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Planning of Transport Systems under Increasing Complexity—Looking into Nature

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ABSTRACT

The planning of transport infrastructure followed in the past the predicted transport demand. The challenges stemming from climate change and losses of biodiversity will force consideration of the increasing complexity of the transport system in future planning. Complexity research in natural science has developed strong concepts that show how natural organisms master complexity problems, recognized by recent Nobel Prizes in Physics and in Chemistry. Taking concepts like boundaries and folding as metaphors for treating complexity problems in transport infrastructure planning generates helpful lessons for its fundamental revision. It places the system's view into the heart of the planning algorithm—instead of single projects—and stresses interactions within the transport system and between transport and interacting systems like economy, environment, and society. Appropriate methods for modelling dynamic systems exist in economics and transportation science but can further be developed analogously to the progress in natural science.

KEYWORDS: Nobel Prizes on complexity research; interactions; boundaries and folding; complexity of transportation systems; treatment of complexity in transportation planning; dynamic analysis of stochastic systems

INTRODUCTION

The Descartes philosophy recommends breaking down problems into smaller sub-problems and solving them one by one, progressing from simple to complex. The traditional cost-benefit analysis methods applied for optimal transport infrastructure development remain at the simple level and apply a partial market approach, assuming that all non-transport markets are in equilibrium so that the evaluation of impacts is restricted to the transport market ("marginalist approach" following the surplus concept of Alfred Marshall [1]). As soon as exogenous transport activity drivers in other sectors change, the demand will adjust and send corresponding signals to the supply side for adjusting the infrastructure adjustment, without further feedback needed. The current planning algorithms for developing the transport infrastructure begin by predicting the exogenous development of socio-economic and

Open Access

Received: 02 March 2025
Accepted: 17 April 2025
Published: 24 April 2025

technological drivers and derive the transport demand using econometric and optimisation modelling, calibrated to past development. Transport infrastructure, then, is designed in a way to meet the predicted demand trends.

This planning concept worked smoothly in the past decades after World War II due to the lack of major disturbances by exogenous drivers, and even some financial crises did not cause any doubts about this scheme. The recent COVID-19 crisis has raised some doubts with respect to the continuity of the linear development of transport systems, because substantial changes of preferences could be observed (see Rothengatter et al. [2]) and logistic supply chains became interrupted (see Ernst & Young [3]). Although some of the effects have slowed down, the COVID-19 crisis can be interpreted as a first indication of the increased complexity in the development of future transport systems. Particularly, the climate change problem and the intended transformation of the economic system towards a zero greenhouse-gas (GHG) footprint will generate repercussions on the transport sector, which make evident its close interactions with the other parts of the social and economic systems so that the marginalist approach to transport planning will no longer work.

Against this background, the current planning paradigm for the transport infrastructure is being increasingly questioned and recommended to be replaced by more holistic approaches. Particularly, the International Transport Forum (ITF [4]) has emphasised the necessity to replace the predominating trend-based demand forecast (“predict and provide”) by a “decide and provide” approach which is based on a system’s analysis and oriented at achieving a set of essential environmental, social, and economic goals.

This paper aims to integrate this holistic approach into the theory of complex systems, which has been recognised by the Nobel Prize awards for Physics in 2021 and for Chemistry in 2024. The Nobel Prize for Physics was awarded to K. Hasselmann, S. Manabe, and G. Parisi for their analysis of complexity in material systems, biology and geo-physics. Parisi [5] demonstrates in his popular book on “In a Flight of Starlings” that the behaviour of flocks of starlings cannot be understood by analysing the movement of a single bird, ceteris paribus. It is necessary to study the patterns of interactions of birds to understand the movements of the flock and its reactions to exogenous changes, such as gusts of wind or the appearance of falcons. Hasselmann [6] and Manabe [7] demonstrate that it is necessary to analyse the dynamic interactions between many sub-systems of the atmosphere, of oceans, and of continental conditions for understanding and predicting the impacts of climate change and the rapprochement to tipping points.

The Nobel Prize 2024 for Chemistry, awarded to D. Baker, D. Hassabis and J.M. Jumper, acknowledges the big step of progress which was achieved for simulating the most complex biological process of the folding of proteins (see Aqvist [8]). The laureates developed new algorithms for stochastic simulation of dynamic folding processes and succeeded in designing new protein structures while increasing the accuracy of prediction to about 90%. Significant progress was made through the use artificial intelligence and machine learning.

This provides the background for analysing to which extent the theory of complex systems—as it has become an important research area in physics, chemistry, and biology—can provide important insights also for socio-economic systems and their development. Particularly, the transport sector is expected to be exposed to transformations, that require new paradigms for adjusting transport planning to manage the upcoming phase transition. We will discuss the properties of complex dynamics and their treatment in natural sciences in a general way for getting a better understanding of the needs of considering complexity in social systems, particularly the transport system. This means that we do not recommend replicating specific methods or models from natural science to socio-economics, as it was previously done with gravity and entropy concepts, or Newtonian mechanics decades ago. We will not go beyond useful metaphors, but this will be enough to generate suggestions for a fundamental change of the presently applied decision support concepts for the planning of transport systems.

After introducing to the topic in Section 1 (INTRODUCTION), we will give an overview of the general characteristics of complex systems and highlight some basic research findings in physics, chemistry, biology, and philosophy in Section 2 (COMPLEX SYSTEMS AND THE COMPLEXITY OF TRANSPORT SYSTEMS). We will show that—on an abstract level—the general dynamic features in human socio-economic systems are not much different from the general characteristics of complexity found in natural science. This leads to the focus on two fundamental evolutionary concepts that were developed in natural science to describe complex systems, which are important for the planning of human-made systems: Boundaries and folding. Boundaries are markers for the frontiers of a system's linear development, which can indicate tipping points or bifurcations. Going beyond boundaries implies a phase transition of the system towards existential risks that is not reversible. Folding describes adjustments of system components before reaching boundaries, which may cause complex dynamics that change the system's structure and orientation. This means that the evolution of the system does not stop when approaching boundaries but rather changes to feasible directions for improving its quality level.

Section 3 (CONSIDERING COMPLEXITY IN NATURAL SCIENCES) briefly discusses the current planning methods for transport systems and provides some examples of national and EU planning/evaluation schemes. It will be shown in Section 4 (NEGLECTION OF COMPLEXITY IN PRESENT TRANSPORT PLANNING) that the approaches described in present textbooks and guidelines and applied in practical master planning are not considering the complexity of the transport system, so that their results lead to the continuation of past trends and a linear trajectory towards tipping points. Section 5 (PRINCIPLES OF CONSIDERING COMPLEXITY IN TRANSPORT INFRASTRUCTURE PLANNING) analyses how the basic principles, learned from metaphors from natural evolution processes, can be transformed to the planning of human-made systems. The concepts of boundaries and folding of organic systems will be emphasised. In Section 6 (CHANGE OF THE TRANSPORT INFRASTRUCTURE PLANNING SCHEME FOR CONSIDERING COMPLEXITY), the consequences for transport planning are derived, particularly the introduction of a dynamic systems analysis for stochastic simulation of complex transport systems. Section 7 (ASSESSMENT METHODOLOGY) gives a discussion of basic findings while Section 8 (DISCUSSION OF RESULTS) and Section 9 (CONCLUSIONS) provide some conclusions for the orientation of future planning of transport systems.

COMPLEX SYSTEMS AND THE COMPLEXITY OF TRANSPORT SYSTEMS

Complex systems have characteristics that require appropriate approaches of research and consideration in planning. The main properties of complex systems will be defined, and the results will be used to analyse the complex nature of transport systems.

Properties of Complex Systems

The key concepts for analysing complex systems were developed in natural sciences such as physics, chemistry, or biology. They have gained attention in recent years and are receiving increasing resonance from other disciplines like philosophy or sociology (see Hooker et al. [9]). The main characteristics mentioned in most publications—which are partly overlapping—are (see Thurner et al. [10] or Skrimizea et al. [11]):

1) Adaptation and self-organisation

At least a substantial part of the system can change its elements or its structure without central interventions and adjust to changing external conditions.

2) Emergence and networks

The change of micro-elements in a system can stimulate corresponding movements of neighbouring elements and produce amplifying synergetic impacts, which may change the macro-state of the system and its dynamic orientation.

3) Dynamic feedback mechanisms and non-linearity

The interactions among elements generate positive or negative feedback mechanisms over time (self-enforcement or self-stabilisation) induced by exogenous changes. In the case of non-linear reaction functions, phenomena like fluctuations, hysteresis, and chaotic dynamics can occur.

4) Bifurcations, tipping points, and phase transitions

Bifurcations occur in non-linear systems if a small change of a parameter leads to a drastic and sudden change of the system's behaviour. A further increase in the parameter will then lead to a phase transition, i.e., to a development path that significantly and irreversibly deviates from the original path of the system. Tipping points indicate the configuration of parameters that cause phase transitions. Tipping points are particularly analysed in climate and biological research, e.g., critical temperature of oceans which leads to dying coral reefs or critical melting levels of Greenland and Antarctic ice sheets which may lead to a change of the Gulf Stream and of the Atlantic Ocean circulation.

These characteristics imply the following phenomena:

1) The dynamic development of a system can temporarily point to an equilibrium configuration. However, major changes to the system are induced by disequilibria, which can be regarded as dynamic engines for systems' development.
2) In principle, it is not possible, to predict the development trajectory of a complex system accurately. It is only possible to estimate probabilities.
3) The characteristics (1)–(4) explain the adaptation of decentrally organised systems to exogenous changes from the past or perceived signals from the present. However, they are not forward-looking and don't include precautionary mechanisms to prevent future bifurcations in system configurations that have not been observed before. The latter issue will require adding human intelligence, including forward-looking and precautionary actions to avoid or manage existential risks.

Complexity of Transport Systems

A transport system consists of infrastructure networks and a superstructure characterised by the activities of agents using the networks. The development of the superstructure is widely subject to individual decision-making of travellers and companies. In passenger transport, individual trip-making by car, bike or feet is dominating the public transport modes such as bus, rail, or air. In the latter case, private and public companies provide the supply of travel facilities while individual travellers decide on their choice of mode. They adjust decentrally to changing conditions within the superstructure system (e.g., the use of vehicle technology, or reactions to congestion) and to external influences (infrastructure supply, prices, taxes, and regulation). Insofar, the self-organising character of complex systems dominates on the superstructure. Highly non-linear interaction schemes can be observed on the micro-level, for example with the dynamics of vehicle flows. Traffic flow theory and micro-modelling of traffic behaviour are using instruments of non-linear dynamics which are also applied in complexity theory, see e.g., Hossain and Tanimoto [12]. Although the latter is not the object of our analysis, it presents the background for the basic proposition that transport systems show an inherent complexity.

Emergent processes can be observed in passenger transport, e.g., in the form of decentral adjustments to congestion or to infrastructure contingencies by an appropriate change of route or modal choices. However, emergent processes oriented to improved sustainability can hardly be observed in the sense that eco-friendly behaviour of individual agents show positive multiplying impacts on the entire transport system. On the contrary, the egoism of car drivers in passenger transport may lead to suboptimal speeds, wrong distance holding, or wrong adjustments to unstable flow conditions, so that problems of congestion, safety, and external costs increase. This means that an appropriate decision environment must be created, by regulation, pricing, and appropriate infrastructure supply, for motivating agents to adjust behaviour towards sustainability goals.

The same holds true for freight transport, which is dominated by trucking for land transport and by maritime shipping in terms of transported tons. The Marpol convention on maritime pollution has been adjusted since decades, but the recent regulations are still far from being implemented by the majority of shippers. The decentralised supply chain management for land transport works perfectly for minimising the individual costs of production, inventory holding, and transport for a single company. However, the competition among companies can lead to numerous uncoordinated services, such as uncoordinated just-in-time services for neighboured warehouses of different organisations, or parallel parcel services in cities. Therefore, there is a big potential for increased efficiency through better coordination among the agents through appropriate organisation (see Schwedinger [13]). Furthermore, there are little intrinsic market forces observed that strengthen environmentally preferable logistic alternatives and reduce transport activities with high carbon footprints. This can be influenced by the appropriate design of the decision-making environment.

The above suggests that emergent reactions on the microscale of the transport superstructure cannot work towards a sustainable configuration unless the agents receive appropriate signals from transport policy and from the infrastructure supply. In the present planning systems of most countries, however, the infrastructure development is planned based on past developments of the user demand, which is projected to the future according to the “predict and design” concept described by the ITF [4]. This projection uses statistical relationships between transport demand elements and exogenous drivers (gross domestic product (GDP), population, and technology). This causes—in most cases—a linear continuation of past trends. Exceptions from this general observation show that alternative planning schemes based on setting of clear objectives are successful but require a long time to achieve the desired impacts. Examples are the “biker city” Copenhagen or the “BRT city” Curitiba.

A brief historical look back to past transport development leads to the conclusion that the trajectories do not show bifurcations or major changes in trends in industrialised countries since World War II. Even the COVID-19 crisis has not led to a substantial phase transition because the usual behavioural and logistic patterns have been re-established for most components of transport demand (see Rothengatter et al. [2]) and not effected a long-term reduction of GHG emissions (see Figure 1). Thus, the question arises about why the transport system may become more complex in the future and may move towards a phase transition. The answer is that the needs for a drastic transformation of technological systems and the associated change in user behaviour will arise from the increasing challenges caused by the deterioration of climate conditions and of biodiversity.

The Intergovernmental Panel on Climate Change (IPCC) predictions of climate problems could change the belief that smooth adjustments—only interrupted by minor temporary disturbances—are enough to manage the global risks. The increase in the world temperature can only be controlled if the GHG emissions are reduced to almost zero (IPCC [14]); Levermann [15]). The contribution of the transport sector is about 23% worldwide (ITF [4] and about 24% in the EU (EU Statistical Pocketbook [16]), related to the year 2022. Contrasting other sectors, the GHG emissions of the transport sector have increased since 1990 in the EU and worldwide. The climate challenges have motivated 195 countries to sign the Paris Agreement on climate change in 2015 (20 years after the Kyoto Protocol) to keep the increase of world temperature below 2 ℃ and invest efforts to achieve even 1.5 ℃. According to ITF [4], this implies a drastic reduction of GHG emissions from about 12 to about 1.5 gigatons within 2 ½ decades until 2050.

Considering the slower pace of reduction in developing and emerging economies, the industrialised countries would have to approximate a zero-emission level in their transport sectors.

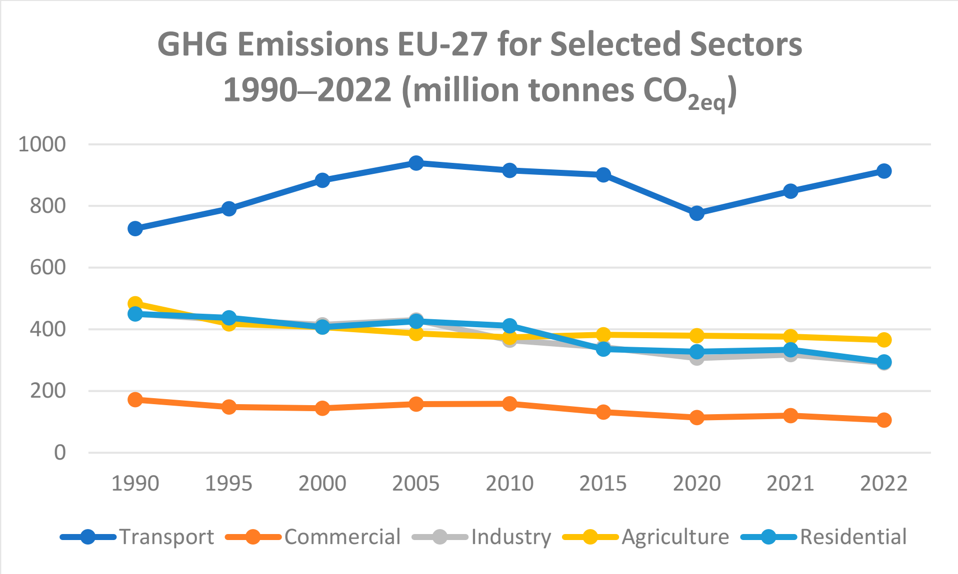

Figure 1. GHG-emissions of sectors in the EU 1990–2022. CO_{2eq}: Equivalent CO_2-emissions. Source: EU Statistical Pocketbook [16]. Complete tables and definitions of indicators can be found in [16].

Figure 1 demonstrates that even regions that are industrially advanced like the European Union are ways off from reaching this arduous objective, and that the transport sector is returning to the GHG emission path before the Covid-19 pandemics. The same holds for other parts of the world where the transport sector can be considered the biggest challenge for reducing GHG. The world community will have to choose among two options:

Option 1: Climate policy appears overly ambitious. Countries will not intensify their reduction policies so that global warming will reach 2.7 °C or higher (scenarios C3/C4 of the IPCC [14]). Under this condition, several tipping points will probably be approached or crossed, impacting phase transitions that will not be reversible. Examples are (see Levermann [15]):

- Accelerated melting of Greenland and Western Antarctic ice sheets. If the Greenland ice sheet loses 10%, the sea level will rise by 70 cm. The C8 scenario of IPCC (+3 °C until 2070; +4.2 °C until 2100) would even imply more than 1 m of sea level rise until 2100 (with a probability of 50%). Melting of ice sheets and glaciers is proceeding at higher speed than forecasted.
- Change of the Gulf Stream. The Gulf Stream may collapse in the future, causing a dramatic change in the continental climate regimes, a drastic reduction in temperature in the Northern Atlantic, and an increase in sea level.
- Change of the Atlantic Meridional Overturning Circulation (“AMOC”), which could drastically cool down the climate on the European continent. Some scientists argue that we are already close to such a tipping point (see Rahmstorf [17]; Ditlevsen and Ditlevsen [18]).
- Increase in catastrophic weather events, extension of arid areas, fire catastrophes and flood plains.

Option 2: Ambitious climate policy actions will not only be agreed upon at next climate conferences, but they will also be successfully implemented. This intends to limit the increase of world temperature to 1.5–2 °C until 2050. The economic and social implications have been described in many scenarios and summarised in the High Ambition scenario of the ITF [4]. Essentials are:

- The transport sector must achieve at least a 90% reduction of GHG worldwide by 2050 compared to 2030, which means almost 100% in industrialised countries. This implies a fundamental change in propulsion technology towards renewable electric energy, either using batteries, hydrogen, or synthetic fuels.
- Improvement of technology ("improve strategy") will not be enough. Production, distribution, and use of electrical energy (including the upcoming needs for artificial intelligence (AI) and cyber money) will cause further externalities so that a moderation of the growth of energy supply will be necessary despite the presently observed trends of rapidly increasing demand.
- A change in attitudes and behaviour in the transport sector is a necessary condition. Customers must accept and demand transport technology that has a zero-carbon footprint. Furthermore, "shift" and "avoid" strategies must be promoted in the transport sector, which involves significantly increasing the use of energy-efficient mass transport modes and utilising transport capacity more efficiently. (The improve/shift/avoid strategy has already been mentioned first in 1994 by the Enquête Commission of the German Parliament and can be found in many publications on sustainable transport (see GIZ [19]).

In the case of Option 1, nature will react with irreversible future phase transitions in natural and human-made systems. If tipping points are reached in the medium-term future, this will lead to phased impacts, initially limited to vulnerable regions, followed by massive continental changes. The living conditions of future generations will undergo to drastic changes. They will be forced to invest high amounts of resources to temporarily reduce severe impacts (e.g., through dike elevations) or to escape to less risk-exposed regions (e.g., by migration). The presently observed political rebound effects underline that Option 1 is not unrealistic, and the IPCC scenario C3, assuming continuation of climate policy according to the past trend and leading to a +2.7 °C world temperature increase, may be even too optimistic.

Option 2 will require a drastic change of technology, travel behaviour and logistics in the transport sector, which can be interpreted as human-made precautionary phase transitions for avoiding future phase transitions of nature. Many international agreements and national initiatives have been developed to meet the global challenge of reducing climate change and other environmental risk (e.g., The Paris Agreement from 2015). Following the internationally agreed goal of limiting the increase of world temperature to 1.5–2 °C, the EU Commission [20] has published the “Green Deal” initiative and the “Sustainable and Smart Mobility Strategy” together with a detailed action plan, and the ITF [4] has developed a comprehensive description of changes, which are necessary in a “high ambition scenario”.

In the following section we will give examples of the way nature is coping with complex problems and how this is analysed in natural sciences.

CONSIDERING COMPLEXITY IN NATURAL SCIENCES

Two concepts of complexity research in natural science are providing useful metaphors for planning and managing economic and transport systems: Boundaries for defining a sustainability space for systems development and folding for characterising decentral interactions of elements towards sustainable development paths.

Boundaries

“Boundaries” and “folding” are two core concepts analysed in natural sciences for studying the way in which natural systems handle complex problems. Rockström [21] and Levermann [15]—both directors of the Potsdam Institute for Climate Impact Research—are protagonists for both research directions. In the history of evolution, changing geological and geothermal conditions, as well as catastrophic events have formed boundaries for the living organisms, which have forced adaptation or mutation. This metaphor suggests studying existential boundaries for the future development and the risks of crossing boundaries.

Boundary research has received interdisciplinary echoes, particularly through the periodicals published by the Stockholm Resilience Centre since 2009 (Rockström et al. [21]). The authors define 9 essential boundaries, which characterise stable and resilient development for mankind on the planet. According to their research, three boundaries were crossed in 2009, four in 2015, and six in 2023. GHG concentration in the atmosphere is one of the critical indicators but not the only one, which is underlined by investigating the complex interactions of bio-physical processes, as for instance with respect to climate and biodiversity interchange.

The work of Hasselmann [6], Manabe et al. [7], and many other researchers contributing to the scenarios of the IPCC [14] in the past decades, focuses on GHG concentration in the atmosphere, climate change and its impacts on meteorological, geological, and biological conditions in all regions of the world. Climate change impacts are interrelated with those from other boundary crossings and are often—also in this paper—used as a leading indicator for the existential risks associated with boundary crossings.

The reaction of biological systems to the rapprochement towards boundaries is adaptation and mutation. Species that were incapable of making such changes disappeared. The human species has neglected this challenge for a long time, and risk-ignorant political as well as economic influential leaders are propagating visionary future technologies (e.g., capturing and storing of all future CO_2 emissions, Geo-engineering) or the option of migrating to other planets (e.g., space colonisation on the planet Mars). However, most scientists prefer preserving conditions on planet Earth, that ensure mankind's survival in a sustainable natural environment. This requires medium-term transformations of technology and behaviour, of which the principles can be learned from the natural processes of folding.

Folding

Levermann [15] argues that the concept of "folding" is fundamental for finding good solutions to the issue of respecting boundaries in a world of increasing challenges for economic and social development. "Folding" can be understood in a mathematical, computational or a biological context. In mathematics, folding is an operator that converts two functions into a third function. This is applied in statistics to replace functional values of two functions with their weighted average values, which has applications in stochastics, neuronal networks and machine learning. In computer science, computational "origami folding" has developed into a branch of research that studies the options for designing final objects successively from an initial configuration.

The study of biological folding has been ongoing for approximately 100 years while the last 50 years have focused on simulating the process of transformation of proteins from one-dimensional amino acid sequences to three-dimensional polypeptides. The resulting proteins (the "native state" of the folding process) provide a variety of functions in organic systems. In human bodies, proteins deliver the sources of energy and contribute to the functioning of muscles, organs, and blood flow. Folding of proteins is a process with a very high degree of complexity, and it was found early by Levinthal that the number of possible combinations is huge so that it is impossible to enumerate all of them in the transformation process from the initial to the final "native" state ("Levinthal paradox", see Shakhnovich [22]). Therefore, it has been a challenge for physics, chemistry, and biology, along with advanced computer science, to study how this complexity problem can be solved.

Essential characteristics of protein folding are (Shakhnovich [22] and Aqvist [8]):

1) The "native" state is characterised by a conformation of molecules that comes close to minimising (free) energy. Free or Helmholtz energy corresponds to the thermodynamic potential of a system.
2) The process is guided—but not completely controlled—by genetic DNA codes, which means, it can take alternative pathways that are found by (decentral) emergent mechanisms characterised by interactions,

neighbourhood effects and affinities. For instance, it is affected by hydrophobic properties which influence the positions chosen by amino sequences.

3) The process is supervised by “chaperones” which correct misfolding and sticking within local energy minima. (This notation is derived from the French “chaperon” which denotes elderly ladies watching the rules of courtesy and institutional etiquettes).
4) Conformations can be changed by “allosteric regulation”, which means that selection pressure or changes in external ambient conditions may lead to changes in dynamic processes and the final functioning of proteins. This opens the door for adaptation and mutation of biological systems.

Understanding and computational simulation of the protein folding processes are known as the “50-year-old grand challenge in biology” (see Aqvist [8]). In the past decades, only modest success for simulating the folding processes has been achieved by combining conventional methods of stochastics (Monte Carlo chains) and optimisation heuristics (e.g., simulated annealing; see Cymerman et al. [23] or Scholz [24]). The work of the 2024 Nobel laureates for chemistry provided a breakthrough in understanding and simulating the protein folding processes through combining stochastic simulation with artificial intelligence algorithms, which were trained by data of a rich protein data bank. D. Baker succeeded in designing advanced protein structures and their functions by developing the “Rosetta” software (see Rohl, C.A. et al. [25]. D. Hassabis and J.M. Jumper developed the “AlphaFold 2” software for simulating the dynamic process of protein folding with a high prediction accuracy of about 90% (see Jumper et al. [26]).

Biological folding offers intriguing analogies for phenomena observed in the superstructure of economic and transport systems. Examples are:

1) Mental association between a native state and a high quality of social life configuration or an economic welfare optimum.
2) A variety of potential dynamic paths to the optimum state, which are characterised by probability distributions.
3) Non-zero probability that processes go to the wrong direction and are not effectively corrected. In the case of human protein folding, serious health problems may follow from misfolding, as for instance neuro-degenerative disease like Parkinson. In the macro-world we can observe crises of the macro-economy or breakdown of transport infrastructure systems following planning failures or overuse.
4) Emergent reactions to changes of ambient conditions that force adjustments or radical transformations of system components and their functionality. Smog in cities gives an example which is widely overcome in industrialised countries but still a big problem in big cities of emerging economies.

Example (4) reintroduces us to the concept of boundaries. Boundaries form the ambient conditions for the development of the superstructure of the transport system. Folding processes within boundaries are sustainable and can increase the system's functionality. Crossing boundaries may induce phase transitions that are not reversible and induce unpredictable impacts.

NEGLECTION OF COMPLEXITY IN PRESENT TRANSPORT PLANNING

The conventional assessment of transport investments is widely standardised and described in many pieces of the literature (for instance Blauwens et al. [27] or Mishan and Quah [28]), and in guidelines (for instance: EU Commission [29]) or standardised country evaluation methods (for instance in France (Quinet Report, [30]) or in Germany (BVWP 2030 [31])).

The assessment process involves two steps: forecasting and project impact analysis/evaluation. The standard evaluation methods for transport planning are generally deterministic and extrapolate past trends. Complexity is widely ignored.

Transportation Analysis and Forecasting

Analysis and forecasting of transport demand are usually based on the "four-step-procedure" of traffic generation, distribution, modal split, and assignment. The first step of transport analysis investigates the dependency of transport activities on exogenous demographic, socio-economic, technological, and political interventions (public pricing or regulation). Descriptive and explanatory statistics are applied, as well as simulation or optimisation techniques. The forecasting approach then consists of estimating the development of exogenous drivers (e.g., population, GDP, technology) and calculating the future transport activities by using the estimated statistical relationships based on time series or cross-section data of the past. This procedure applies to all infrastructure investment candidates so that project-relevant data on future generation, distribution, modal split, and assignment are generated which are inputs for the project evaluation.

Project Impact Analysis and Evaluation

In many countries, a welfare-based cost-benefit analysis is applied on the project level, starting from the surplus concept of Alfred Marshall [1], intending a maximisation of consumer's surpluses. Consumer's surplus is defined as the sum of payments, which consumers are willing to pay beyond the market-price and can be measured by using demand and marginal cost curves. The concept is based on neoclassical welfare theory, assuming a set of rigid assumptions on individual decision behaviour ("homo oeconomicus") and the configuration and situation of markets ("polypolistic" markets with perfect competition). The reference situation is a global equilibrium for all markets except for the transport market, so that it is only necessary to analyse the changes induced by infrastructure investment in the transport market, ceteris paribus.

The assessed projects are assumed to be independent of each other. The impact measurement is performed "with" and "without" the project candidate for a future year. As the measurement of surpluses requires—mostly not available—quantitative information on the demand functions, it is often replaced by approximations using the differentials of generalised costs (time and operation costs of users), plus savings of external costs caused by the considered project. Practical applications and solutions to problems arising can be found in BVWP 2030 [31] and Intraplan et al. [32]. The data generated by project-related forecasts (Section 4.1 (Transportation Analysis and Forecasting)) are used for a monetary evaluation of the benefit components (time, operation costs, and external costs), which are finally aggregated to benefit/cost ratios or differences (e.g., EU Commission [29]). The selected projects form the basis for the transport investment plan. The approach is deterministic, i.e., only one future outcome is considered for the variables and for the transport system.

Time and operation costs represent the heart of the benefit measurement. This is demonstrated by Figure 2, which shows the share of benefit components for road evaluations in the German Federal Transport Master Plan (BVWP 2030 [31]). The savings of travel time and operating costs make up 87.7% of total benefits of road investments while the impact on climate is negative (−3.3%).

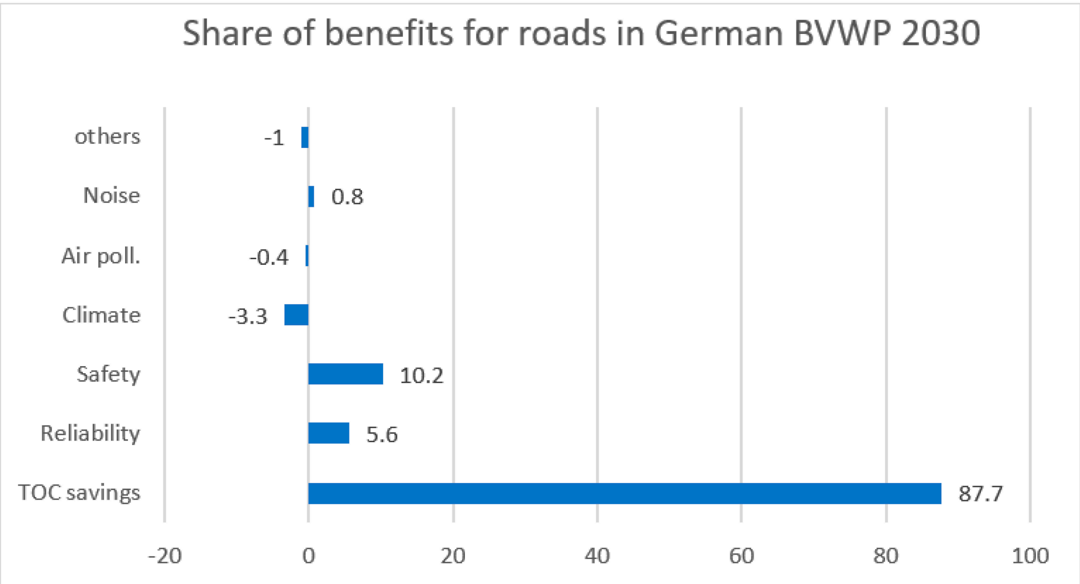

Figure 2. Share of benefit components for roads in the German BVWP 2030 (%). TOC: time and operation costs; Air poll: Air pollution. Source: BUND [33].

The evaluation of climate costs of transport has started from a very low level in the 1990s. The Stern Review [34], which resulted in a CO_2-price of

85 $/ton, was even regarded as an upward outlier by neoclassical economists at that time. The EU Handbook [35] suggested 100 EUR/ton for short and 269 EUR for long-term, whereas the German Federal Environmental Agency (UBA [36]) recently recommended 435 EUR/ton with a discount rate of 1% and 1080 EUR/ton without discounting for the year 2050. The difference between figures with and without discounting highlights a fundamental problem with climate monetisation. The damages will occur in future decades or even centuries and applying a discount rate implies drastically reducing the long-term impacts. Therefore, a discount rate may be interpreted as a rate of rapacity of the present generation versus future generations. This was first argued by Harrod [37] and revived by Brumby and Clautier [38]. Future risk is devalued, although it is expected to increase.

Contrasting the recently higher estimations for climate costs in environmental studies, the CO_2 certificate price for the ETS (European Trading System) is only about 75 EUR/ton (not including the transport sector), while in Germany the transport sector is included in the certification starting with 55 EUR/ton in 2025. These figures are far below the levels, which could significantly influence transport behaviour, but in other parts of the world, CO_2-emissions are not priced at all.

The shares of benefit components shown in Figure 2 indicate that climate change and other existential risks currently play an almost negligible role in conventional cost-benefit analysis (CBA). Investments in climate-efficient modes like railways or investments into electrical charging stations—which would require high investments to generate changes in the decision environment of users—have little chance of achieving high CBA rankings. From this follows that the predicted growth of transport modes, derived from econometric estimations based on time series or cross-section data of the past, is driving the infrastructure development to the future according to past trends without considering the increasing risks described by Option 1.

PRINCIPLES OF CONSIDERING COMPLEXITY IN TRANSPORT INFRASTRUCTURE PLANNING

The above description of project impact assessment relates to the standard component of CBA, which can be found in most country applications. However, many countries have developed variants or extensions of conventional CBA. This involves considering wider economic impacts (e.g., UK), additional environmental criteria, which are not evaluated in monetary terms (e.g., Germany), integrating CBA into a multi-criteria analysis (e.g., Switzerland), or applying a systems analysis (e.g., New Zealand). CBA can also be extended by applying computed general equilibrium modelling (e.g., Australia). The EU Commission requests that consultancies in charge of assessing large transport projects or policy interventions should add a system analysis on top of a CBA.

Nevertheless, most country-based assessment approaches in the Organisation for Economic Co-operation and Development (OECD) are related to projects and not to comprehensive system configurations, and they are based on growth predictions using time series of past developments. Therefore, a revision of the infrastructure planning algorithm is suggested that takes into account the lessons learned from complexity research in natural science.

Stochastic System's Approach Replacing Deterministic Project-Based Assessment

A basic lesson to be learned from complexity research in natural sciences is placing a dynamic system's analysis into the core of the planning methodology. Parisi's observations on starling movement highlight the significance of considering the interactions of birds in a flock. Hasselmann's and Manabe's findings provided quantitative insights into the interactions between GHG-concentrations, world temperature, weather, and various tipping points. The studies on protein folding illuminate the huge variety of interactions of molecules and their amino sequences for approaching the "native state", which provides the functionality of organic processes.

From this follows that considering the complexity in transport infrastructure planning requires:

- A dynamic system's analysis including the basic interactions between system components: Internal, i.e., within the transport system, and external, i.e., between the transport system and other systems (economic sectors, environment, social system).
- A stochastic approach, which replaces the cause-effect paradigm with a probability paradigm.

The neoclassical assumptions of CBA do not take into account such basic requirements. Economic research in the past has already addressed these weaknesses (e.g., Keynes' psychological theory of business cycles (Keynes [39]), Schumpeter's theory of economic dynamics and creative disruptions (Schumpeter [40]), Kahneman's theory of thinking fast and slow (Kahneman et al. [41])), but they could not replace the mainstream of neoclassic and are not found in the literature on CBA. Recently, the acknowledgement of observation-based theory of economic behaviour has gained greater acceptance. For instance, the Nobel Memorial Prize for Economics 2017 was awarded to R.H. Thaler, who demonstrated how real human behaviour is deviating from the axiomatic neoclassical approach (Thaler [42]). Human decision-making is heavily influenced by the social context (interactions between family members, friends, and neighbours) and social media (preferred information sources), and can hardly be changed without changing the communication flows from this decision environment.

Constructing a Sustainability Space from Boundaries

Transposing the concept of boundaries into transport infrastructure planning results in setting long-term global constraints to

- GHG emissions (e.g., approaching zero emissions).
- Biodiversity conservation (e.g., no deterioration, effective compensation measures, World Health Organisation (WHO) or Strategic Environmental Assessment (SEA) limit values, EU Directive 2001/42/EC).
- Air pollution concentrations (e.g., WHO limit values).
- High safety risk (e.g., >50% reduction of fatalities in the next 25 years).

Such constraints can virtually form a sustainability space. Sustainable infrastructure development plans would be located within this space. Figure 3 provides a simple numerical example for the graphical representation of a sustainability space. It illustrates the distances between the present situation and future scenarios according to trend development and to constraint settings (normalised on a scale between 1 (ideal) and 10 (most pessimistic)). The distances indicate the major challenges for infrastructure planning for approaching a sustainability path.

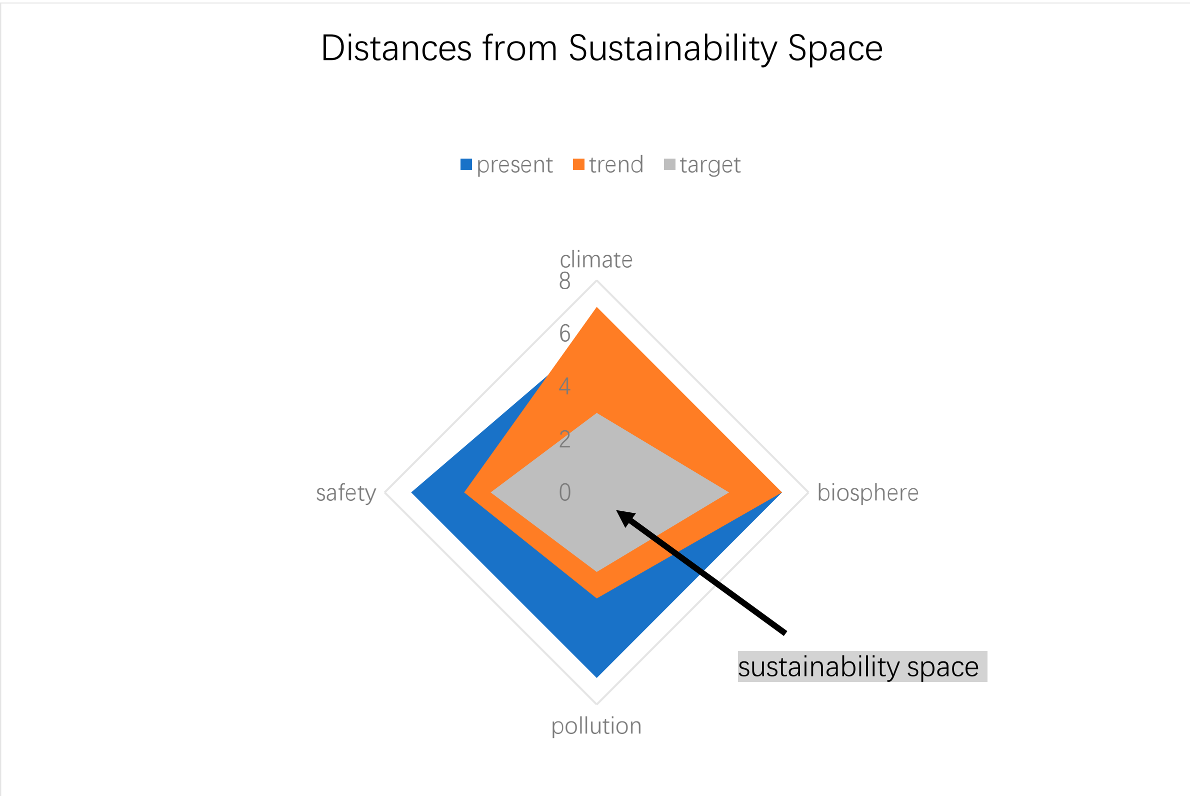

Figure 3. Sustainability space and distances to present and trend situation.

It could be argued that the boundaries mentioned are reflected in the cost values for external diseconomies as suggested in CBA manuals. But it can be questioned whether existential risks such as long-term climate change impacts or losses of biodiversity can be traded off by monetary compensations. However, it is a principle of CBA to monetise all impacts so that, for instance, health impacts or fatalities of exposed people can be compensated by high time savings of users. Nevertheless, pricing is an effective—but not sufficient—instrument for influencing decisions of agents on the superstructure.

Folding as a Metaphor for a Successful Adjustment Process

While the setting of boundaries appears necessary in the context of infrastructure planning to consider existential risks appropriately, avoiding boundary crossings requires an adequate adjustment of human behaviour on the superstructure. The protein folding metaphor illustrates that this does not presuppose following a central planning code, but rather requires the active, decentral interaction of elements in an emergent process. This means for social systems:

- Common acceptance of the general goals and of the path directions to their achievement.
- Flexible application of legal regulation and pricing instruments that are considered socially balanced, fair and efficient.
- Effective control mechanisms to avoid leakages, which could result in potential profits for non-followers.
- Support of emergent (bottom-up) processes through information, communication, and campaigns.
- Appropriate design of the decision environment, such as provision of infrastructure and public services, based on a long-term consistent strategy. Other types of infrastructure such as electrical charging stations or communications systems for automatic driving on roads could be included into a transport master plan, while the traditional linear expansion strategy for road infrastructure could be stopped.

The metaphor of protein folding shows that emergent processes towards a “native state” require a synchronising of individual elements, which decentrally discover better possibilities for adjusting to changing ambient conditions. This implies for social systems that people must not be enforced rather than convinced so that interactions in the small are initiated, which find societal acceptance and further dissemination in the large. While natural systems react to perceived signals, the human species may be assumed intelligent enough for including long-term precautionary outlooks into their present decision environment.

This presupposes that people don’t interpret their contribution to the transformation process as a sacrifice. Pricing of external diseconomies (climate, pollution, accidents) is an important instrument to set incentives right, but—contrasting neoclassical economic theory—pricing cannot serve as the only instrument rather than must be integrated into a bundle of measures including appropriate infrastructure supply. Such bundles can be designed depending on country preferences and may include pricing of the consumption of fossil energy, vehicle taxation, parking regulations, subsidies for the purchase of electrical cars and trucks, as well as subsidies for public transport and shuttle services to stations. The continuity of these measures over the long term is more important than the severity of a single temporary measure.

The success of Scandinavian countries in convincing households, industry, and transport users to apply low-carbon technology illustrates that transparent long-term public planning concepts are needed for starting social diffusion processes, which are carried on by individual social contacts and communication. For example, the number of installed heat pumps per 1000 households is 69/62/39/30 in Finland/Norway /Sweden/Denmark while it is 7 in Germany. In Norway, 89% of newly licensed cars in 2024 are electric cars. The biking share of transport modes in the central area of Copenhagen is 50%.

The contrasting last years' political attempts in other countries of Europe and in the US by pushing fast transformations in the superstructure of technology and behaviour show that people may feel overburdened with too many changes of their daily life and become afraid of green sacrifice and dictatorship. Therefore, compensatory measures (e.g., fee and dividend payments) and permanent positive feedbacking demonstrating individual economic benefits are necessary in the short and medium run to increase confidence in the long-term strategy starting emergent societal processes.

It follows from this observation that the transformation process in the transport sector should start with changing the decision environment, particularly providing good alternatives, e.g., enough electrical charging stations on roads, better quality of public transport, improving the door-to-door service for public transport, modest but continuous increase of prices for fossil fuels. State policy—following the folding metaphor—should refrain from detailed rules of conduct for users and leave to them the choice of alternatives.

CHANGE OF THE TRANSPORT INFRASTRUCTURE PLANNING SCHEME FOR CONSIDERING COMPLEXITY

While metaphors from nature observations are helpful for understanding complexity, it is important to keep in mind the differences between the objects studied. Animals like birds or fish in the ocean can spontaneously move into three-dimensional directions. Travellers and logistic companies in human systems generally plan their mobility deliberately and are constrained by the available network infrastructure. This is considered in transport planning by using a transport model, which includes networks for all modes that can be chosen, i.e., road, rail, and air for passenger transport, and additionally waterways for freight transport. Transport models are generating data on traffic generation/attraction, choices of destination, choices of modal split and choices of routes in the modal networks. These data are processed in the sequence of transport planning stages.

Four Stages of Transport Infrastructure Planning

An appropriate general planning concept would consist of four interrelated stages: (1) strategic foundation, (2) system design, (3) project selection, and (4) project budgeting. The main change compared with traditional planning schemes consists of placing the system's design into the heart of the planning algorithm. The designed configurations of the transport system can be checked in this phase to ensure that they achieve essential goals before evaluating single projects in detail.

The above steps can run through some feedback loops, which end with tentative project lists and prioritisation schemes fulfilling, at the end, the set of goals and their specific targets. It is important from the environmental point of view that the strategic environmental assessment (SEA) is included as well in step (2) on the network level as in step (3) on the project level. The detailed design of projects should ensure that the environmental targets are met. Step (4) is important for excluding the possibility that projects that cannot be implemented within the fiscal planning period for financial reasons, are automatically carried on to the next fiscal period. As the assumptions on future exogenous (essentially unpredictable) developments can change the planning inputs, the process should be revised in medium-term intervals according to the principle of rolling investment planning.

Assessment Methodology

Assessment of system development

As the main issue of systems evaluation consists in constructing infrastructure configurations, that guide the transport system towards and in keeping it within sustainability boundaries, the focus of the methodology lies on dynamics and interaction modelling. This implies:

- Definition of global boundaries and constructing a sustainability space (see Section 5.2 (Constructing a Sustainability Space from Boundaries));
- Determining of corridors leading to the sustainability space on the network scale and identifying improved positions for the transport system through the provision of appropriate infrastructure;
- Designing feasible system configurations by modelling the interactions and dynamic feedback loops of the transport sector with economic, environmental, and social systems.

Systems analysis is a suitable interdisciplinary method for simulating the interactions of elements in a holistic context. Bertalanffy [43] was one of the founders of the general systems theory, its mathematical modelling, and its applications to biology, cybernetics, and other fields. System dynamics was developed by Forrester [44] and applied for preparing the world model of Meadows et al. [45] for the Club of Rome. Schade [46] developed the large system dynamics model ASTRA (Assessment of Transport Strategies), which includes all EU countries and regions. It models the interactions between transport, the economy, the environment, and the technological development until 2050 (see www.astra-model.eu). System dynamics integrates cybernetics, decision theory, numerical simulation, and mental creativity. This provides the possibility of simulating interaction processes between the transport sector and other sectors, and forecasting them to a long-term future, subject to changes of the decision environment for the agents during the planning horizon. System dynamics modelling is particularly appropriate for studying breaks of trends as they are expected in a future phase of economic transformation.

Systems analysis does not require a detailed modelling of project design, including specific geographical parameters for the alignments. A functional description of project properties will be sufficient. This is important insofar as the issue of integrating complexity implies the construction of many feedback loops and the generation of alternative development paths, which finally can be assessed by multi-criteria analysis or other methods. The generation of data inputs for the assessment of future systems configurations requires the application of a host of sub-models, which can be run on a common digital platform ("integrated assessment modelling, IAM", see Rothengatter [47]).

The analysis of complex system dynamics in natural sciences has resulted in remarkable progress with respect to dynamic stochastic simulation models calibrated by artificial intelligence (AI). This can show the direction for future research on IAM applications in the transport sector. However, basic principles of considering complexity can already be integrated into existing models using system dynamics or agent modelling. System dynamics can be extended by integrating Monte Carlo simulation to incorporate stochastic elements into the dynamic feedback processes (see Brun [48]).

Assessment of projects

Only projects, that are compatible with the functional results of the systems analysis should enter the evaluation phase, i.e., if they are promising in moving the system towards or achieving better positions within the sustainability space. As projects are not specified in detail in the systems' analysis, it will be necessary to start with a detailed specification of alignment and design parameters and a detailed network modelling. Often, there are several planning alternatives that may be suitable for meeting the functional requirements, but with different achievement levels for the sub-goals. Therefore, a first step of project evaluation consists in a selecting among project alternatives.

The concept of using boundaries for essential goals instead of prices or weights can be utilised for an initial elimination of candidate projects. It is possible to check projects by a set of "safe minimum" levels, which should be achieved by considering regional and local conditions for limiting environmental and human risk, based on SEA and WHO limit values. For instance, projects that are expected to increase GHG emissions could be excluded. This exclusion principle is for instance applied in Austrian planning for express road projects.

Projects that have passed the "safe minimum" thresholds, then can be assessed either by cost-benefits analysis (CBA) or by multi-criteria analysis (MCA). CBA is required in the fiscal legacy of many countries and can in principle follow the evaluation schemes required by the country regulations. Some revisions could be considered, such as not considering time savings, which are not economically usable, while increasing the weight of quality criteria such as punctuality, reliability, or resilience. Time spent on mobility is not in any case lost time which should be minimised in any case. For instance, more than one-half of business travellers in Germany are using the on-board time in railways for business activities.

Alternatively, or in addition to the CBA, an MCA could stress quality-of-life improvement including non-users (see Hayashi et al. [49]).

Feedback loops and decision support

Final feasibility checks, and feedback loops will be necessary, which may change the priority list or motivate changes in the design parameters of the projects. As exact predictions and numerical optimisations fail in the case of complex systems, the recommended simulation or system dynamics modelling could result in a few alternative system development paths. A final evaluation of these alternatives could be carried out by a committee of independent experts, who would prepare a recommendation for the transport master plan of the responsible ministry. The increasing complexity, which is expected for the transport system in the future, would give rise to apply a rolling planning scheme, repeating and updating the planning steps periodically, and to establish a standing committee of experts for preparing the decision for the policymakers.

DISCUSSION OF RESULTS

In natural sciences, the investigation of tipping points, phase transitions, and complex dynamics has been a subject of intense research for decades. Linear one-directional developments of natural systems are limited by boundaries, for which crossings cause bifurcations. This can be transferred to the transport sector by defining boundaries for long-term existential risks as rigid constraints in transport infrastructure planning. Since the potential damages caused by existential risks cannot be traded off with money compensations, it is suggested to construct a sustainability space by explicitly setting boundaries as constraints for the system's development. This applies, for instance, to reducing GHG emissions and intrusions of biodiversity.

Another area of biophysical research, which can be used as a metaphor for complex transformation processes, is the folding process in organisms for generating functional proteins. This process, generally guided by genetic code but partly decentralised allowing for adaptation and mutation, gives rise to studying similar phenomena in human systems like transport. It finds a parallel in transport systems in that individual decisions and interactions at the micro-level of the transport superstructure may influence the direction of the system's development. It is necessary to set incentives right that motivate individuals to make deliberate decisions in the small, which then may be synchronised with many other users to generate sustainable solutions in the large. This implies introducing a bundle of measures—adjusted to country conditions—which are reliably applied over a long time-period instead of forcing a fast change of behaviour by single rigid measures.

Transport infrastructure development is planned in many countries based on a project-oriented assessment using a "predict-design" approach, which projects the past development to the future. Time and cost savings are the main benefit criteria of standard cost-benefit analysis, while existential risks stemming from climate change, damaged biodiversity, and other externalities, are undervalued. Complexity in terms of dynamic non-linear interactions between system components is widely neglected, so that changes in trends, which are necessary for achieving socially desired transformations of economic sectors, are not considered.

The metaphors derived from the natural sciences give strong indications that following the historical appraisal philosophy will accelerate the path to approaching tipping points, which may lead to crossings of existential boundaries. Therefore, it is suggested to:

- base the project-oriented assessment upon an integrated dynamic systems analysis that includes the interactions between transport, the economy, the environment, and the social system,
- introduce explicit boundaries into the assessment of systems development and establish a sustainability space for transport infrastructure configurations,
- introduce constraints on the level of project assessment for existential risks (e.g., exclude projects generating higher GHG emissions or producing higher risk or regional and local biodiversity), and
- apply a bundle of incentive-compatible instruments to stimulate emergent reactions of individuals and organisations. Prices for internalisation of externalities play an important role but compensations are needed for avoiding socially unfair allocations of burdens.

The basic tools for transformation of appraisal methodology are existing. Nevertheless, the advancement in complexity modelling in natural science indicates that there is still unexplored potential for modelling micro-macro interactions in social systems. Therefore, future research could focus on using AI to better integrate decision making of individuals and groups into micro-based stochastic simulations of future transport system configurations.

CONCLUSIONS

The results of the paper, summarised by the bullet points in Section 8 (DISCUSSION OF RESULTS), appear heterogenous: While it is suggested to introduce rigid constraints for considering the existential boundaries in the case of infrastructure planning, the behaviour of agents on the superstructure should be influenced by bundles of moderately designed instruments beyond the provided changes of infrastructure supply. The principle is to stimulate voluntary adjustments in the small to achieve emergence impacts in the large. Rigid and ambitious policies—as they are often suggested by environmentalists based on backcasting from future ideal configurations—are exposed to high risk of failure in democracies due to missing acceptance. Preferences for climate and the environment are volatile, and expert warnings find different echoes. Therefore, long-term continuity of a bundle of soft policy measures can be more efficient than introducing rigid interventions for a short period.

While an elite class in democratic societies is fighting against climate policies for defending their profit interests, the low-income class is afraid of green dictatorship of the intellectuals and of taking the risk of green transformation by losses of jobs and income. Therefore, the lessons learned from analysing emergent processes in biological systems suggest first creating a broad societal confidence that zero-carbon technology will pay in the future and negative distributional impacts will be avoided or compensated. "Working class environmentalism" (Bell [50]) may be a key for increasing a broad acceptance of sustainable planning paradigms. This will presuppose translating the basic principles of coping with complexity into uncomplicated and concise messages like "stopping mankind from cooking the planet Earth" (Andrew McAfee [51]) and following the advice of Albert Einstein [52]: "Look into nature, and then you will understand everything better".

DATA AVAILABILITY

No data were generated from this study.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interest.

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How to cite this article:
Rothengatter W. Planning of Transport Systems under Increasing Complexity—Looking into Nature. J Sustain Res. 2025;7(2):e250023. https://doi.org/10.20900/jsr20250023