Author(s): Auvinen, Heidi; Ruutu, Sampsa; Tuominen, Anu; Ahlqvist, Toni; Oksanen, Juha

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Process supporting strategic decision-making in systemic transitions

A case study of emission-free transport in cities by 2050

(Brief running title: Strategic decision-making in systemic transitions)

Abstract

This paper introduces a process for supporting strategic decision-making and policy planning in systemic transitions related to grand challenges such as climate change. The process uses the multi-level perspective (MLP) as an underlying theoretical framework and combines various methods and tools from the fields of foresight, impact assessment, simulation modelling and societal embedding. Decision-makers such as public sector authorities and politicians are the main target group, accompanied by other stakeholders and interest groups whose involvement throughout the process is stressed.

The process is presented as a stepwise methodological working process and demonstrated by a theoretical case study. The demonstration explores the vision of ‘emission-free transport in cities by 2050’ in the context of motorised passenger transport in the Helsinki metropolitan area in Finland. The case study serves as an example of how to implement the process and how to make case-specific selections from the methods and tools from suggested fields.

Keywords

Decision-making, policy, simulation modelling, transition, transport system

Highlights

- We propose a process supporting strategic decision-making in transitions

1 MLP, multi-level perspective [1]
• The process integrates elements from various theoretical fields

• Narrowing the gap between theory and policy planning is the main contribution

• Practical tools are provided for the use of stakeholders of socio-technical systems

• In our case study we explore transition towards emission-free transport in cities
1. Introduction

Responding to the grand challenges related to the environment, natural resources, security or demographics requires systemic transitions. In order to understand both the local and global impacts of such transitions, political, economic, social, technological and environmental dimensions and their complex interrelationships need to be analysed. Systemic transitions unfold over long periods of time, and hence a long-term perspective is important in developing, assessing and making decisions on strategies and measures to aid the transitions.

Currently decision-making systems do not adequately take into account the complexity of the operating environment, its dynamics, rapid change and rebound effects. Although various actors of e.g. energy or transport systems are aware of these challenges, decision-making is yet based on fragmented information on the operating environment and wider societal impacts. Also, ability and sensitivity to changes are often lacking [2].

Strategic planning and decision-making in transitions can be supported by interdisciplinary, systemic and integrated research approaches that present alternative future visions and pathways [3, 4, 17-20, 27]. In the fields of foresight and impact assessment new methods are emerging to combine systemic perspectives with deeper participation and policy support approaches. Also, the framework for socio-technical change provides one such approach [1, 5].

Socio-technical change and the concomitant approach of transition management have recently gained a great prominence in the European research agenda. So far, research efforts have focused largely on building theoretical frameworks to understand transitions, and to use these to interpret historical chains of events in retrospect, e.g. [1, 5-10]. Forward-looking application areas, such as topics linked to climate change, have been identified, but practice-oriented processes and tools to facilitate and support hands-on decision-making and policy planning have not been introduced. Integration of approaches and tools from different theoretical backgrounds, to support transitions through the framework of socio-technical change, has not been common either.
In this paper we aim to expand the scientific discussion on socio-technical change and to narrow down the gap between theoretical advances and practical decision-making and policy planning. The challenge is addressed through the following research questions:

1. How can the fields of foresight, impact assessment, simulation modelling and societal embedding be integrated to study and understand transitions in complex socio-technical systems?

2. How can the methodologies from these fields be put to use to support strategic work of decision-makers such as public sector authorities and politicians in practice?

We present a process supporting strategic decision-making and policy planning in systemic transitions related to grand challenges. The proposed five-step process begins by scoping the decision-making situation and by applying theoretical tools to build an understanding of the system. Measures and actions to influence the system are developed, and their impacts are assessed using simulation modelling.

We demonstrate the stepwise workflow of the process through a case study of urban passenger transport in the Helsinki metropolitan area in Finland. The demonstration gives a concrete example of our approach when applied in the socio-technical system of transport, where a systemic transition is required to address harmful transport emissions. The case study stems from an ongoing Finnish research project STRADA (aiding strategic decision making and steering transformation) that aims to develop methods and tools to support decision-making in complex transition contexts such as healthcare, transport and bioeconomy.

The paper starts with an introduction to the theoretical background of the developed process. First, key concepts of socio-technical systems and transition processes are discussed. Short descriptions of foresight, impact assessment, simulation modelling and societal embedding are provided, together with overviews on selected key theories and tools from these fields and their potential in supporting societal change. As a platform deepening each of these fields and integrating them into one another we use the multi-level perspective (MLP) approach [1]. The core of the paper presents the developed process and tools involved. Each of the five steps of the process is presented first from the methodological perspective, followed by a demonstration of how it was implemented in the case study on the transport system. The case study shows
how the process was applied and how one possible selection of tools was employed. Contributions of the work carried out and implications for further research are then discussed.

2. Theoretical background

2.1 Socio-technical systems and transitions

The notion of transitions in socio-technical systems is central to our approach. According to Geels [1], socio-technical systems involve the interaction of production, diffusion and use of technology. Geels [1: 900] articulates that a socio-technical system consists of “the linkages between elements necessary to fulfil societal functions” like transport or communication. The elements in the socio-technical system are production, distribution (consisting of markets, networks and infrastructure) and use of artefacts. The socio-technical system is thus a web consisting of these three elements and resources to endorse them, like knowledge, capital, labour and cultural meaning. A major shift in a socio-technical system is realised when structural changes take place in the elements of the system. These socio-technical transitions entail co-evolution and multi-dimensional interaction between industry, technology, markets, policy, culture and civil society [1-10]. A socio-technical system and its transition from one configuration to another can be studied using the MLP [1]. The concept of the MLP is best summarised by Geels [11: 642] as follows: “The MLP distinguishes three analytical levels: the niche-level that accounts for the emergence of new innovations, the socio-technical regime level that accounts for the stability of existing systems, and the socio-technical landscape that accounts for exogenous macro-developments.” Our research approach builds on the concept of the MLP, which we use as the platform to deepen methods and tools from various disciplines — namely foresight, impact assessment, simulation modelling and societal embedding — and to link them together. The MLP is thus employed in an instrumental manner, providing structure and interfacing between methods and tools within the process we introduce.

As an example and the object of our case study, we use the socio-technical system fulfilling the need for mobility: the transport system. In Fig. 1 we picture the key components of a socio-technical system of
transport in the ‘three-level transport system framework’ [12]. The components are users, vehicles and transport infrastructure. In addition, in the middle of these components is a fourth: transport system organisation, governance and regulation. Each of these components is further elaborated into key elements that characterise them. For example, transport vehicles and other means of transport rely on various manufacturing technologies and materials and require maintenance. Different vehicle solutions make use of fuels and other energy carriers resulting in different types of environmental impacts. Furthermore, the use of vehicles involves behavioural patterns and business models, and different types of solutions are available concerning issues such as vehicle ownership. The interaction between any two components as well as between all of them (thus fulfilling the function of the transport system by definition) can be illustrated using arrows.

![Fig. 1. The components of a transport system (adapted from Auvinen and Tuominen [12]).](image-url)
The transport system components and elements can be analysed using the MLP [1] as shown in Fig. 1. The three levels of landscape, regime and niche are adjusted to the transport domain as landscape (A), transport system (B) and technologies and solutions (C). The components and elements are positioned on the most appropriate levels to indicate their main application areas. This type of structuring is supported by the recent work by Geels [6], where similar steps are taken in exploring the MLP in the study of transitions in the transport sector. Geels drafts the automobility system in the context of the MLP when studying transitions towards low-carbon futures. Also van Bree et al. [13] have used the MLP in structuring the socio-technical system for land-based road transport. In their work, hydrogen and battery electric vehicle scenarios were mapped focusing on the relationship between car manufacturers and consumers. A forward-looking approach is presented also by Marletto [14], who has developed socio-technical pathways for car and the city. Nykvist and Whitmarsh [15] have analysed climate change in the transport context with the help of the MLP approach, and Whitmarsh [16] has discussed the usefulness of the MLP for transport and sustainability research. Nykvist and Whitmarsh [15] highlight the importance of expanding and improving the MLP to elucidate how behavioural-institutional change might occur. This is seen as particularly critical for transport research, given the expressed and observed public resistance to changing travel behaviour.

By presenting practical tools and interacting elements from various scientific backgrounds, our approach answers one of the key issues raised in the above literature, i.e. narrowing down the gap between theory and practical policy planning. It contributes also to the field of science and technology studies (STS), particularly to the notions of Mode 2 knowledge production and co-production discussed e.g. by Gibbons et al. [17], Nowotny et al. [18], Jasanoff [19] and Lemos & Morehouse [20]. In STS, Mode 1 is presented as more or less synonymous with what has traditionally been called science. Mode 2 instead puts great emphasis on the significance of ‘social’ in the practice constitution of science. By this it implicates that science can no longer be regarded as an autonomous space clearly demarcated from the ‘others’ of society, culture and economy [18]. Attributes in Mode 2 knowledge production include trans disciplinary,
heterogeneity and organisational diversity, social accountability and reflexivity, quality control and, last but not least, knowledge produced in the context of applications.

The co-production concept [20] refers to the institutionalised practices by which ‘usable science’ is co-produced in the context of everyday interaction between scientists, policy makers and the public. Here, substantial commitment to the three identified components, interdisciplinarity, stakeholder participation, and production of knowledge that is demonstrably usable, is required. Others have referred to co-production as the dynamic process by which science and society continually shape, constitute and validate one another, e.g. [19, 21, 22].

2.2 Foresight, impact assessment, simulation modelling and societal embedding

Our contribution, the proposed MLP-driven process, supports decisions on systemic transitions and integrates elements from four theoretical fields: foresight, impact assessment, simulation modelling and societal embedding. It includes several of the attributes required by Mode 2 knowledge production and co-production concepts. The proposed integrated process is aimed to respond to the different scales of analysis and to expand the problem definition. A variety of methods and tools for problem solving are and can further be included into the process. This allows the user of the process to maintain flexibility in analysis. As the methods are largely participatory in nature, continuity and mutual learning over time may be achieved and as a result, shared socially desirable policy interventions identified.

The four theoretical approaches, which form the backbone of the integrated process are presented briefly in the following sections. The approaches can jointly be labelled as strategic intelligence tools or activities employed to support decision-making in the search to identify and assess options in e.g. policy formulation or within change processes. The term strategic intelligence refers here to a multitude of exercises that provide inputs to decision-making [23, 24]. In our view strategic intelligence activities share certain characteristics with each other including future orientation, inbuilt process approach, knowledge production in support of decision-making, use of participatory methods and facilitation and stimulation of learning processes. In a decision-making situation individual strategic intelligence tools and their
combinations may provide “a communication medium for moderation processes and put to practical use in
negotiations systems” characterised by diverse perspectives of participating actors [25: 132].

‘Foresight’ can be defined as action-oriented and participatory strategic intelligence focused on alternative
futures. Knowledge is produced interactively between multiple stakeholders with specific interests and
differing perspectives towards the topic under exploration. A further aim is to facilitate interaction
between the relevant stakeholders and catalyse the desired developments and strategies, e.g. [26].

Foresight is based on present knowledge about future options that are collected and ennobled with
different methods. The aspect of alternative futures has traditionally been the key aim in scenario
methodologies, but also linking of the past, present and future may bring relevant alternative views to the
future potentials (see e.g. [27]). In the field of foresight, an action-oriented mode towards the future is also
present (see [28]), with the practical idea that the “idea is to look for options and opportunities for change
before the business is forced to change” [29: 67]. This separates it from passive mode towards the future,
in which the future is seen as something that is inescapably beyond the present actions. A holistic system
perspective is the basis of futures studies and foresight. The system perspective has usually been utilised as
a philosophical orientation or as an analytical context. This has meant that practical methods or tools like
system dynamics modelling and analytical impact assessment methods have not been widely used in
futures studies and foresight. In our approach, we focus on this particular aspect and aim to integrate
methods from the above fields in building visions, vision paths and system transition roadmaps for the
emission free transport and assessing their impacts.

‘Impact assessment’ refers to structuring and supporting the development of policies. The action-oriented
mode towards the future is consistent within the field of impact assessment, which assumes that policy
measures can be used to shape the behaviour of a system. In this process the main options for achieving
the objective are identified and their likely impacts often in the economic, environmental and social terms
are analysed. Impact assessment outlines the advantages and disadvantages of each option and examines
possible synergies and trade-offs [30]. One refers alternatively to ex-ante, mid-term and ex-post
assessments, to describe assessments carried out during the planning or policy-formulation phase, implementation or the decision-making phase or after the project, programme or policy implementation respectively, e.g. [31-33]. Ex-ante assessment is by definition future oriented; it focuses on evaluating policies and their potential impacts for reaching a given target, however not so much on examining alternative futures. While impact assessment shares many of the characteristics of foresight, and similar analytical and participatory methods may be employed, one distinctive difference is that foresight typically opens the future horizon broad and far whereas impact assessment in general seeks for more concrete intelligence on a handful of near-term future options.

Difficult as it may be, taking into account systemic aspects (e.g. role of networks, institutional capabilities and functions or cluster policies and policy mixes) is understood to be an increasingly important part of impact assessment. Impact assessment is also closely linked to rationale for public intervention, and for instance in the field of research and development attention is increasingly paid to systems failures as targets of policies. Notwithstanding the above, there are practical challenges and tools are lacking to support systemic views in impact assessment. Value of participatory techniques and consultation of interested parties in the impact assessment process is acknowledged for instance by the European Commission in its impact assessment guidelines [30]. Consultation of interested parties is seen “an essential tool for producing high quality and credible policy proposals” and in that way to contribute to effectiveness and efficiency of policies while simultaneously increasing the legitimacy of action from stakeholders and citizens perspective (ibid. [31]). Also humanitarian and development agencies have been interested in to introduce participatory techniques to impact assessment (e.g. [34]). However, it is evident that there is need to develop further participatory approaches and consultation of those who will be affected by policies introduced. More broadly, the entire orientation of impact assessment should preferably be more than assessing value for money, i.e. helping in the negotiation and deliberation process, through which socially desirable actions are identified [3]. Furthermore, impact assessment has potential to support learning and action provided that motivation behind an impact assessment exercise is to improve the intelligence of decision-making and contribute to improving for instance a programme or an
organisation (cf. formative evaluation). In this context, impact assessment can be seen as a learning process.

‘Simulation modelling’ aims to understand complex systems by using computational means. Different simulation modelling approaches have been used to model transitions, see Holtz [35] for an overview. Here we focus especially on ‘system dynamics simulation modelling’ (cf. [36, 37]). Systems thinking and system dynamics emphasize the feedback structure of complex systems in creating its behaviour [38]. Within the system dynamics methodology, causal loop diagramming is one qualitative technique that can be used to illustrate how different variables in a system are related to each other. Feedback loops can be either balancing or reinforcing. However, when there are multiple feedback loops in a system, it is very difficult to deduce system behaviour from its feedback structure only using verbal reasoning. Researchers studying socio-technical transitions have also acknowledged the importance of feedback and nonlinearities regarding transitions: “There is no single ‘cause’ or driver. Instead, there are processes on multiple dimensions and at different levels which link up and reinforce each other (‘circular causality’). Scholars who study transitions therefore emphasize lateral alignments, unexpected linkages, thresholds and tipping points.” [6]. However, one shortcoming of the MLP model is its “narrative and conceptual model” without “causal explanation power” (Ulli-Beer et al) [39]. From a practical standpoint, identifying a particular feedback (i.e. circular causality) or threshold does not imply that system behaviour is understood or that effective policies could necessarily be formulated. Rather, nonlinearities, time delays, and feedbacks make the system dynamically complex [38]. While individual processes may be understood, the interactions can make the system behave in unintuitive ways. Because of this, the role of simulation is emphasized in the system dynamics methodology [38]. Simulation is especially useful to understand the interaction of various processes. An advantage of simulation is that it forces the creation of an internally consistent description of the system structure causing the behaviour. Running a simulation can be seen as a ‘virtual experiment’ to test the effects of different policies and to identify leverage points for system improvement. This is useful in socio-technical systems, because real-life experimentation would often be too slow, costly or unethical [40]. As such, in our approach we use system dynamics modelling and simulations as a method in foresight.
(generation of alternative future paths of development) and impact assessment (evaluating the potential effects of different policies ex-ante or explaining how and why a system has behaved in a certain way ex-post). We also want to highlight importance of participatory aspects and strengthen the emphasis on client and stakeholder involvement in system dynamics methodology, e.g. [38,41].

‘Societal embedding’ of innovations is a research and development approach, which aims at facilitating, initiating and nurturing new sustainable innovations in a multi-actor network. Embedding is thus a participatory and learning dimension that expands and pervades decision-making and other such processes. On the other hand, it continues as an additional end-stage activity of implementation with stakeholders. The approach has been developed since the mid-1990s to promote the societal quality of potential innovations and facilitate the distribution of e.g. medical ICT (information and communications technology) solutions for wider use [42]. Typically these innovations have required a new kind of collaboration between the public and private sectors in order to become sustainable. In the context of the MLP, the role of societal embedding can be seen as a process for shared problem definition and vision building in a multi-actor environment. It can also facilitate building consensus on the implementation of policy measures in a multi-actor environment. We consider societal embedding both as a theoretical approach of its own as well as a mutual, interconnecting and action-oriented method complementing foresight, impact assessment and simulation modelling.

As a preface to the introduction of our MLP-driven process to support decisions on systemic transitions, we argue that when integrated, the elements and tools from the above approaches have major potential to put scientific knowledge in use in strategic policy planning.

3. A novel approach to study transitions

Fig. 2 presents the proposed process to support strategic decision-making and policy planning in systemic transitions. The process consists of a non-exclusive array of research methods and tools that are structured along the successive steps of the adaptable workflow. The steps follow the common ‘problem solving cycle’
adopted in various contexts in decision-making, policy planning, system dynamics modelling, etc., see e.g. [3, 30, 31, 38]. It starts with problem definition, continues with analysis and development of alternative solutions and ends with selection, assessment and implementation of actions.

The process brings fields of foresight, impact assessment, simulation modelling and societal embedding together, and methodologies and tools from these fields can be combined and sequenced within the five steps. The three levels of the MLP approach, and the related perceptions of how a transition from one regime configuration to another may evolve, provide the overall background to our process. We use the MLP approach when outlining the decision-making situation, the socio-technical system and the systemic transition under study. The MLP approach is present in each of the five steps, interlinking different methodologies but also maintaining a consistent systemic view.

The process development proceeded in parallel with a demonstrative case study, where the stepwise workflow was created and iterated. A theoretical case study was designed around the societal challenge to the transport system, as a major transition is required to cut down transport-induced air pollution and greenhouse gas emissions. The demonstration shows how to implement the process and how case-specific selections on methods and tools are made. On the other hand, the lessons learned from the case study allowed us to revisit and evaluate the proposed process. In general, the successful execution of the demonstrative case study validated the developed process as functional and useful. Furthermore it produced important insights on how flexibility and configurability are important characteristics of the process, allowing it to meet the most versatile decision-making context. The case study was also helpful in revising the titles of the five steps and in finding the appropriate, generic enough level of detail that each step should be described.

Work to develop the process and to carry out the case study was a collaboration of a research team of mixed expertise. Fields of foresight, impact assessment, simulation modelling and societal embedding were all represented, and most researchers had lengthy experience in studying socio-technical systems and incremental changes or major transitions in them. The concept of the MLP was familiar to most
researchers, and they had been applying it in their respective fields. The team included also experts of the transport domain, and deep knowledge of transport systems, transport policies, impact assessment of transport, etc. was brought along.

The first three steps of the process (Fig. 2) aim to analyse and structure the challenge being addressed. To begin with, ‘Identification of the decision-making situation’ creates understanding of the strategic targets within the given decision-making context. At this stage, statements describing the vision of the desired future and vision path solutions leading to it are formulated. The second step, ‘Analysis of the socio-technical system’, explores the existing system and its possible future directions within the defined decision-making context. Tools such as the three-level transport system framework can be used. Next, changes and drivers leading to systemic transition in this socio-technical system are identified. Step three,
'System transition roadmap: vision paths and policies', produces full presentations of the alternative or complementing vision paths and the policy measures employed within them. The fourth step, ‘System dynamics modelling and simulations’, gathers the analytical output from preceding work, and a simulation model of the socio-technical system is built. The created vision paths are simulated to show the impacts of their policy measures. In the last step, ‘Interpretation of the results’, outcomes of the simulations and the accumulated knowledge gained throughout the process are assessed. Final conclusions may typically be further communicated as policy recommendations or suggested policy actions.

The developed process proposes a stepwise, adaptable workflow, and the selection of tools to be used depends on the application area. The process should not be treated as a straightforward, one-shot effort. Instead, iterations to repeat the steps may be required. For instance, the simulation results from the system dynamics model may require the policy measures to be readjusted (see return route a in Fig.2). This loop would then be repeated until satisfactory simulation results are obtained. On the other hand, the once completed run of the entire, iterative, process could be revisited at a later time. New knowledge of the system brings the process back to the second step (return route b): for example, having used the process to formulate policy measures, the impacts of near-term actions, when implemented, could be assessed to validate and justify the next actions. Or, if significant changes were identified in landscape or regime developments, e.g. a shift in priorities in the political agenda, a visit back to the start would be needed (return route c).

3.1 Identification of the decision-making situation

Method

The rationale of the first step of the process is to identify the challenge being addressed. This starts by scoping the decision-making context at hand and by finding consensus on the strategic objectives and targets extracted from e.g. policy papers. The desired image of the future is captured by formulating a vision statement in a participatory process with relevant stakeholders.
We define the term ‘primary vision’ as a clear description of a desired future state of the socio-technical system. In addition we propose using the term ‘secondary vision’ for a partial solution leading towards the primary vision. The distinction between primary and secondary visions is somewhat analogous to that between fundamental and means objectives in decision analysis [43]. Secondary visions may compete with one another, but they could also materialise as parallel or successive efforts. For example, a secondary vision could be one alternative solution preferred and advocated by a certain stakeholder group. In contrast, the primary vision defines the desired future through the positive outcomes and impacts in the new socio-technical system configuration. This statement is typically neutral in terms of mechanisms providing the solutions. Descriptions of actions and events that sum up to each secondary vision are created along step three. We use the term ‘vision path’ when referring to these descriptions of system behaviour over time.

Within the first step, the theoretical emphasis is on foresight, most importantly through vision building. Societal embedding is also largely included, as participatory methods to involve relevant stakeholders in identifying the challenge and in drafting the visions play an important part. Societal embedding may also provide the means to build common understanding and consensus among stakeholders whose cooperation is required.

Demonstration

The starting point for the case study was selected from the goals set by the European Commission [44] in the White Paper on transport. The White Paper presents a roadmap to a competitive and resource efficient transport system, where a reduction of 60% of greenhouse gas (GHG) emissions compared to benchmark year 1990 is targeted by 2050. As benchmarks for this target, a list of ten goals is given, the first of which addresses new and sustainable fuels and propulsion systems in urban environments. Next, the relevant sections of the White Paper are excerpted:

“...a reduction of at least 60% of GHGs by 2050 with respect to 1990 is required from the transport sector...”
“Halve the use of ‘conventionally-fuelled’ cars in urban transport by 2030; phase them out in cities by 2050; achieve essentially CO₂-free city logistics in major urban centres by 2030.”

Based on the White Paper target and goals, a primary vision and three alternative secondary visions with three corresponding vision paths were formulated by our research team. The primary vision, ‘emission-free transport in cities by 2050’ proposes that in 2050 passenger transport will produce no GHG emissions in cities. We concentrate on personal mobility by means of private cars and public transport, and for the simulation modelling we chose to explore this vision in the context of the Helsinki metropolitan area in Finland. Three alternative vision paths emphasising three different solutions (secondary visions) to reach the primary vision were then mapped as an outcome of freeform round table discussions among the research team. The first vision path aspires to substitute conventionally-fuelled cars in urban transport with electric vehicles. The second one emphasises replacing conventional transport fuels with low carbon biofuels. The third one highlights modal shift from private cars to public transport. These vision paths were intended to be studied first as alternatives and then as parallel, complimentary developments.

The first two vision paths, electric vehicles and biofuels, represent technological solutions where conventional vehicles or fuels are replaced by more sustainable alternatives. The emphasis is thus on technological substitution. The third path, public transport, involves thorough behavioural change and addresses not only challenges of climate change and air quality but also congestion in cities, access to transport services, etc. All of these concerns are raised in the White Paper on transport [44] and the importance of elevating the share of collective transport is emphasised. Therefore, by maximising the shift from private car use to efficient public transport, the third vision path suggests a more profound socio-technical transition than the other two. The technological aspects of this path were left open, to allow public transport on roads and rails fuelled by electricity and biofuels.
3.2 Analysis of the socio-technical system

Method

The second step analyses the visions and vision paths in the relevant socio-technical system. To begin with, the components and elements of the system are identified and studied against the landscape, regime and niche levels of the MLP. In case of a transport challenge, the three-level transport system framework can serve as the tool to first explore the existing system and then expand towards possible future directions. The broad scope, where the entity of the socio-technical system is studied comprehensively, ensures that all important aspects are acknowledged. A less structured approach could limit the study of links and interactions to only a few elements based on intuition.

Once the main components in the system have been identified, causal loop diagrams are drawn to illustrate the relationships between different parts of the system. Causal loop diagrams are a part of systems thinking and system dynamics and are used to identify interactions and feedback loops in the system [38].

This step builds understanding of the current socio-technical configuration. Components and elements of the system, as well as stakeholders involved, are identified and specified in the chosen decision-making situation and with respect to the previously defined primary vision and secondary visions. These tasks link foresight and societal embedding methodologies, and the workflow continues towards simulation modelling, for which the causal loop diagrams serve as preparatory work. In addition, several aspects of impact assessment are evident in the analysis of interactions in the system.

Demonstration

Fig. 3 shows, using the three-level transport system framework, our view on the key components and elements of the transport system case study. Concrete transport needs and transport culture motivate transport users in their choices between public and private transport. Transport vehicles are portrayed by the alternatives of powertrains and fuels, but also possible future changes in vehicle ownership schemes or investments in the automotive industry may develop. Relevant aspects regarding transport infrastructure
include urban structure considerations and new functions for fuel stations and charging systems. Public and private sector activities are characterised by accessibility, ease of use and public transport service level. These in turn influence user behaviour. Also links to e.g. the vehicle market and build-up of new transport infrastructure are provided.

The arrows in Fig. 3 illustrate the interaction between any two transport system components as well as the collective interaction between all four of them. Interactions between users, vehicles and infrastructure are shown with dotted line to imply that this interplay needs to be included in the system dynamics model to be constructed later on. However, the arrows between transport system organisation, governance and regulation and the other three components are shown in full line arrows. Furthermore the outbound arrowheads from this central component are emphasized. By this we want to illustrate that the very focus of the case study is to identify the means of the transport system organisation, governance and regulation to facilitate and manage the desired transition. Policy measures to ensure availability of transport infrastructure for electric vehicle charging are an example of such interactions, which would later on constitute the core of the simulation model.
Fig. 3. Key components and elements of the transport system to be studied in the case study.

Next, a causal loop diagram of the transport system was structured as a joint effort of the research team. System boundary selection is always a balancing act to include all relevant aspects while keeping the system as narrow as possible, a task that was in our demonstration managed by close interaction and cooperation between researchers representing different domains of expertise. Fig. 4 shows the main feedback loops of the case study:
- Awareness of public transport and private cars (reinforcing feedbacks \( R_1 \) and \( R_2 \)): An increasing trip fraction by a particular means of transport increases its familiarity in the population, thus making its use more common.

- Congestion (balancing feedback \( B_1 \)): Private car use causes congestion. This increases travel time by private car and makes it a less attractive alternative.

- Build roads (reinforcing feedback \( R_3 \)): Congestion increases the pressure to build more road capacity and reduce the trip time by car.

- Population movement (balancing feedback \( B_2 \)): Congestion makes areas with access to public transport more attractive, thus lowering the trip fraction by private car.

Fig. 4. Causal loop diagram of the main interactions and feedback loops.
3.3 System transition roadmap: vision paths and policies

Method

In the third step, the findings of the preceding two steps are further processed to give body to the vision paths. A vision path can be understood as a viable action plan describing the steps required to enable the desired socio-technical transition. A vision path is therefore a hypothesis of one plausible way of system behaviour resulting in system transition. Paths are created and structured corresponding to each secondary vision.

‘System transition roadmap’ is a tool we have developed and used to facilitate vision path generation, and it is formed on the basis of the three level transport system framework and the causal loop diagram. The system transition roadmap adapts and combines key levels of the MLP with extrapolation of the systemic development phases defined by the authors. As a parallel effort, actions such as policy measures to support progress towards the vision are mapped and prioritised for each vision path. The system transition roadmap serves as a graphical tool and a template for mapping systemic changes and transitions as shown in Fig. 5.
Fig. 5. System transition roadmap – a template for generating vision paths. Drivers and changes are structured on the three levels of the MLP (horizontal rows) and along the three temporal phases (vertical columns) leading towards the vision. Examples of drivers and changes are: related trends contributing to favourable environment for change (A and B), technological innovations initiating the change (C, D and G), policy measures supporting desired development paths (E and F) and envisioned future (H).

The system transition roadmap (Fig. 5) illustrates the vision path of a shift from one socio-technical system to another. Not only technological but also political, social, cultural, economic, environmental, legal and other dimensions can be captured. Theoretical foundation of the system transition roadmap is based on combining temporal dimension to the MLP approach. The temporal, systemic development phases in the system transition roadmap are the following:
Emergence: Initial statements appear that set the agenda for the systemic transition. Regime is at the start of the transition due to internal regime dynamics and pressure from both the landscape and niche levels. Initial structures of a new system are introduced.

Diffusion: The system transition agenda is deepening and diversifying. A range of key stakeholders push the transformation along multiple fronts. Awareness of these transformations is spreading in society and common rules of the new system are forming. Legislation and institutionalisation begins, and new enabling technologies are emerging and are connected to the needs of the novel system.

Consolidation: The novel system is at the phase of institutionalisation and stabilisation. The system is structured in the consciousness of the surrounding society. It has a legitimised role and activities within the society, and there are legitimate core stakeholders that are the official representatives of the system.

Step 3 has a strong focus on foresight methods and tools when applied to the MLP approach. Characteristics of impact assessment and societal embedding are also brought along in identification and selection of policy instruments and in assessing their impacts or the chained effects of various events and actions.

Demonstration

Along step three, the policy measures corresponding to each secondary vision and their respective vision paths designed in the case study were mapped and analysed. We chose to appoint one researcher to administer each of the three vision paths, and the practical work consisted of alternating sessions of individual work (by the three researchers) and group sessions involving the entire research team. Vision paths were thus formulated in a way that ensured both topic-related focus and mutual alignment.

First, policy instruments were identified in three groups, i.e. supply- and demand-side measures and systemic instruments. The supply-side policy measures address the public and private sector stakeholders, whereas the demand-side measures directly address the transport user by encouraging use of electric
vehicles, biofuels or public transport. This division is used by e.g. Edler and Georghiou [45], who also provide a detailed definition of the latter category in the innovation policy context: “Demand-side innovation policies are defined as all public measures to induce innovations and/or speed up diffusion of innovations through increasing the demand for innovations, defining new functional requirement for products and services or better articulating demand.” In defining the third category (systemic instruments), we adapted relevant literature emphasising the linkages between systems thinking and policies, e.g. [46, 47]. With this third category – systemic policy instruments – we refer to enabling regime-level structures, based on different actor coalitions and institutional configurations, that help build and manage stakeholder communities. Systemic policy instruments therefore act as a sort of platform or ecosystem in which the policy mix composed of a selection of supply- and demand-side measures is implemented. Thus, one could more widely use the concept of systemic policies, referring to the mix of policies combining supply, demand and systemic instruments. Systemic policies address the entire transport system and are a central tool in building vision paths and hence nurturing transitions.

Second, the instruments were placed into the temporal and thematic contexts of the system transition roadmap. Anticipated future trends, technological innovations and a feasible selection of policy measures were allotted for each of the three vision paths, and these policy mixes were incorporated into the system transition roadmaps that were drafted for each vision path respectively (see Figs. A.1, A.2 and A.3 in the Appendix).

Third, policy instruments were characterised and packaged for system dynamics simulations. In practice three iterative discussion rounds were arranged with the entire research team to decide on the procedure and to carry out the tasks. Here the impacts of the proposed instruments on transport system users’ modal choices, compared to the current situation, were considered against three criteria on a five point scale (from -2 to +2). The criteria were identified when building the causal loop diagram in step 2 of the process and included (a) willingness to consider (WTC) the means of transport under consideration, i.e. public transport, electric vehicles and biofuel vehicles, (b) end user costs and (c) time used for travelling. These
three criteria comprised the attractiveness of a modal choice for trips considered. In addition, start and end years and potential implementation delays were proposed for each of the policy instruments. When incorporating the vision path policy instruments into the simulation model, certain simplifications had to be made. Based on the listing and characterisation of policies, actions with similar impact mechanisms were bundled up to create the simulation scenarios.

3.4 System dynamics modelling and simulations

*Method*

The fourth step of the process has the objective to gather the analytical output from tasks carried out along the preceding steps. Based on these, a simulation model of the socio-technical system is built. As in standard system dynamics methodology [38], the model is constructed based on the previously built causal loop diagram. Once the model has been built, it is used to test the feasibility of the vision paths. The simulation results then show if and how effectively the policy measures formulated for the vision paths enable, speed up and steer the development towards the primary vision.

Alternative vision paths may be simulated as such, whereas vision paths with complementing characteristics can also be simulated as parallel or successive runs. Because of the interactions of different policies in a complex system, it is useful to test combinations of different policies iteratively using the simulations model to find effective policies for reaching the primary vision.

By definition, step four involves most importantly simulation modelling. This is parallel to impact assessment tasks to explore how to run the simulations and to make decisions on whether adjustments or further iterative rounds are needed.

*Demonstration*

This step started with final decisions on system boundary definition for the part of the transport system to be modelled. As stated by the primary vision, the focus was on cities, and the model was built to portray urban passenger transport in the Helsinki metropolitan area. The simulation model was thus scaled to
corresponding regional characteristics, historical data and available future forecasts (demographics, transport volumes, modal split, etc.) that were obtained from the Helsinki Region transport system plan [48]. The build-up of the model was guided by the three-level framework structure of the transport system as a reminder of all the components and elements that should be acknowledged. Work in this step was also guided by previous modelling efforts. In particular, Struben & Sterman [36] have assessed transition challenges of alternative fuel vehicles using a system dynamics model, and Sterman [38: Ch. 5] has discussed the role of issues such as road building in making private car use attractive and causing a public transport death spiral. Links and causalities between parts to be modelled were established and additional elements on a more detailed level were added when necessary. Next, the building parts of the three vision paths, as illustrated in their respective system transition roadmaps, were brought to the simulation model. The same applied to the policy measures and their expected impacts on costs, travel times and user attitudes and how they were anticipated to translate into user behaviour in terms of vehicle ownership and modal choices.

The simulation model included three means of transport: public transport, combustion engine cars and electric vehicles. Biofuels were considered as an alternative fuel that could be used in the combustion engine car fleet. A distinction was also made between different transport user segments in terms of mode: users of combustion engine cars, users of public transport, users of electric vehicles and users of biofuel-driven combustion engine cars. By public transport users we mean those using public transport as their prime transport mode. Car owners are categorised under user groups named after the different powertrains and fuels, but also use of public transport by these user segments is acknowledged. The number of users and trips by each means of transport depends on the relative costs and travel time. In addition, users’ willingness to consider a particular mode of transport is taken into account.

When structuring the simulation model and interactions of the transport system components and elements in it, it was considered important to highlight the role of the transport system user as a critical actor in materialization of the primary vision. In contrast to technology-oriented approaches where e.g. alternative
vehicle powertrains and fuels are brought to the centre, we wanted to concentrate on analysis of the transport users’ choices. Introduction and availability of the new transport technologies of electric vehicles and biofuels are among the key factors in this model, but even more emphasis is put on their uptake. Similarly, provision of high-quality public transport is central, but more emphasis is given to the choices in using these services. The simulation model is used to analyse user behaviour in the transport system, and the main results are assessed in terms of ‘fraction of trips’ and ‘number of users’ by transport means: combustion engine car, public transport or electric vehicle. Uptake of biofuels is monitored within the combustion engine car fleet.

A full description of the simulation model equations and the simulated policies are presented in the Technical appendix.

3.5 Interpretation of the results

Method

The fifth step concludes the process, and the outcomes from all preceding steps are assessed. Accumulated knowledge together with the simulation modelling results is used to draw final conclusions for policy support and decision-making, a task that requires profound stakeholder involvement. The objective of this step is to crystallise the outcomes and results of the process into concrete actions and ensure that, based on the information gained, the journey towards the desired future of the primary vision is initiated. This may imply evidence for the basis of decisions, formulation of policy recommendations or preparatory work on suggested policy actions.

It is essential to understand that along this step the results do not necessarily pinpoint one superior vision path with an exclusive list of steps and policy measures and a guarantee of attaining the primary vision. The conclusion may be that the vision paths and policy measures designed in step three were not sufficient and need readjusting (see return route a in Fig.2). Another possibility is that the scope of study regarding the socio-technical system is too narrow, and additional dimensions need to be included in step two (return
route b). The results may even suggest that the approach chosen does not contribute adequately to the original challenge of the identified decision-making situation at step one, or the environment where the ultimate targets are set may have changed (return route c). In any case, the fifth step should not be perceived as an ending point, but rather as a starting point to initiate concrete actions to implement the positive, mature results into practice or an evaluation step to decide what still needs to be studied in more detail.

The final step combines elements from the fields of impact assessment and societal embedding, highlighting participatory working ways to committing stakeholders to implement the results and interpret them as actions.

Demonstration

Because the case study was carried out as a methodological demonstration with no real decision-making mandate, not all aspects of the final step were applicable. Interpretation of results was thus limited to an assessment by the research team of how well the vision paths and policy measures contributed to the primary vision and the valuable lessons learned along the working process. Possible policy implications were also considered but no comprehensive policy recommendations were drafted.

Furthermore, this paper does not delve into a full presentation and analysis of the simulation results of the vision paths and their policy measures. Numerous simulation rounds in varying combinations of policies were carried out, but we only present the overall results regarding selected policies. The simulation model and different policies are described in detail in the Technical appendix. An earlier version of the simulation model is described in [49].

The case study simulations confirmed that none of the three vision paths alone were enough to attain the targeted primary vision of emission-free urban transport system by 2050. But when combined, the modal share of public transport could be substantially elevated. This mixed strategy to combine the policy measures from the three vision paths was able to address all user groups and provide the most efficient result.
The simulation model also showed that instead of a shift from fossil fuels to the use of electricity and biofuels, the maximisation (optimisation) of public transport usage was the topic to be addressed first. Promoting the use of public transport and discouraging the use and ownership of private cars should be prioritised, as it is the most desirable change given its positive impact not only on the case study goals addressing climate change and air pollution, but also on other transport policy goals addressing congestion and transport safety. Both increasing the number of public transport users (those not owning a private car) and increasing the public transport trip fraction of car owners should be pursued.

After ensuring maximum use of good quality public transport, complementing policies can focus on addressing the technological change from conventionally fuelled combustion engines to vehicles using electricity or biofuels. These policies should target private cars as well as vehicles used for public transport. And while structuring these policies, it is of upmost importance to ensure that (1) an undesired shift does not occur from users of public transport to owners of private cars and (2) that it does not discourage private car owners from changing their transport behaviour so that trips previously made by public transport are then carried out by private car.

Figure 6 shows the results of four scenarios corresponding to different sets of policies. For each scenario, the trip fractions up to year 2050 of public transport, combustion engine cars and electric cars are shown in separate diagrams. The graphs do not make a distinction between conventional fuels and biofuels, but both options are represented by the curves for combustion engine cars. The simulated policy scenarios are the following: (1) policies to increase electric car adoption (infrastructure construction, purchase subsidies, and marketing), (2) same policies to increase electric car adoption, but marketing duration is longer, (3) policies to increase public transport usage (infrastructure construction, price subsidies and marketing) and (4) policies to increase both electric car and public transport usage (policies of scenarios 2 and 3 combined). The policies in the simulations are activated at year 2012.
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Fig. 6. Four simulation scenarios

A comparison of the first two scenarios shows that policies supporting electric cars need to be active for a long period of time for successful electric car adoption. If electric car marketing is stopped too early, there is a risk that adoption will decline after a successful initial growth phase. However, more active policies to promote the use of electric cars also reduce the trip fraction by public transport. In the fourth scenario, combined policies to promote the use of electric cars and public transport lead to the biggest decrease in combustion engine car trip fraction. However, in this scenario the use of electric cars is somewhat less prevalent than in the scenario with only electric car policies in place.

Summing up the interpretation of the simulation modelling results, the following conclusions (e.g. possible policy implications) were drawn based on numerous simulation rounds in various combinations of vision paths and policy measures.

First, measures that lead to an increase in fraction of trips or number of users in public transport always contribute towards the vision. A shift from private car use (whether from combustion engine cars using conventional or biofuels or from electric vehicles) to public transport is always desired. Measures that lead
to a decrease in fraction of trips or number of users of combustion engine cars always contribute towards the vision. A shift away from use of conventional fuels is always desired. Measures that lead to an increase in fraction of trips or number of users in either electric vehicles or biofuels are more complex. If the fraction of trips or number of users of combustion engine cars also increases (or stays constant), the measure is inefficient. The essential thing is to investigate what transport choices and user groups are affected. A shift from public transport to either electric vehicles or cars using biofuels is not desired.

Second, potential unexpected impacts left outside the simulation model need to be acknowledged: as an example, low-priced public transport tickets may result in new users coming from user segments that used to walk or ride a bicycle, not only from the intended user segments of private car owners.

Third, timing and scheduling of measures is essential, and they should be carefully bundled up and built into a continuum. Impacts of the measures should also be assessed regularly to find out if the intended effects are achieved. Long delays regarding transitions need to be taken into account. For example, successful adoption of electric cars may require continued marketing lasting several years [36].

4. Discussion

This paper introduced a process to support strategic decision-making and policy planning in systemic transitions, and various aspects and tools from the fields of foresight, impact assessment, simulation modelling and societal embedding were combined. The MLP was used as a platform to deepen each of these fields and to integrate them to one another. The stepwise, adaptable workflow of the developed process can be implemented in the hands-on working environment of decision-makers, and the generic core process, and the tools within, can be applied to various sectors of the society. The process was demonstrated by a case study exploring the urban passenger transport vision of ‘emission-free transport in cities by 2050’. The methodological contribution of the paper is twofold: contribution to the study of socio-technical systems and knowledge production to support their change in general and contribution with special focus on the transport system.
4.1 Methodological contribution

Our first research question inquired how the fields of foresight, impact assessment, simulation modelling and societal embedding could be integrated, rather than be used respectively, to study and understand systemic transitions in complex socio-technical systems. We approached the challenge by bringing experts of each of these fields together to our research team. Work began by identification of possible links between theories, methods and tools across the fields and how inputs and outputs could be circulated. A central starting point was the notion how all four fields could accommodate and contribute from the MLP approach, thus providing a shared framework to study systemic transitions in socio-technical systems.

A key finding between the research fields was that all of them shared, a stronger or weaker, forward-looking dimension and methods within the fields had the aim to support strategic planning and decision-making on different levels. There are, however, differences between the fields. For example in the field of ex-ante impact assessment, the traditional practice has been to use research results and statistics from the past and the present as the basis for future visions and assessments on reaching the visions. The changing operational environment and its actors have received less attention. In our approach, the future operational environment with its pressures (both from the landscape and niche levels) acts in a new way, as a key element in the socio-technical analysis.

Further, in our case, producing new knowledge or solutions and simultaneous learning procedure between the research fields was seen more important than the actual methods and tools used. Finally, we identified that foresight, impact assessment and embedding are more than just theoretical approaches. Together, they can be combined and sequenced to channel the socio-technical change. We also found that this provides a platform to study transitions between the levels of the multi-level framework.

The second research question addressed the challenge of how to put the methodologies from these fields to actual use to support strategic work of decision-makers in practice. As an answer, a process was developed to contribute to closing the gap that separates advances in theories and analytical research on socio-technical change and transition management from the more practical, forward-looking decision-
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making and policy planning. The process facilitates the development of practical strategies to steer and accelerate transitions towards desired directions while employing desired solutions. Means to analyse the impacts of the systemic policy packages in the context of a complex socio-technical system in a rather manageable way are also provided. The actual tools provided include primary vision, secondary vision, vision path and system transition roadmap. These tools help the user (civil servants, politicians and other decision-makers) to clarify the problem definition and to present solutions or instruments on different scales. The iterative nature of the suggested tools also builds learning over time. In future research cases and applications the methods and tools to be included in the process need to be selected, adjusted and integrated case by case to fit for the purpose of the practical decision-making case. This contributes to the request of the field of STS on ‘knowledge produced in the context of applications’.

In our approach, we also showed how system dynamics modelling and simulations can be used as a tool to generate alternative future scenarios and assess the impacts and interactions of different policies over time. A benefit of simulation is that the interaction of various change processes can be examined. Here, the simulations helped understand the potential and limits of specific policies. In terms of the policy measures, the simulations showed the benefits of a comprehensive approach in terms of choice, prioritisation, combining and sequencing. The impact of different policy mixes could be analysed to understand whether the different policies balance one another or lead to undesired directions. This helped to design policies in unison in a way that they worked well together and did not undermine each other. A concrete benefit of the simulations was the finding that individual vision paths (such as public transport, electric cars and biofuels in our case study) should not only be analysed separately. Instead, the opportunities to integrate them in a meaningful way should form the core of analysis. Simulation modelling offers a practical tool to examine the interactions between different subsystems within a complex system.

Societal embedding has an important role in our methodological combination that conditions the entire process described here. In our case study, societal embedding can be approached through two perspectives. The first perspective emphasises iterative learning. In this perspective, societal embedding is
perceived as continuous process of setting a target vision, building a system dynamics model, and modifying vision paths and policy mixes on the basis of simulations. During this process, the actors engaged in it will learn, phase by phase, the key components and linkages in the system under scrutiny and understand how different feedback loops in the system manifest in the context of policy actions. Thus, engaging in the process is societal embedding as such. The second perspective emphasises the role of societal embedding as a sort of ex-post activity that is realised after the actual system dynamics model has been built. In this perspective, the results of simulations are perceived as triggers that start a distinctive process of societal embedding aimed at forming particular policy actions. In this process, actors in a certain system context test different policy mixes and related actions and run through several rounds of simulations. During this process, actors learn the key components and linkages in a system, but the primary emphasis is to learn about the dynamics of varied policy mixes and plan actions through iterative test runs.

To conclude, the developed process could be characterised as the means and resources in the search for the most effective window of opportunity to reach given policy goals, emphasising the user perspective as well as extending it to wider stakeholder networks. Also, the process can help prioritise different factors and find systemic gaps and lock-in mechanisms. In future efforts research work is still needed to study and develop more refined techniques to shape designed vision paths and policy measures in the system transition roadmap, so that they best serve the input requirements of simulation modelling and vice versa. Especially gaining more understanding on systemic policies and finding the best approaches for active stakeholder participation is important. Methods and tools from foresight, impact assessment, simulation modelling and societal embedding explored in the current work already showed abundance of fruitful interlinking opportunities, only a few of which could be demonstrated. Further work should aim to experiment and possibly systematise this methodological potential.

4.2 Case study specific contribution

Building on the methodological and theoretical answers and results to our two research questions, an important parallel task was to translate these findings in the socio-technical system of transport, where a
systemic transition is required to address transport emissions. The case study showed one way of employing and linking the four fields while the MLP gave structure to the sector-specific transition process. The case study provided substantial contribution to the transport domain by showing in a concrete manner how to implement system dynamics and simulation modelling to facilitate formulation and assessment of policy measures on the comprehensive transport system level.

The case study was carried out in parallel to the work to develop the process. Therefore it provided direct feedback to the process development and allowed the research team to assess and adjust the process accordingly. Whereas this feedback did not call for actual changes to the process, it accentuated its nature being flexible and configurable to meet the most versatile decision-making contexts.

The following lessons learned present the most valuable outcomes from the case study. Firstly, the developed tools and concepts: the three-level transport system framework, primary and secondary visions and system transition roadmap together with the dynamic model formed an illustrative description of the socio-technical transport system, its elements, linkages and transition paths. Formulated policy measures of different scope were simulated per vision path and in different combinations. System level assessment of policy impacts enabled effective policy combinations to be packaged and sequenced.

Secondly, the study of the entire socio-technical system of transport was considered highly fruitful, and to assess vision paths of different nature was a novel and welcome approach. To include public transport as a parallel solution to more technology-oriented electric vehicle and biofuels vision paths was not only effective considering the targets of the primary vision, but also justified regarding targets excluded from this study (e.g. those addressing congestion, mobility and land use) or real-life practical implementation in the systemic environment. In future research the study boundary could be extended even further, and a comprehensive simulation model to include walking and cycling alongside motorised transport could be developed.

Thirdly, the intentional decision to emphasise user behaviour and choices proved successful. Whereas research efforts often focus on technology-oriented issues and may therefore fail to capture behaviour
related issues such as acceptance, take-up or new behavioural patterns, we highlighted users in the active role. The system dynamics model was designed to help understand user decisions by the urban resident when choosing the means and mode of transport. This included firstly the long-term decision on whether or not to purchase a private car powered with fossil fuels, biofuels or electricity. It also included the daily short-term consideration of car owners on whether to go by car or public transport. Instead of such a comprehensive user-targeted approach, many of the on-going modelling efforts are technology led.

Fourthly, the simulation modelling exercise increased mutual understanding of the socio-technical transport system, its elements and linkages. Even if all links and interactions are not understood, it may help to identify, interpret and understand the new developments and signals and thus monitor how the system is changing. This in turn allows stakeholders to make more informed decisions and formulate well-targeted policy measures in the long run. The ambitious objective to model and simulate the behaviour of a complex urban transport system should, however, be treated with some reservations. At present, the results of the simulations can be used to assess how well-specified assumptions can generate certain qualitative dynamic behaviour of the system, such as growth and collapse or sustained growth in the use of a particular means of transport. Our approach emphasises action-orientation and alternative possible futures and acknowledges that accurate quantitative predictions are unattainable due to inherent uncertainties in a complex socio-technical system. The results of simulation modelling should always be interpreted together with an adequate knowledge of the transport substance. Specific topics where more effort and further research is still required include completion of background data, statistics and mobility preferences of various user groups, refinement of causal loops and interactions, a more detailed approach to policy measure formulation and modelling and enhanced stakeholder involvement in the process. An important topic for further research is to use stakeholder analysis to identify and understand involved stakeholders and their roles in the transition under study. Also, participation of the key stakeholder entities in the process will be central, and methodological discussion needs to be initiated together with decision-makers and politicians on how to integrate and implement the developed process and suggested tools into the hands-on decision-making environment.
In fact, it could be argued that detailed technologies and solutions facilitating transition to emission-free transport are in general already available. This applies in many respects to all three vision paths. Supply- and demand-side policy measures are required to further promote these technologies and solutions and their uptake. While these are important, the measures could be complemented with the systemic policy approach, as suggested in this paper. The systemic policy approach could just be the key to overcome the challenge of moulding policy actions in the context of complex socio-technical systems, in which stand-alone measures addressing specific areas, such as tax incentives for electric vehicles, may prove to be insufficient. At its best the comprehensive systemic approach could provide the environment where all elements and stakeholders of the transport system are aligned in favour of the changes leading to the envisioned transition.

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References


Appendix

Fig. A.1. Public transport vision path: system transition roadmap.
Fig. A.2. Electric vehicles vision path: system transition roadmap.
### Emission free transport in cities 2050 / Biofuels vision path

<table>
<thead>
<tr>
<th>Phase 1. Emergence</th>
<th>Phase 2. Diffusion</th>
<th>Phase 3. Consolidation</th>
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<td>Production of fuels, local and global directions</td>
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<td>Climate change</td>
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</tbody>
</table>

| **Transport system** | | |
| Transport white paper | Constructing specific legal frameworks for biofuels | Emision free transport in cities by biofuels |
| Changing transport policies | Public procurement | Policies building on comparative and absolute advantages |
| Market and price mechanisms | Subsidies and tax incentives | Seven axes of EC’s biofuel policy (see EU strategy on biofuels, 2006) |
| | | |
| Coalition building among energy providers and vehicle industry | Certification of fuels, standardisation | Building sustainable and efficient land use policies for production of biofuel feedstock |

| **Technologies and services** | Biofuels | Development of second generation biofuels, e.g. lignocellulosic biofuels |
| | | Development of conversion processes |

Fig. A.3. Biofuels vehicles vision path: system transition roadmap.
Technical appendix

Simulation model

The time period of the simulation is from 2010 until 2050. The three transport modes are referred in the equation subscripts as follows: public transport (1), combustion engine car (2) and electric car (3). The parameter values reported correspond to the values used in the article for illustrating different dynamic patterns over time. Some parameter values are based on similar existing simulation studies [36] and data about the Helsinki transport system [48].

Choice of means of transport

The choice of means of transport is divided into short term and long term choices. The attractiveness of each transport mode \((a_i := \text{long term attractiveness}, a_i' := \text{short term attractiveness})\) is calculated based on costs and performance. The performance of each transport mode is assumed to depend on the travel times such that the performance is high if travel time is low.

\[
a_i = \left( \frac{C_i}{C_i'} \right)^{-\alpha} \cdot \left( \frac{P_i}{P_i'} \right)^{\alpha}
\]

\[
a_i' = \left( \frac{C_i'}{C_i} \right)^{-\alpha} \cdot \left( \frac{P_i}{P_i} \right)^{\alpha}
\]

In the equations, \(C_i\) is the long term cost of a given transport mode: \(C_1 = 0.5, C_2 = 1, C_3 = 2\) (\(C_3 = 0.5\) if electric car purchase subsidy policy is active). \(C_i'\) is the short term use cost of each transport mode: \(C_1' = 1.2, C_1' = 0.8\) if public transport cost subsidy policy is active), \(C_2' = f_{\text{bio}} + (1 - f_{\text{bio}}) \cdot P_{\text{oil}}, C_3 = 0.2\). The costs for combustion engine cars depend on the availability of biofuels \((f_{\text{bio}})\). The construction of biofuel capacity is modelled using a third order delay of 30 years when the corresponding policy is activated. \(P_{\text{oil}}\) is the price index of oil that is assumed to grow at 2% per year, starting from a value of 1. In the model, biofuels are assumed compatible with combustion engine cars. Thus, the use of biofuel by combustion engine car users does not require additional investments (unlike with electric cars that require purchasing a new type of car). \(P_i\) is the performance of each transport mode (see equation 9). \(C^* = 1, C^{**} = 1, P^* = 1\) are the reference values of costs, use costs and performance, respectively. \(\alpha = 1\) is the sensitivity of attractiveness to attribute values.

In the short term, car owners have the option of either to make an individual trip by private car or use public transport. In the long term, people decide whether to purchase a car and which type of car to purchase. In the costs of the transport modes of the baseline simulation we assume that the fixed costs of car ownership are higher than those of public transport, but the short term costs (costs of an individual trip) are lower.

In the model, people can be the primary users of one of the three transport modes. People who own a combustion engine or an electric car are users of the corresponding car type, and people without a car are users of public transport. The share of primary users of a transport mode \(i\) switching to transport mode \(j\) is represented by \(\sigma_{ij}\) and the short term users switching to another transport mode is represented by \(\sigma_{ij}'\). These are calculated based on the perceived relative attractiveness of the transport modes. The willingness to consider a particular means of transport \((W_{ij})\) is taken into account when assessing the perceived attractiveness.
In the equation above, \( x_{ij} \) is the possibility to use a particular transport mode in the short term, and is set to 1 if \( i = j \) (everyone can continue to use the same mode of transport) or if \( j = 1 \) (everyone has the possibility to use public transport). Otherwise it is set to 0.

The change in the number of primary users \( U_i \) is calculated as follows:

\[
\frac{d}{dt} U_i = \sum_j \sigma_{ij} \frac{U_j}{\lambda_j} - \sum_j \sigma_{ij} \frac{U_i}{\lambda_j} + \Delta \text{POP} \cdot \frac{U_i}{\sum U_i}
\]

The first term of the equation is the sum of inflows to transport mode \( i \) from users of transport modes \( j \), and the second term is the sum of outflows from transport mode \( i \) to transport modes \( j \). \( \lambda_i = 10 \) (years) is the decision interval to change ownership mode, and corresponds to an average life of a car. The third term is the increase of users due to population increase. \( \Delta \text{POP} = 11900 \) (people/year) is the increase in population, which is based on an existing estimate [48].

The initial number of users is set as follows: \( U_1(0) = 0.3 \cdot \text{POP}_0 \), \( U_2(0) = 0.7 \cdot \text{POP}_0 \), \( U_3(0) = 0 \). \( \text{POP}_0 = 1360\,000 \) is the size of the initial population [48].

The change in the number of trips \( (U_i') \) is calculated using exponential smoothing:

\[
\frac{d}{dt} U_i' = \left( \sum_j \sigma_{ij}' \frac{U_i'}{\tau'} - U_i' \right) / \tau'
\]

where \( \beta = 2.8 \) is the average number of trips per person per day [48] and \( \tau' = 2 \) (years) is the delay of usage change.

**Road infrastructure and population movement**

The level of road infrastructure \( (I_r) \) is assumed to adjust to a suitable level depending on the number of trips by car. The delay in road construction is modelled using a third order delay of 5 Years. Additional road construction can also be deactivated using a corresponding policy.

The adequacy of road infrastructure capacity \( (a_r) \) is calculated based on the existing road infrastructure and the number of trips by car \( (U_2' + U_3') \):

\[
a_r = \left( \frac{I_r}{U_2' + U_3'} \right) ^ \delta
\]

where \( \delta = 6 \) is the sensitivity to congestion. If \( I_r > U_2' + U_3' \), the adequacy is set to 1.

The adequacy of road infrastructure affects the attractiveness of car use and population movement. A low adequacy of road capacity gives people the incentive to move to areas with better public transport coverage. The change in the fraction of people with no access to public transport \( (f_{\text{pop}}) \) is calculated using exponential smoothing:
where $f_{\text{pop}}^* = 0.8$ is the maximum population fraction with no public transport and $\tau_{\text{pop}} = 20$ (years) is the delay of population movement.

**Performance of the transport modes**

The performances of the transport modes are calculated as follows:

$$P_1 = (1 - f_{\text{pop}}) \cdot I_1$$  \hspace{1cm} (9a)

$$P_2 = a_r$$  \hspace{1cm} (9b)

$$P_3 = a_r \cdot I_3$$  \hspace{1cm} (9c)

The performance of public transport depends on the fraction of people who live in areas with good public transport coverage ($1 - f_{\text{pop}}$) and the public transport infrastructure ($I_1$). For cars, the performance depends on the adequacy of road infrastructure. For electric cars, infrastructure specific to electric cars ($I_3$) is also taken into account. Infrastructure construction of public transport (e.g. building new city railway lines, upgrading current bus transport infrastructure and functionality of bus network and nodes) and electric cars (e.g. services for electric cars) are modelled using third order delays (delay of 10 years) when the corresponding policies are activated. After the delay an increase of 1 unit is added to the value of the corresponding infrastructure. The starting values of infrastructure for the transport modes are 0.5, 1, and 0 for public transport, combustion engine cars, and electric cars, respectively.

**Willingness to consider**

Willingness to consider (WtC) reflects users’ awareness of the different available means of transport. We have drawn from the model by Struben & Sterman [36], who have used the willingness to consider construct to examine the adoption of alternative fuel vehicles. In their model, WtC depends on the size of the installed base of a particular car type relative to the total installed base of all cars. In our model, we assume instead that WtC depends on the trip fraction of the means of transport. This is because we consider not only the adoption of different types of cars but also the use of public transport and because car owners can also make trips by public transport.

In the model, $W_{ij}$, i.e. the willingness of users of means of transport $i$ to consider $j$ is dependent on exposure and a decay rate:

$$\frac{d}{dt} W_{ij} = \eta_{ij} \cdot (1 - W_{ij}) - \phi_{ij} \cdot W_{ij}$$  \hspace{1cm} (10)

$\eta_{ij}$ is the social exposure of the transport mode and $\phi_{ij}$ is the fractional decay of willingness to consider, which are calculated as follows:

$$\eta_{ij} = M_i + \sum_k c_{ijk} \cdot W_{kj} \cdot \frac{U_{ij'}}{\sum U_{ij'}}$$  \hspace{1cm} (11)

$$\phi_{ij} = \phi_0 \cdot \frac{\exp[-4 \cdot \epsilon (\eta_{ij} - \eta^*)]}{1 + \exp[-4 \cdot \epsilon (\eta_{ij} - \eta^*)]}$$  \hspace{1cm} (12)
The social exposure is the sum of marketing and word of mouth exposure. If a marketing policy is active, $M_j = 0.025$, otherwise $M_j = 0$. The contact rate, $c_{ijk}$, refers to the word of mouth contact rate for users of transport $i$ to hear information about $j$ from users of $k$. Direct and indirect word of mouth are modelled by setting $c_{ijk} = 1$, if $i = j$; $c_{ijk} = 0.25$, if $j = k$; and $c_{ijk} = 0.15$, if $j \neq k$. In direct exposure, people learn about a means of transport from users of the same means of transport, while indirect exposure refers to learning from non-users. $\phi_0 = 1$ is the maximum decay rate, $\eta^* = 0.05$ is the reference rate of social exposure, $\varepsilon = (2 \cdot \eta^*)^{-1}$ is the slope of WtC decay rate at the reference rate. For details, see Struben & Sterman [36].

The initial values for willingness to consider is set as follows: $W(0)_{ii} = 1$, if $i = j$ (assumed that everyone is willing to consider the current transport mode); $W(0)_{ij} = 1 \forall i$ (assumed that everyone is willing to consider a combustion engine car); $W(0)_{13} = W(0)_{23} = 0.6$; $W(0)_{21} = W(0)_{31} = 0.6$. 