Towards understanding potential rebounds and problem-shifts for MyFairShare

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Rationale

Understanding potential rebounds and problem-shifts due to the various measures tested in the LivingLabs (LL) and the modelling requires clear definitions of system boundaries and activities/processes investigated. Herein, we provide several short conceptual summaries on key concepts, a generalized systems definition and a structure for the LivingLabs and the modelling to define and locate their research scopes within that generalized definition.

Figure 1 shows a simplified system definition described in more detail below. The key idea is to represent the socio-economic mobility system embedded in the national economy as well as other economies and the environment, and the interactions between these systems. This systematic and integrated perspective enables us to discuss interlinkages and potential rebounds within and outside of the investigated LL mobility system and the choices we make in designing these LL.

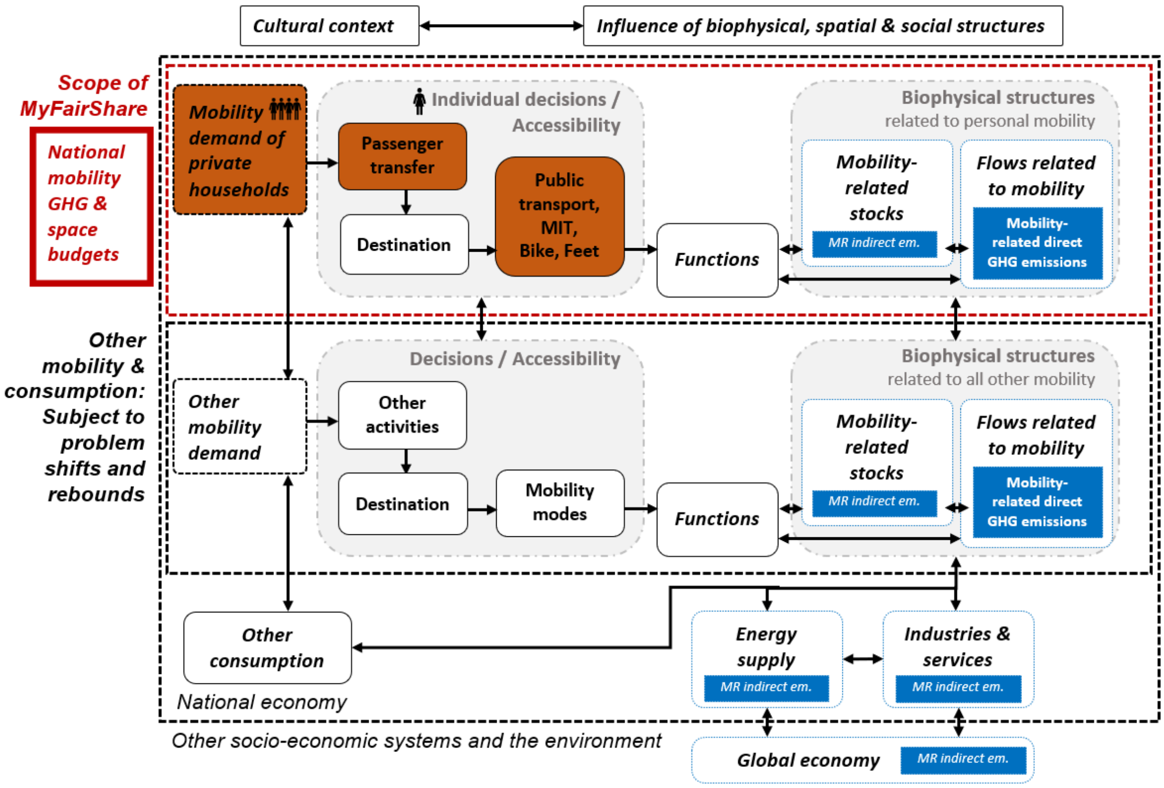


Figure 1. Conceptualization of the socio-economic mobility system according to socio-metabolic principles (own representation, based on Kalt et al. 2019 and Virág et al. 2022). System boundaries decisions are indicated in red/orange coloring, processes/systems producing emissions are indicated in blue. Abbr.: MR indirect em.= Mobility-related indirect emissions

A systems perspective on mobility and production-consumption relations

A systematic, interdisciplinary and integrated perspective on the interlinkages between human and natural systems is essential to investigate potential feedbacks and problem shifts. Several concepts and methods have been developed to address social and natural structures and processes on an equal epistemological basis (Haberl et al., 2016). Especially the concept of the **social metabolism** proved helpful to address systematic shifts (Ayres and Simonis, 1994; Haberl et al., 2019; Pauliuk and Hertwich, 2015). The social metabolism concept represents the self-reproduction and evolution of the biophysical structures of society (i.e., material stocks, people and livestock) and aims to monitor required biophysical flows of materials, substances and energy from their production via consumption to their final disposal in a mass-balanced way (Pauliuk and Hertwich, 2015). A useful set of methods to quantify the scale and composition of the social metabolism is termed as **economy-wide material and energy flow accounting (ew-MFA)**, which enables in combination with other methods like life cycle analysis (LCA) or input-output analysis (IOA) to quantify the biophysical flows of certain socioeconomic systems in a consistent and double-counting-free way. Ew-MFA systematically quantifies flows of biophysical resources associated with defined social systems or their components. It investigates the socioeconomic transformations of natural resources and traces outputs of waste and emissions to the environment (Haberl et al., 2019). The concept of the social metabolism and its related methods help to provide a foundation for application-oriented interdisciplinary research as done in the MyFairShare project.

In ew-MFA, we strictly distinguish between **material flows and stocks**: the former can be material throughput, which is not stored for very long and is further processed to serve a certain purpose, or can accumulate in the socioeconomic system as material stocks for a longer time period, as which they are used to serve a certain purpose. These purposes that materials are fulfilling in the socioeconomic system are recently commonly termed **material and energy services**, which are defined as a set of benefits or wellbeing contributions that can be delivered to people from the usage of materials or energy (Carmona et al., 2017; Creutzig et al., 2020). The term should help researchers to identify options to foster social wellbeing with the least possible amount of biophysical resources and thus provides a much richer conceptualization than the usual juxtaposition of environmental data with economic activity (Haberl et al., 2020; Wiedenhofer et al., 2020). The interrelations of material stocks, flows and services have recently come to the fore of socio-metabolic research, as it allows researchers to open new research directions that will help to better understand biophysical foundations of sustainability transformations (Haberl et al., 2017).

A first conceptualization of rebounds and problem-shifts

The mobility budgets investigated in MyFairShare should take **systemic feedbacks or rebound effects** into account or should at least respond to it as concretely as possible. It is known that efficiency improvements are often partly or totally compensated by a reallocation of saved resources and money to either more of the same consumption (direct rebound, e.g. using a fuel-efficient car more often), or other impactful consumptions (indirect rebound, e.g. buying plane tickets for remote holidays with the money saved from fuel savings) (Reimers et al., 2021; Sorrell et al., 2020). It can also generate structural and behavioral changes in the economy that induce higher consumption (macroeconomic rebound, e.g. more fuel-efficient cars reinforce a car-based transport system at the expense of greener alternatives, such as public transport and cycling) (Parrique et al., 2019).

In addition to economic rebound effects, **co-benefits, co-burdens and potential spillover effects** should be considered (Hertwich, 2005). From a socio-metabolic perspective, we usually consider more than one environmental aspect (such as GHG emissions), as every action typically has several types of environmental and social impacts, which might not necessarily change in the same direction. Most environmental and social impacts do not generally cause internal costs, so that the reduction of these pressures does not imply a cost reduction and therewith a rebound in demand. Behavioral as well as technical changes can have positive and negative side and spillover effects that are not mediated through the price mechanism. Examples for co-benefits and co-burdens of emission saving measures in the mobility system might be: more active mobility leading to health benefits, expansion of rail systems leading to sealed soils and noise pollution in fragile ecosystems or electric vehicles leading to higher burdens from lithium extraction. Spillover effects might occur, e.g., when environmentally-friendly behavior in one area facilitates the same in another area or cleaner electricity results in a higher feasibility of cleaner transport technologies using more electricity (Hertwich, 2005).

A short overview of different emission accounting methods available to assess rebounds & problem-shifts

MyFairShare is focusing on the applicability of carbon mobility budgets partitioned between individuals, which is why the question on the specific carbon accounting methods is crucial for the whole project. It has to be clear which GHG emissions are included or excluded within the socioeconomic mobility system and what implications and limitations of a certain accounting methodology are. We identified, for instance, five aspects that can be considered when defining **system boundaries of emission accounting factors** in mobility systems:

1. Emissions from the operation of transport interfaces and bodies (direct emissions acc. to UBA), e.g., car emissions at exhaust or useful energy used while cycling
2. Emissions from the operation of transport interfaces (indirect emissions acc. to UBA), e.g., upstream emissions of fuel and electricity production
3. Emissions from the production, maintenance & final treatment of transport interfaces (indirect emissions acc. to UBA), e.g., cradle-to-grave processing emissions of a car or a train
4. Emissions from expansion, maintenance, operation and final treatment of transport infrastructure, e.g., emissions from construction or heating of a gas station
5. Emissions from public & private services that facilitate the production, operation and organization of transport interfaces & infrastructures, e.g., emissions from insurance companies providing automotive insurances

Production of transport infrastructure, interfaces and fuels takes place in international supply chains, which are increasingly extending over several countries. Therefore, there are various options available in which emissions originating from the same activity **can be attributed to different agents along the supply chain**. Typically, four main perspectives are often distinguished: (1) the production-based approach, which attributes emissions to the territory in which emissions physically occur during production (IPCC, 2006); (2) the consumption-based approach, which attributes emissions occurring throughout the production process to the final users and their place of residence (Davis and Caldeira, 2010); (3) the extraction-based approach, which attributes emissions to the extraction place of the fossil fuels that allow for these emissions (Davis et al., 2011); and (4) the income-based approach, which attributes emissions along the supply chain to specific agents according to their value added to production (i.e., earned income) (Marques et al., 2012). These approaches differ in the information they provide to the individual agents on the effect their actions have on global emissions and they may also, to varying degrees, prove useful in supporting an effective and just sharing in climate responsibilities (Steininger et al., 2016). National GHG budgets are typically defined using a production-based approach, whereas activities of individual consumers are typically accounted for from a consumption-based perspective. When designing carbon mobility budgets based on the merging of national GHG targets with individual activity-based carbon accounting, this has to be taken into account.

Table 1 gives an overview on the main **emission accounting methodologies** identified from the scientific literature. Their main features and limitations are given, as well as the scopes of system boundaries that can be addressed by each method (numbered according to the system boundaries defined above).

Table 1. Emission accounting methods, distinguished according to their features, limitations and scopes. The meanings of the numbers identifying the scope of system boundaries (1-5) are given in the list above.

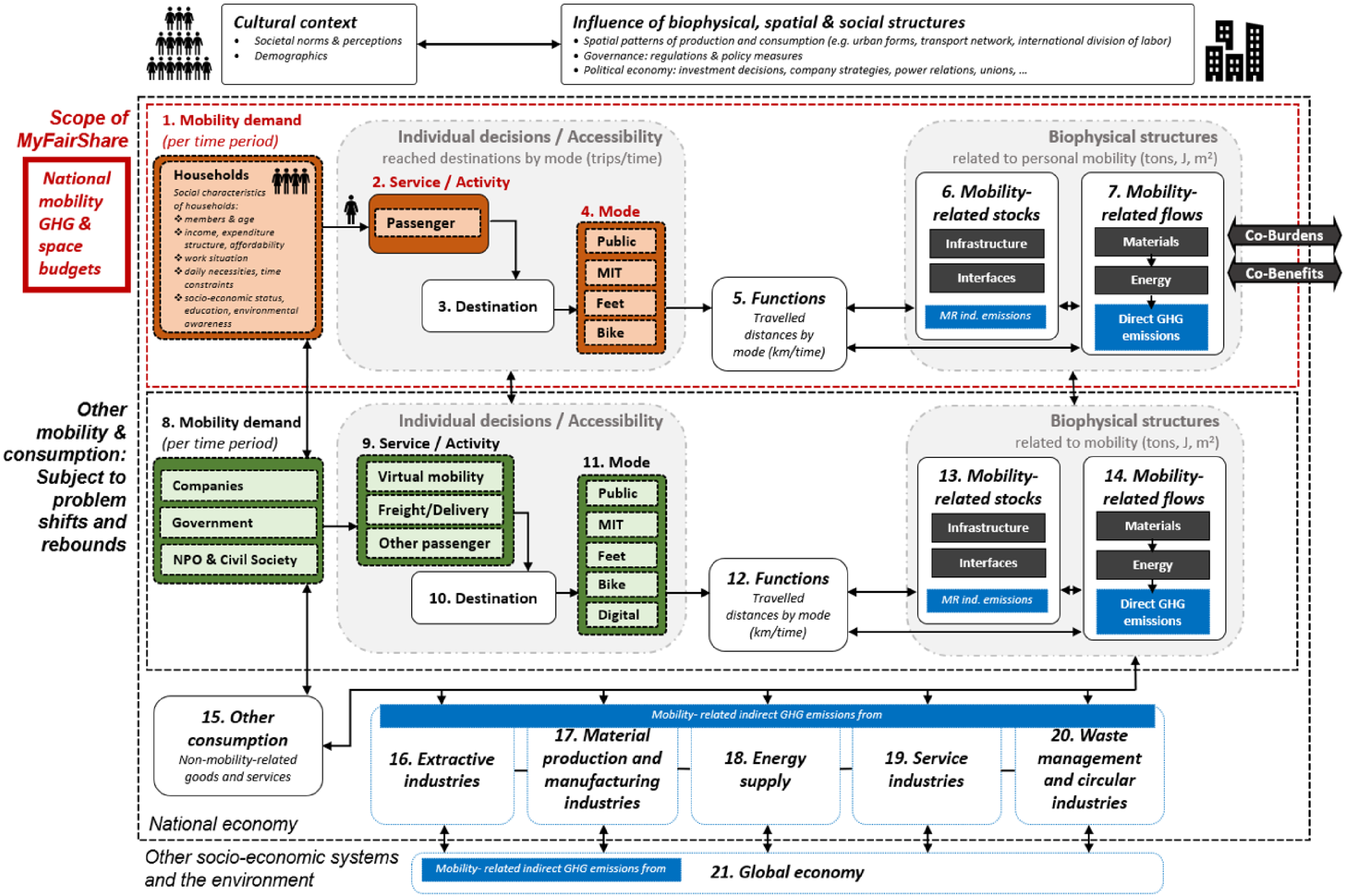
ACCOUNTING METHOD	FEATURES	LIMITATIONS	SCOPE OF SYSTEM BOUNDARIES
Production-based inventories	Emissions calculated from fossil fuel usage and other emission-relevant processes, methods defined by IPCC along 3 tiers[1], no supply chains	Uncertainties increase along 3 tiers	(1) is fully and (2) & (3) partly covered
CIF: community-wide infrastructure-based carbon footprinting	Emissions direct from and embodied in key infrastructure and food provisioning to cities, hybrid method of production-based accounting and LCA, cut-off supply chains	Supply chains only partly covered	(1) and (4) are largely covered, (2) & (3) only fragmentary
Attributional process LCA	Attributing emissions to products/processes/activities in a static system, based on factors, cut-off supply chains	Unclear system boundaries, data scarcity, low comparability, uncertainties hardly assessed	(1) fully, (2) & (3) only fragmentary, depending on system boundaries
Consequential process LCA	Future scenarios that determine emissions that may occur as a consequence of (technological/societal) change in a dynamic system, cut-off supply chains	High complexity, many assumptions, high uncertainties of results	(1) fully, (2) & (3) only fragmentary, depending on system boundaries
EIO-LCA: economic input-output life-cycle analysis	Sector-level data from IO tables on direct and indirect emissions applied to products/processes/organizations/sectors, full supply chains	sectoral averages, translation of monetary transaction flows into environmental impacts, IOA assumptions	(1), (2) & (3), and partly (5) are usually covered
EE-MRIOA: environmentally-extended multi-regional input-output analysis	Allocation of direct and indirect emissions via monetary models and interrelations on global supply chains to final use sectors and consumers, full supply chains	not really applicable on the product level, translation of monetary transaction flows into environmental impacts, IOA assumptions	(1), (2), (3) & (5) can be fully covered, capital-augmented EEIOA can also cover (4)

A first systems definition for assessing LivingLabs and modelling

In Figure 2, we present a **conceptualization of the socio-economic mobility system relevant for MyFairShare**, based on socio-metabolic principles and a useful operationalization of the material stock-flow-service nexus: the 'energy service cascade' (Kalt et al., 2019). The different perspectives and approaches chosen to investigate the applicability of mobility budgets in the different Living Labs

[1] GHG emissions are calculated indirectly from fossil fuel usage and other emission-relevant processes such as industry and agriculture, following a gradation in three tiers, along which more and more GHG emissions are considered and methodologies become more sophisticated and uncertain. Tier 1 employs default methods and emission factors described in the IPCC Guidelines, tier 2 applies emission factors and other parameters that are country-specific, while tier 3 applies more details regarding technology and equipment (IPCC, 2006).

(LL) should be embeddable in this framework. Deliberate decisions have to be made on what is included and excluded in the system, i.e., the system boundaries. The framework enables us to combine a structural with an individual perspective, as it gives us the pathways through which individual decisions affect biophysical structures and, vice versa, how biophysical, spatial and social structures shape mobility patterns and everyday life decisions of individuals.



Cultural context
Societal norms & perceptions
Demographics
Influence of biophysical, spatial & social structures
Spatial patterns of production and consumption (e.g. urban forms, transport network, international division of labor)
Governance: regulations & policy measures
Political economy: investment decisions, company strategies, power relations, unions, ...
Scope of MyFairShare
National mobility GHG & space budgets
1. Mobility demand (per time period)
Households
Social characteristics of households:
members & age
income, expenditure structure, affordability
work situation
daily necessities, time constraints
socio-economic status, education, environmental awareness
Individual decisions / Accessibility
reached destinations by mode (trips/time)
2. Service / Activity
Passenger
3. Destination
4. Mode
Public
MIT
Feet
Bike
5. Functions
Travelled distances by mode (km/time)
Biophysical structures
related to personal mobility (tons, J, m²)
6. Mobility-related stocks
Infrastructure
Interfaces
MR ind. emissions
7. Mobility-related flows
Materials
Energy
Direct GHG emissions
Co-Burdens
Co-Benefits
Other mobility & consumption: Subject to problem shifts and rebounds
8. Mobility demand (per time period)
Companies
Government
NPO & Civil Society
Individual decisions / Accessibility
9. Service / Activity
Virtual mobility
Freight/Delivery
Other passenger
10. Destination
11. Mode
Public
MIT
Feet
Bike
Digital
12. Functions
Travelled distances by mode (km/time)
Biophysical structures
related to mobility (tons, J, m²)
13. Mobility-related stocks
Infrastructure
Interfaces
MR ind. emissions
14. Mobility-related flows
Materials
Energy
Direct GHG emissions
15. Other consumption
Non-mobility-related goods and services
Mobility- related indirect GHG emissions from
16. Extractive industries
17. Material production and manufacturing industries
18. Energy supply
19. Service industries
20. Waste management and circular industries
National economy
Other socio-economic systems and the environment
Mobility- related indirect GHG emissions from
21. Global economy

Figure 2. Conceptualization of the socio-economic mobility system according to socio-metabolic principles (own representation, based on Kalt et al. 2019 and Virág et al. 2022). System boundaries decisions are indicated in red/orange coloring, processes/systems producing emissions are indicated in blue. Abbr.: MR indirect em.= Mobility-related indirect emissions, NPO= Non-profit organizations

The definition of **system boundaries** is highly important as it has a high impact on accounting results. Therefore, it is an accounting convention to be absolutely transparent about the system of interest and its limits – on what can and cannot be investigated by a specific study. System boundaries can be identified for each aspect that defines a system: time, region, activity, material, etc. If our system of interest is, e.g., as in MyFairShare, the mobility system in a city or city district, relevant system boundaries can be understood as follows:

- *Temporal*: time period of interest, e.g., a year
- *Spatial*: region of interest, e.g., a city district
- *Human*: which individuals are included, e.g., residentials, commuters, employees or users
- *Activity*: what kind of mobility, e.g., passenger, work/leisure, transport of goods, …
- *Process-related*: which processes along the supply chain are included, e.g., emissions of operation, production or related infrastructure usage
- *Modal*: what mobility modes are included, e.g., pedestrian, bicycle, public transport (rail/air/water/road), motorized individual traffic (MIT), …
- *Physical units*: which physical aspects are measured, e.g., tons, joule, m^2

The mobility system addressed by MyFairShare and its related system boundaries are indicated in red and orange coloring in Figure 2. Rebound effects can exist within each box, but also via the interlinkages indicated by the arrows in the figure. Especially mobility activities or services and mobility modes are highly susceptible to rebound effects, within the system of interest for MyFairShare as well as with other mobility demands, activities and modes (indicated in green in Figure 2). Individual decisions and accessibility are linked to biophysical structures related to personal mobility, which are the actual sources of GHG emissions, via mobility functions (often measured in travelled kilometer). The color blue indicates GHG emission sources, that are either direct emissions from flows related to mobility or indirect emissions from mobility-related stocks and global supply chains. The investigated mobility system is constrained by the national mobility GHG & space budgets as well as influenced by the overall cultural context and the biophysical, spatial and social structures that it is embedded in.

System-related classifications of each LivingLab

Herein, we propose to adapt the ODD (Overview, Design Concepts, Details) Protocol for the purpose of systematically comparing and understanding the LivingLabs (LL). The ODD protocol is widely used in agent-based and dynamic stock-flow modelling (Grimm et al., 2010; Müller et al., 2014), herein we simplify and adapt it. The proposal is, to very shortly and concisely answer these questions (1-2 sentences per item).

	Aspect	*Questions*	*Example answers*
Overview	Purpose	What is the investigation framework for and the purpose of the LivingLab?	[What you want to look at, what you want to find out]
	System overview	Which processes, stocks and flows are considered in the investigated mobility system and how?	[Which boxes and arrows in figure 2 can be investigated]
	Basic principles	What are the basic principles underlying the LL study design?	Empirical study, modelling, retrospective or prospective, …

	Methods	What are the specific methods chosen to investigate the system?	Surveys, scenario modelling, data analysis, workshops, …
	Context	In how far is the cultural and structural context considered in the LL study design?	[Cultural context and influence of biophysical, spatial and social structures (examples in figure 2)]
Design concepts/ System boundaries	Study population	Which individuals are included in the LL? What part of the total population is investigated?	Residentials, commuters, users, employees, …
	Study sample	What is the specific sample size?	Share of the study population, absolute, representatives, …
	Activities	Which (mobility) services/activities are investigated?	Passenger, work/leisure, transport of goods, virtual, …
	Spatial and temporal scale	What is the spatial and temporal scale of the study?	City district, territorial city boundary; months, years, …
	Mobility modes	Which mobility modes are considered?	Pedestrian, bicycle, public transport (rail/ air/ water/ road), motorized individual traffic, …
	Physical units	What are the physical units measured?	tons, joule, m^2, km, time, …

	Emission accounting	What emission accounting factors and methodologies are applied? What are their system boundaries in a global economy?	[See overview on emission accounting methods above]
Details	Initial condition	How is the initial state of the LL set?	[Describe the starting point and the basic conditions for your study in more detail]
	Hypothesis	What is the main hypothesis on the results of the LL? Which are results you would expect?	[Describe how you expect your starting point to evolve over the study period]
	Exogenous data	What exogenous data is used to investigate the LL?	[Describe the data sources you use for investigation]
	Endogenous data	What endogenous data is generated in the LL?	[Describe the data you will generate during the study]
	Evaluation	What methods are used to evaluate the results?	Comparisons, cross-checks, expert evaluation, …
	Uncertainty	How does the LL study design consider uncertainty and potential biases?	Qualitative or quantitative, statistical methods, …

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