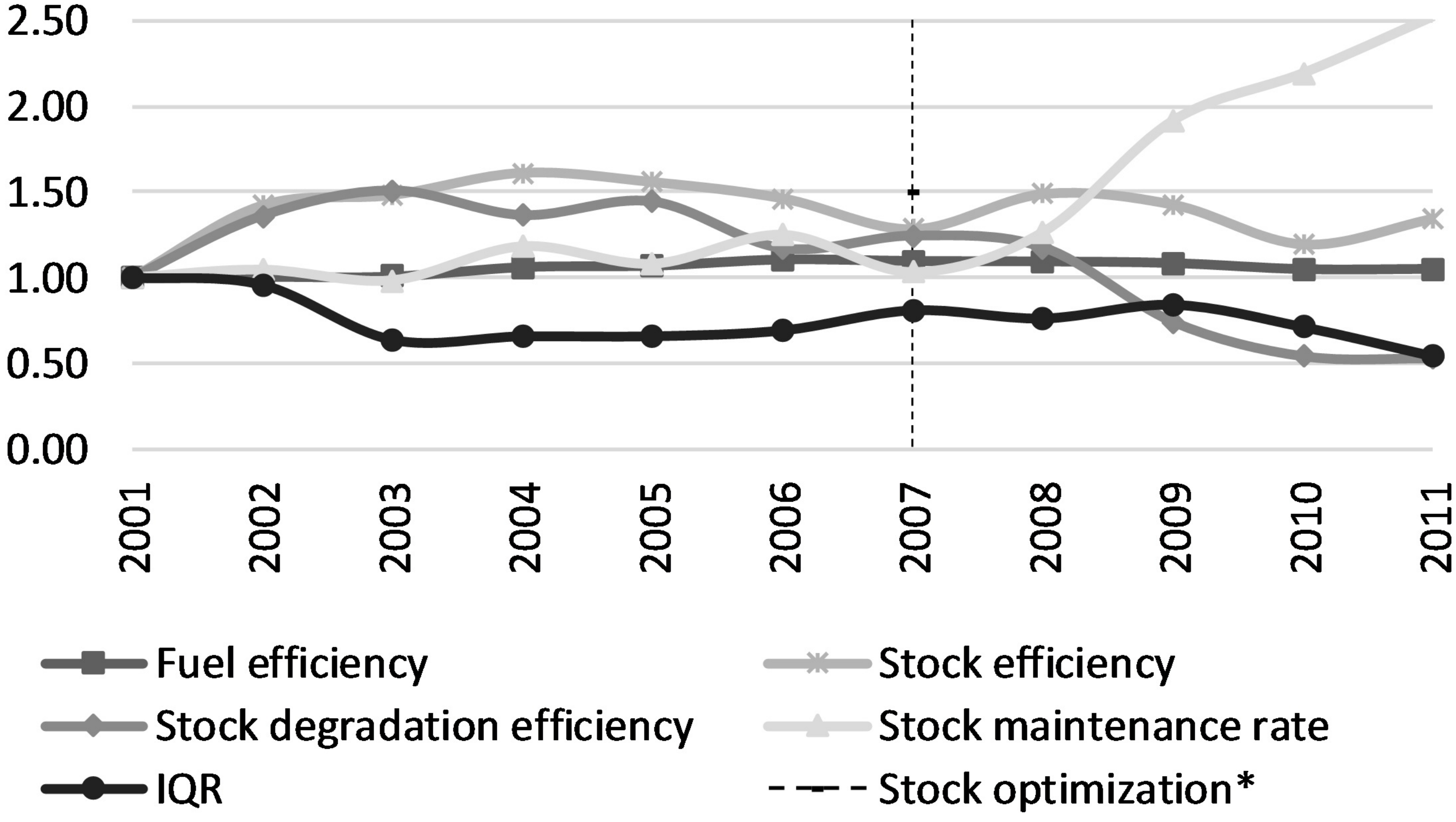

Figure 7. Nexus indicators normalisation. (*) dashed line represents the starting year for the implementation of the stock optimisation strategy