Structural LCA as a Tool to Environmental Neutralizability of Products and Services

Sebastian Brun,[1] Domen Hojkar,[2] Špela Tertinek,[4] Drago Bokal[3,4]

[1] University of the Bundeswehr Munich, Department of Economics and Management, Neubiberg, Germany
sebastian.brun@unibw.de
[2] University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia
domen.hojkar@fs.uni-lj.si
[3] University of Maribor, The Faculty of Natural Science and Mathematics, Maribor, Slovenia
drago.bokal@um.si
[4] Databitlab d.o.o., Maribor, Slovenia
spela.tertinek@databitlab.eu, drago.bokal@um.si

Environmental neutralizability is a recently introduced concept to study the reduction of the environmental impact of products and services on their production costs. In this paper, we combine the ISO 14040 and ISO 14044 based LCA and cost price models, highlighting the similarities between both models and the processes of their development. The combination of these models provides information on the environmental neutralizability of products and services. Crucial to understanding environmental neutralizability of a given product is structural LCA, which distinguishes between fixed and recurrent emissions. We demonstrate the applicability of the introduced models and concepts on data obtained for the German transportation sector.

Keywords:
environmental neutralizability, structural LCA analysis, mobility sector, GHG target emissions

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1 Introduction

The 2030 climate and energy framework outlines EU-wide targets and policy objectives spanning from 2021 to 2030. Emphasising the reduction of net greenhouse gas emissions by a minimum of 55% compared to 1990 levels, the European Commission's proposals in July 2021 aim to align climate, energy, transport, and taxation policies towards this ambitious goal. These measures pave the way for the EU to achieve climate neutrality by 2050, positioning it as a trailblazer on this front (European Commission (a), n.d.). Key targets within the 2030 climate and energy framework include a notable increase in ambition:

- Greenhouse gas emissions: A shift from a 40% to at least a 55% reduction (relative to 1990 levels).
- Renewable energy: An elevation from a 32% to a 42.5% share.
- Energy efficiency: Targets set for final energy consumption rising from 32.5% to 36%, and for primary energy consumption reaching 39%.

The EU's target to achieve climate neutrality by 2050, creating an economy with net-zero greenhouse gas emissions, forms the core objective of the European Green Deal (European Commission (b), n.d.). This commitment aligns with the EU's pledge to global climate action under the Paris Agreement (European Council, 2024). The transition toward a climate-neutral society represents both a pressing challenge and an opportunity to forge a more promising future for everyone. This transformation involves every facet of society and economic sectors, spanning from the power sector to industry, mobility, buildings, agriculture, and forestry.

The European Union's commitment to achieving a 55% reduction in EU emissions by 2030 is legally enforced under the European climate law. In line with this obligation, EU nations are actively drafting new legislation to meet this target and ultimately achieve climate neutrality within the EU by 2050 (European Council, 2024). The Fit for 55 package encompasses a series of proposals designed to amend existing EU laws and introduce fresh initiatives. Its primary objective is to align EU policies with the established climate objectives as agreed upon by both the Council and the European Parliament. The term 'Fit for 55' is coined in reference to the EU's ambitious goal of reducing net greenhouse gas emissions by a minimum of 55% by 2030.

In pursuit of its 2050 target, the EU is actively addressing the reduction of emissions from cars, given that road transport contributes to one-fifth of the EU's CO2 emissions. By 2030, the EU is targeting a 55% reduction in car emissions and a 50% reduction in van emissions compared to 2021 levels. This effort is aimed at achieving the objective of zero emissions from new cars and vans by 2035.

The Council has approved a new regulation, part of the 'Fit for 55' package, imposing stricter CO2 emission standards for new cars and vans in the EU. Key aspects of the regulation include reduction targets of 55% for new cars and 50% for new vans by 2030-2034 compared to 2021 levels, achieving 100% emissions reductions for both by 2035, introduction of a regulatory incentive mechanism for zero- and low-emission vehicles (ZLEV) from 2025-2029, rewarding manufacturers meeting specific sales benchmarks and lastly consideration for e-fuels and a review in 2026 to assess progress towards emission reduction targets, examining technological advancements and the transition to zero emissions. Other provisions involve gradual reduction in emission credits for eco-innovations, the development of a common EU methodology for assessing CO2 emissions, and derogation for small volume manufacturers until 2035. This regulation revises previous rules, holding manufacturers accountable for their fleet's average CO2 emissions, with penalties for exceeding targets. This initiative aligns with the broader 'Fit for 55' package, aiming to reduce net greenhouse gas emissions by 55% by 2030 and achieve climate neutrality by 2050.

Best available techniques (BAT) refer to the most advanced and effective stage in the development of activities and operational methods. BAT signifies practical methods suitable for establishing emission limit values and permit conditions, aimed at preventing or, when not feasible, minimizing emissions and their impact on the overall environment. Under this definition 'Techniques' encompass not just the technology used but also the installation's design, construction, maintenance, operation, and decommissioning. 'Available techniques' refer to those developed at a scale feasible for implementation in the relevant industrial sector, considering economic and technical viability. 'Best' signifies the most effective methods for achieving a high level of environmental protection overall (WeCOOP, n.d.).

The aforementioned policies build upon the concept of environmental neutrality. In ESRS (European Union Law, 2023 (b)), it is introduced through the concept of net zero target. To quote, *setting a net-zero target at the level of an undertaking aligned with meeting societal climate goals means: i. achieving a scale of value chain emissions reductions consistent with the abatement required to reach global net-zero in 1.5°C pathways; and ii. neutralizing the impact of any residual emissions (after approximately 90-95% of GHG emission reduction with the possibility for justified sectoral variations in line with a recognized sectoral pathway) by permanently removing an equivalent volume of CO2*.

In our analysis, we concentrate on the transportation sector. Thus, we need to look at how these global targets are translated to sector goals. These details are left to the countries themselves. As the first case, we look at Germany. The German government defined their goals to achieve the target of the 1.5 °C pathway in their climate protection plan 2050 (BMUB, 2016). This plan defines the overall targets in line with the EU targets and then goes into separate targets by sector for 2030 and 2050. The transportation sector has so far been considered a challenging sector that could not achieve great reductions compared to 1990 so far. Currently the tariff sectors just about manage to keep the CO2e values at an even level.

Projections for traffic in Germany see an increase in traffic volume. The only solution available is to reduce the specific emissions of any given vehicle sufficiently that it overcompensates the increase in traffic volume. With current state-of-the-art, BEV are the best available technology to achieve this (fuel cell vehicles are a proposed alternative but are insufficiently produced). In the climate action plan 2030, the German government emphasises this by introducing plans for incentives to buy BEV for individual cars and trucks (BMU, 2019).

The current aims of the climate plan of Germany for the transportation sector aim for a reduction from 163 million tons in 1990 to 98 million tons in 2030 which is a reduction target of about 40%. This will not achieve the overall 55% reduction target and thus other sectors need to compensate for 2030 though there is hope that additional activities to increase railway traffic as well as individual mobility by alternative means will help to achieve a higher reduction in transportation. Still by 2050 the transportation sector needs to achieve the same target as all others of 90-95%. This means that after 2030, the rate of reduction has to accelerate in comparison to other sectors (BMUB, 2016).

In our contribution, we use the Life Cycle Assessment approach to provide new insights into the structural challenges of Environmental neutrality or more formally the above stated net-zero target. As stated, we concentrate on transportation and the obvious product to look at here are the vehicles for individual transportation. Here, the net-zero target clearly separates into what we call fixed emissions and recurrent emissions. In the example, fixed emissions result at the beginning and at the end of the lifecycle and can be attributed to producing the vehicle that will be used in transportation and recycling its salvageable components at the end of lifetime. Recurrent emissions can be attributed to using the vehicle for actual transportation. We then show that net-zero target of transportation then translates into either significantly reducing both fixed and recurrent emissions, or reducing the recurrent emissions significantly, allowing the fixed emissions to be reduced less. On the other hand, for products of significant recurrent emissions, it is impossible to sufficiently neutralise their lifetime emissions by just focusing on the fixed emissions.

The above distinction is relevant for any product or sector. A generalisation of the approach shows that if recurrent emissions of a sector, industry or product could not meet the target, the residual emissions will be neutralised by permanently removing enough greenhouse gases from the atmosphere. For recurrent emissions, this induces an extra (recurrent) cost to each unit of the product, affecting its competitiveness and inducing a push towards best available technologies. Additionally, this observation motivates development of CO2 capture technologies.

2 Models and methods

In this section, we describe the models used in our study.

2.1 The base model

The base model we apply is a linear cost and linear production model, which we outline in this chapter but will be detailed in a different contribution. In it, the decision vector of desired outputs of the technology is a m-dimensional vector $x \in R^m$, and it specifies all the desiderata of the production process that are in control by its managers. The vector of the change of the state of the world achieved of the production (including products, byproducts, pollutants, as well as change in resources such as (raw) materials, partial products, energy, labor, time, money) is a m-dimensional vector $y \in R^m$. For the sake of completeness, we may assume that the state of the world contains all the products and all the resources required for their production. Similarly, we assume all these coordinates can participate in decision making, thus justifying the same dimension of the vectors x and y. The (linear) technology producing change of the state of the world y given decision x is described by technology matrix A (which is a square matrix by assumptions) and initial state of the world y_0. The technology matrix has, for each relevant output dimension i, a single row of coefficients A_i that describes the amount of output y_i produced following a single decision x_i resulting in the total production of $A_i\, x$ of output y_i from the complete vector of inputs x. Accounting for the investment production of output (usually pollutant) $y_{\{0,i\}}$, we get the final equation $y_i = A_i\, x + y_{\{0,i\}}$ for the production of output i, or $y = A\, x + y_0$ as the vector equation for the production of all the outputs. Similarly, the cost of production of y is $c_y = c^T x + c_0$ (1) where c_y is the production cost (scalar) of the vector of outputs y, c is the (column) vector of costs of decisions, x is the decision vector, and c_0 is the total of fixed costs of production.

From the above model, we focus on two components of the output vector, the production of a product i, $y_i = A_i x + y_{\{0,i\}}$ (2) and the production of a pollutant $y_p = A_p x + y_{\{0,p\}}$ (3). Then, $y_p(n) = nA_p x + y_{\{f,p\}}$ (4) is the amount of pollutant p produced in the lifetime of the production plant, where A is the previous technology matrix, A_p is it's p-th row, and $y_f = y_0 + y_1$ is the vector of fixed outputs including fixed set-up production vector y_0 and the fixed decomposition production vector y_1. Then, $y_{\{f,p\}}$ is the p-th component of this vector. The p-pollutant footprint of a unit of product i as f_p and y_i as the number of units of product y produced in a single batch/year of production. We obtain

$$f_p = \frac{nA_p x + y_{\{f,p\}}}{nA_i x + y_{\{f,i\}}} \quad (5)$$

2.3 Understanding net-zero footprint production.

Net-zero footprint is earlier defined as reaching the societal targets of sufficiently low production of pollutants. There are two possible interpretations of this definition. First, we say that a product has a strong net-zero footprint if both fixed and recurrent footprint are reduced by its appropriate fraction. To allow for generality we find relevant in current practice, we assume different fractions r_r, r_f ,$0 < r_r, r_f \leq 1$ in recurrent and fixed footprint reduction. Introducing $y_{\{r,0\}} = (A_p x)$ as initial recurring footprint results in $t_r = r_r y_{\{r,0\}}$ as recurring threshold, and $y_{\{f,p,0\}}$ as initial fixed footprint results in $t_f = r_f y_{\{f,p,0\}}$ as a fixed threshold. Thus we obtain $(A_p x) \leq t_r$ (6) for recurring footprint and $y_{\{f,p\}} \leq t_f$ (7) for fixed footprint. A product respecting (6) and (7) has reached a strong net-zero target both in its fixed and recurrent component of the footprint.

Given the above, a product may not reach both constraints (6) and (7), yet it may still reduce the footprint sufficiently. For this case, we say that a product reaches a weak net-zero target, if the combined footprint is reduced by the required amount. After some algebra we omit due to page restrictions, and introducing d_r as the discrepancy in the recurrent footprint and d_f as the discrepancy in the fixed footprint, we obtain $nd_r + d_f \leq 0$ (8)

As n is the lifetime of the production facility in the number of batches produced, which is a positive number, equation (8) is always satisfied for strong net-zero products, which have both d_f and d_r smaller or equal zero. At least one needs to be negative for the equation (8) to hold. If only the d_f is negative and d_r is positive, we obtain $-\frac{d_f}{d_r} \geq n$ (9), an infeasible constraint as it converts the fixed footprint into recurrent footprint, due to the coupling of the lifetime of the facility with the (small) number of the units of product produced. Assuming d_f is positive and d_r is negative, the inequality reverses and we obtain: $-\frac{d_f}{d_r} \leq n$ (10).

In this case, the significant reduction of recurrent footprint allows for lesser reduction in the fixed footprint, provided the lifetime of the facility is long enough. Moreover, the greater the reduction of the recurrent footprint, the larger the d_r and hence the smaller the required reduction of the fixed footprint. It is even possible to estimate the reduction of the recurrent footprint that would, given a lifetime, allow for no reduction in the fixed footprint. In this case, $d_f = y_{\{f,p,0\}} - t_f$ and we obtain $d_r = \frac{d_f}{n} = \frac{y_{\{f,p,0\}} - t_f}{n}$ (11)

Another interesting scenario is completely decarbonizing recurrent emissions (for instance, by providing emissions-free electricity), and observing the lifetime that allows for reaching net-zero target without reducing the current fixed emissions. In (8), we have $d_r = -t_r$ and $d_f = y_{\{f,p,0\}} - t_f$, implying $\frac{y_{\{f,p,0\}} - t_f}{t_r} \leq n$ (12)

We continue by integrating the proposed mathematical model into the process of LCA analysis through structural LCA analysis.

3 Structural LCA

The structural environmental footprint model proposed in this paper is based on the Life Cycle Assessment (LCA) methodology standardised in the ISO standards 14040 and 14044. The LCA methodology provides a framework for comprehensive environmental footprint assessments. It includes four main phases:

i. goal and scope definition,
ii. life cycle inventory (LCI) analysis,
iii. life cycle impact assessment (LCIA), and
iv. interpretation of the results.

In our model, we are using phases (i), (ii) and (iii) to assess the environmental footprint of the technology, while in the phase (iv) - interpretation of the results, we propose a new classification of technology's environmental footprint. We argue that the total footprint can always be divided into two segments, the fixed footprint and recurrent footprint. In relation to LCA, the recurrent footprint aligns with the technology's operational phase while the fixed footprint aligns with the material extraction, manufacturing, and end of life phases, as they are usually defined in the goal and scope definition phase of LCA analysis.

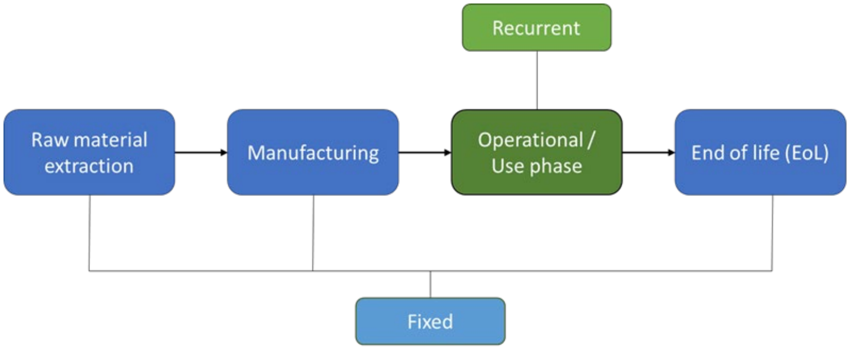

Figure 1: LCA product's stages and connection to Fixed and Recurrent environmental footprint

Source: own source

For a given technology, we can define its environmental footprint as a sum of its fixed footprint and recurrent footprint. Each technology can be described with a set of material and energy inputs, and each material or energy input can be considered a technology and therefore described with a set of material and energy inputs. By knowing a fixed and recurrent footprint of each technology, we can link all inputs as shown in Figure 2.

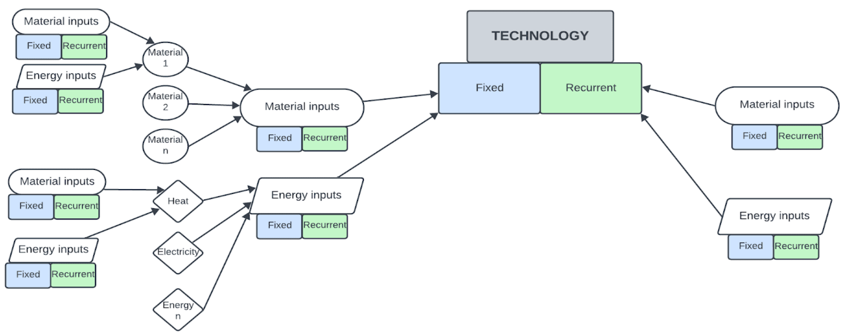

Figure 2: Structural breakdown of a technology

Source: own source

The main difference between conventional and structural LCA is how we combine the data on fixed and recurrent footprint. In structural LCA, we split material and energy inputs into fixed and recurrent footprint. In conventional LCA, we would assign both (fixed and recurrent footprint) to the operational/use phase, while in structural LCA, we assign recurrent to recurrent and fixed to fixed (Figure 3).

We can show the difference with an example of a battery electric vehicle (BEV) that uses electricity from solar panels (Table 1). In conventional LCA, we would assign all emissions from manufacturing of solar panels and emissions from producing electricity to the use phase. In Structural LCA, we treat this differently. We assign the emissions from manufacturing of solar panels to the fixed footprint and the emissions from producing the electricity (i.e. produced by maintenance) to the recurrent footprint. The reasoning is that once the solar panels are built, the emissions are already fixed in the environment, irrespective of our use of electricity.

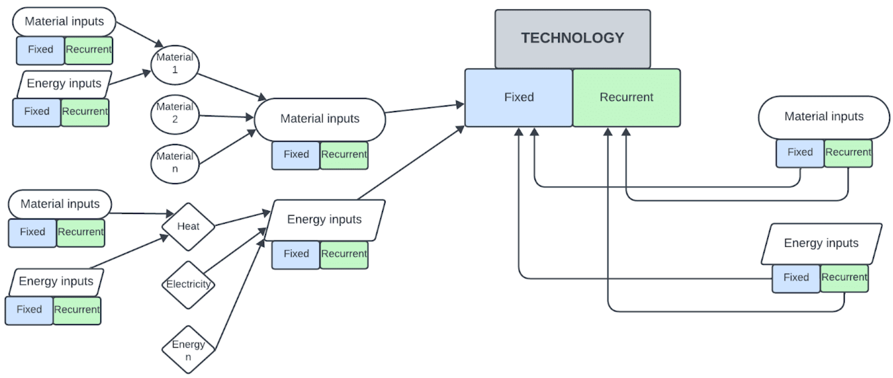

Figure 3: Assigning fixed and recurrent footprint in structural LCA
Source: own source

Table 1: Applying conventional and structural LCA to the case of BEV

Example	Conventional LCA	Structural LCA
Manufacturing of BEV	Manufacturing phase	Fixed
Manufacturing of solar panels	Use phase	Fixed
Electricity from solar panels for driving	Use phase	Recurrent

We can further define different levels of technology's environmental neutrality. Technology can either be:

i. environmentally not neutral,
ii. neutral by offsetting,
iii. neutral by permanent pollutant removal (e.g. carbon capture & storage) or
iv. neutral by design.

We can argue that technology that is environmentally not neutral is unsustainable, and it will eventually have to become neutral. To achieve neutrality, a technology can rely on external assistance in terms of offsets or permanent pollutant removals. In this case, the technology is not neutral but it can be "net-neutral" when we expand system boundaries.

Offsetting can offer a short-term solution to sustainability but in a finite world, we will eventually run out of offsetting possibilities. Furthermore, there is a growing concern about the effectiveness of carbon offsets and their use in greenwashing which increases the importance of high-quality carbon offsets and a well-regulated carbon market (Greenfield and Harvey, 2023).

Therefore, a better long-term solution is net-neutrality by permanent pollutant removal. In theory, we should be able to capture and store pollutants that a technology is emitting. The problem is that this approach uses significant resources which incur additional costs. If the cost of permanent pollutant removal is higher than the cost of making a technology neutral by design, then the technology will not be competitive. In this case, only difficult to neutralize (by design) and high value-added technologies might stay on the market in the long term.

When analyzing a given technology and its neutralizability, we first need to examine the neutrality of its inputs. The inputs are split into fixed and recurrent. We consider fixed inputs as a one time event and recurrent inputs as all inputs that will be needed during technology's lifetime. Recurrent inputs are often resources used for the operation and maintenance (fuels, materials, electricity…) but they may also include inputs needed to extend technology's lifetime (i.e. repairs, upgrades…).

Both fixed and recurrent inputs can either meet the net-zero target or not. We analyse four different scenarios of a technology reaching the net zero target and what can be done to neutralize the technology in the short or long term (Figure 2).

Table 2: Technology's neutrality based on inputs and options for the neutralizability of the technology

Technology's inputs		**Technology status**	**Neutralizability options**	
Fixed footprint net-zero target	Recurrent footprint net-zero target	Technology net-zero target	Short term Neutralizability	Long term Neutralizability $n \to \infty$
no	no	no	By offsetting or permanent removals	Permanent removals
yes	no	no	By offsetting or permanent removals	Permanent removals
no	yes	no	By offsetting or permanent removals	By offsetting or permanent removals
yes	yes	yes	no need	no need

We see in Table 2 that only the technologies with fixed and recurrent inputs reaching net-zero target can be considered net-zero technologies. In all other cases, we can neutralize the technologies in the short term by offsetting or permanently removing pollutants. Offsetting may also be a viable option for long-term neutralizability in case that recurrent footprint is reaching a net-zero target, as we only need to neutralize a set amount of fixed initial footprint. However, when the recurrent footprint does not meet the net zero target, the neutralizability can be achieved only by permanent removals. This is due to the assumption that extending the lifetime to infinity, the amount of inputs reaches infinity and requires offsetting an infinite amount of pollutants which is not viable. By permanent removals, we can form a closed-loop where the emitted and removed amounts are always equal. This however implies recurrent costs to the technology.

4 Applying structural LCA to the mobility sector – use case

As stated above, Germany will be the demonstration case. In Table 1, we show the number of privately owned cars in column 1, the traffic volume in column 2 and the GHG emissions in column 3. For 1990 and 2019, we use historical data from the environment agency of the German government (Umwelt Bundesamt (2023(a,b,c)). For the years 2030 and 2050 we use projections the same agency published for the number of cars and traffic volume (Umwelt Bundesamt, 2018) and the climate protection plan of the German government for the GHG targets in 2030 and 2050 (BMUB, 2016).

The two remaining columns follow from the first two. The average km a car drives in a given year is the traffic volume divided by the number of cars and the GHG in CO2e gramm per km follows from that and the GHG emissions.

Table 3: Indicators in transportation

Year	Number of cars in million	Traffic volume in billion km	CO2e in million t (only for fuel consumption)	Av. km per car per year	CO2e in g per km (for the av car)
1990	36.8	496.4	164.4	13489	331.19
2019	47.1	644.8	164.9	13690	255.74
2030	48.5	641	98	13216	152.9
2050	47.5	655	8.5	13789	12.98

With Table 4, we have the recurrent emissions historically and the target recurrent emissions for the average car in the transportation sector in Germany. For the presented model, we also need the fixed emissions per car produced for both current values and the target values.

In Table 4, we use a summary published by the scientific service of the German parliament of reported data on the GHG balances in transportation to get the current values for different types of cars (Deutscher Bundestag, 2022).

Table 4: Production and lifetime GHG profile of cars

Car Type	**CO2e in t from production**	**Total CO2 in t over lifetime**
ICE gasoline	6.35	31.05
ICE Diesel	6.5	28.6
BEV (current electricity mix)	9.6	22.95
BEV (100% renewable electricity)	9.8	10.5

The last variable missing for the model is the target value for fixed emissions from car production. For this, we look at the target in the industry sector in table 5. Historical data on the GHG numbers is provided by the environmental agency of the German government (Umwelt Bundesamt, 2023(d)) and the targets are published in the climate protection plan of the German government (BMUB, 2016).

Table 5: GHG targets in the industry and manufacture sector in Germany

Year	**CO2e from industrial processes in million**	**Reduction in % compared to 1995**
1995	238.9	0
2019	181.99	23.8
2030	141	40.9
2050	10	95.8

For the calculations according to equation (11) and (12) of the model, these reductions are applied to car production in 2030 ($t_{\{f,2030\}}$) and 2050 ($t_{\{f,2050\}}$). From Tables 3 to 5, we can thus create Table 6 with the values of the variables needed to compute the model.

Table 6: Variables needed to compute the model

	BEV emissions	**fixed / recurrent**
Current fixed GHG emission per car produced ($y_{\{f,p,0\}}$)	9.8t CO2e	fixed
Target fixed GHG emissions per car produced in 2030 ($t_{\{f,2030\}}$)	7.6t CO2e	fixed
Target fixed GHG emissions per car produced in 2050 ($t_{\{f,2050\}}$)	0.5t CO2e	fixed
Target recurrent emissions per car in 2030 ($t_{\{r,2030\}}$)	152.9g CO2e/km	recurrent
Target recurrent emissions per car in 2050 ($t_{\{r,2030\}}$)	12.98g CO2e/km	recurrent

In terms of vehicles, privately owned cars are responsible for the major share of both traffic volume and emissions. Since we concentrate on cars as a product, we will also concentrate on them in regard to the data. The EU targets are all compared to the year 1990.

A usual car has a life expectancy of 12 years. For BEV additional importance has to be put on the lifetime of the battery. In Germany for BEV, the total of 160,000 km (or a 8 year lifetime of normal use) is the accepted norm (Rudschies, 2022).

For equation (12), this results in an $n \geq 14{,}388$ for 2030 and $n \geq 716{,}487$ for 2050. The model thus shows that, to reach the 2030 goals if all cars would be electric with carbon neutral electricity, their lifetime would have to be at least 14,388 km to compensate for their complete fixed carbon footprint. While the lifetime is achievable, the condition that all cars go electric by 2030 is not. Similarly, assuming all cars go electric with carbon neutral electricity, to reach the 2050 goals, lifetime of 716,487 km would compensate for the current fixed footprint of BEV production.

5 Conclusions and further research

In our contribution, we analysed an abstract mathematical model behind generic pollutant-footprint neutrality. The model yields a set of constraints that together define a feasible set of strategies towards reaching neutrality of a specific pollutant. In the model, the distinction between fixed and recurrent emissions plays a crucial role. We apply the findings of the model to propose structural LCA, based on bookkeeping the distinction between recurring and fixed pollutant emissions. We illustrate the model using the data of the German transportation sector and demonstrate the trade-off between increasing lifetime of the vehicles vs. reducing the footprint of the car production.

Several similar trade-off constraints can be produced using the stated mathematical model. Altogether, these constraints define a feasible set of general policies and individual approaches to carbon neutralizability of various products and services. Our prototype investigation has piloted some of the constraints on the German transportation sector. In the future research, we plan to extend the model with additional constraints that can be investigated given the available data, thus allowing to formalise the concept of feasible policy set. Furthermore, we plan to investigate the availability of the data for sectors beyond transportation and countries beyond Germany.

Structural LCA that we introduced has applications both in political and corporate decision making (through the above-described feasible set of policies) as well as in corporate planning and decision making. Furthermore, it allows management to identify opportunities and clearly communicate corporate policies to investors, clients, employees, local communities, and other stakeholders. In our future research, we will investigate these aspects of the newly introduced concepts.

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