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CHAPTER 12

MODELLING THE DECARBONISATION AND DIGITALISATION TRANSITION IN LOGISTICS SYSTEMS

Jonathan Köhler[a], Clemens Brauer[a] and Lóránt Tavasszy[b]

[a]*Fraunhofer ISI, Germany*
[b]*Delft University of Technology, The Netherlands*

ABSTRACT

The most important development in shaping the future of logistics is digitalisation, but while digitalisation and decarbonisation are extensively discussed in industry and scientific literature, there are no comprehensive visions of a digitalised, decarbonised logistics system. This chapter addresses the challenges of this transition management process, by framing and illustrating it with quantified scenarios for the future. As a starting point for the autonomous evolution of logistics systems, i.e., without considering politically driven decarbonisation targets, we take the vision of the physical internet. We critically assess this vision with respect to its potential to autonomously bring about the desired levels of decarbonisation. The remaining gap towards targets needs to be actively managed. We develop a transition scenario to complement the physical internet with decarbonisation incentives and assess their combined deployment in the freight system using a quantitative model that simulates transitions in the logistics system.

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We find that specific combinations of digitalisation and decarbonisation incentives are needed to achieve long-term targets.

Keywords: Freight transportation; climate mitigation; decarbonisation; physical internet; digitalisation; transition management

INTRODUCTION: THE DIGITALISATION–DECARBONISATION TWIN TRANSITION IN LOGISTICS

The freight transport and logistics industry has entered a period of transformation. Increased logistics efficiency and reductions in transport costs have enabled the continuing growth of global supply chains and demand for logistics services. This globalisation process is combined with the development of digital technologies that are transforming market structures and logistics business models.

Logistics practitioners are developing new trend analyses and visions to show how these drivers will cause innovations in logistics that change business and transport systems structures. ALICE AISBL (2017) places a push to low carbon, low energy, and the circular economy as a first major trend, with rapid technology developments in 'Industry 4.0 and 3D printing, automation, robotics, IoT, Big Data, Future Internet, machine learning and connectivity' (ALICE AISBL, 2017, p. 18). DHL (2021) argues that innovation in logistics has rapidly increased in the two years since their previous trend report. Some major developments are omni-channel logistics for extended customer services, a move towards zero emissions logistics, digital technologies (blockchain, artificial intelligence (AI), internet of things (IoT)), robotics, and automation in logistics systems. The World Economic Forum (2016) identifies e-commerce giving consumers more possibilities. These include logistics control towers, data analytics as a service, digital international logistics platforms, autonomous vehicles and drones for delivery, three-dimensional (3D) printing and crowdsourcing for production and logistics processes, the circular economy and shared logistics assets as themes of the digital transformation of logistics, with an estimated potential of $1.5 trillion in value for the logistics industry. New logistics concepts such as synchro-modality (Giusti et al., 2019), logistics control towers (Alias et al., 2015), and the physical internet (Montreuil, 2011) have been introduced to implement these changes. Ideas for new or newly combined transport modes – e.g., cargo sous terrain, bicycle/e-vehicle freight transport, intermodality, and shared mobility – are being proposed whose benefits cannot be fully assessed with current tools and methods.

At the same time, the environmental impacts of logistics have become a central theme. The IPCC AR6 report assessed the greenhouse gas (GHG) emissions of transport:

> Meeting climate mitigation goals would require transformative changes in the transport sector. In 2019, direct GHG emissions from the transport sector were 8.7 GtCO2-eq (up from 5.0 GtCO2-eq in 1990) and accounted for 23% of global energy-related CO2 emissions. Road

> vehicles accounted for 70% of direct transport emissions … Freight travel activity grew across the globe by 68% in the last two decades. Growth has been particularly rapid in heavy-duty road freight transport. (Jaramillo et al., 2023, pp. 251–252)

Freight transport flows and emissions are continuously growing due to increasing demand for transport (rising population and consumption, ongoing globalisation) and an increasing fragmentation of flows (individualisation of services, growing complexity of supply chains). It is difficult to make changes in the system as there are few built-in incentives to decarbonise, and costs and service quality considerations dominate supply chain decisions. Also, there is a strong inertia in the system due to its many assets, slow processes of changes in business culture, and distributed responsibilities. Digitalisation drives or supports most of these developments which could lead to increased emissions. Although it is true that digitalisation also increases transport efficiency, which should allow more growth with less energy, it is not expected to be sufficiently strong to allow the system to achieve its decarbonisation targets without intervention.

These far-reaching innovations are changing the structure of transport systems and markets. They will generate new needs for risk analysis and assessment of socio-economic impacts. The trends towards new (mostly big) data generation and analysis require the development of new methods and tools for analysis. The need to deploy new technologies to achieve decarbonisation through, for example, electrification of transport systems and the development of autonomous vehicles requires new assessments of how to manage and optimise transport systems. New issues for research, freight transport policy analysis, and transport planning arise from these.

In order to achieve its decarbonisation targets, the system should be directed towards more sustainable states. Along the lines of the Kaya identity,[1] various strategies have emerged to reduce the emissions of the sector, including demand reduction, reducing the volume of trips, transport efficiency improvements, increasing energy efficiency, and use of renewable energy (ALICE, 2019; McKinnon, 2018; Montreuil, 2011). So far, however, these measures have only led to very few modest successes, as found by the IPCC AR6 transport assessment. The need for rapid, transformative change in transport that contributes to meeting the Paris 2°C target is increasing.

An important lesson from the past is that the sector is difficult to decarbonise due to its international, complex, and dynamic nature. We argue that this complexity has to be recognised and tackled by applying changes in those components that drive systemic change. In addition to market and technology-specific support policies, strong system-wide incentives need to be introduced such as binding targets, high carbon prices, and recognition of positive results. Additional actions may be needed to identify and re-build institutions and governance structures which currently block change. Today, we are only seeing a piecemeal deployment of such measures, with efforts mostly focused on short-term gains and cost reduction. Decision-makers should be made aware of how comprehensive policies propagate and aggregate inside the system, and how they can help to reduce overall emissions. This requires an interdisciplinary approach that can account for system change. A relevant approach is the idea of sustainability transitions (Köhler et al., 2019). Transition theory is an emerging field in science which has framed the problem of the complexity of managing system-level changes, inspired by notions of institutional and evolutionary economics (Geels, 2012). A key understanding from the transitions literature on sustainable innovation is that system change is not linear. Rather, it is a co-evolutionary process between all the elements of the logistics 'socio-technical' (in the language of transitions thinking) system.

Rather than delving into the detailed components of the socio-technical system of logistics, we investigate the emerging properties of the system, in the sense of its main driving technologies and supporting policies, and how these are adopted within the system. In addition, we focus on quantitative, model-based predictions of how the system performs, to understand which logistics systems and technologies could be successful and how much time transitions between these could take. In this chapter, we present a model that can portray the co-evolutionary process between groups of decision-making agents, and technologies. The model directly predicts policy success in terms of the achieved system-level change within national freight transport systems.

The remainder of this chapter is structured as follows: The next section introduces the MATISSE model, with the agent-based architecture connected to the multilevel perspective of transition management. The third section presents different scenarios for technological futures in the logistics system, ranging from the current approach of Third-Party Logistics (3PL) service provider models to platform-based, synchromodal, and physical internet-inspired systems. Following this, we present the results of the modelling with MATISSE and discuss the implications of this exercise for logistics decarbonisation policy. The final section concludes this chapter with a summary of the findings and recommendations.

SIMULATING TRANSITIONS IN LOGISTICS

Limitations of Current Models

Recent reviews of freight transport analysis methods and models have identified several challenges that follow from the transformation of freight transport and logistics. Meersman and van de Voorde (2019) point out that current transport models have not been successful in predicting the effect of structural, organisational, and behavioural changes on transport demand, and this is one reason why there has been limited success in reducing negative externalities from freight transport. Tavasszy (2020) identifies three challenges for descriptive and predictive transport models. The new structures have to be represented, improved analyses of decision-making in logistics are needed, and enhanced capabilities for analysis of dynamics in freight models should be developed. However, there is no literature that explores the new policy questions that these changes generate. More recently, Köhler and Brauer (2022) have addressed this question. They argue that current freight transport policy models do not address the transitions processes required for systemic change and do not consider the 'twin transition' of combined digitalisation and decarbonisation.

System transitions are hard to model as they are emergent phenomena, a result of many interactions inside the system which have no direct relationship with landscape-level objectives. Because of many interdependent, time-dependent, and often random behaviour of parts of the system, outcomes of change in such systems are difficult to assess. Transition models link the niche level of innovations (e.g., electric vehicles) with regime level (e.g., industry support) and landscape level (overall emissions) changes, so that some innovations can fail and others succeed. These models recognise time dependence, needed as the targets are time-bound and also important as many parts of the system show inertia or have other dynamic responses.

From among the many different possible techniques, we have seen system dynamics and agent-based simulation as the most important approaches. Perhaps the most famous model is the world model used for the 1972 Limits to Growth publication of the Club of Rome (Meadows & Randers, 2013). It predicted, two decades before the Kaya equation was presented, that the world could not sustain continuing growth of population and economies. That marked the start of the sustainability movement, however, this model did not lend itself very well as a description of the transition challenge, as it lacked the levers for transition management. Since then, however, our insights have improved about how to describe such complex and dynamic systems that we wish to manage. Besides system dynamics models being developed further, agent-based models (ABMs) came to the forefront which not only allowed an explicit description of transition management levels but also had a much better operationalisation of the lowest levels, in particular individual decisions, so that policy levers and agent behaviour could be added (Holtz et al., 2015; Köhler & Holtz, 2019).

The remainder of this section introduces a very recent implementation of such a model for the freight transport system and presents an application to demonstrate its importance for decarbonisation policy.

The MATISSE Model

This model portrays how new logistics systems might be adopted in the logistics industry. It defines dimensions to describe in general terms the characteristics of logistics systems. New or alternative logistics systems structures were identified from discussions with the industry and a literature review (Köhler & Brauer, 2022). The adoption/investment decisions of logistics companies about which system they use are then modelled in an ABM framework using a multi-criteria decision rule. The model simulates the time paths of the adoption, to illustrate how the current system might be replaced by new systems. The model is a further development of the approach described in Köhler et al. (2009). Its conceptual structure is described in detail in Haxeltine et al. (2008), while Bergman et al. (2008) provide detail on the equations for the original MATISSE model. The MATISSE model implements the multi-level perspective on transitions using an ABM approach (Köhler et al., 2018), as illustrated in Fig. 12.1. It has two types of agents. There is a small number of logistics system agents which represent the current (regime) and alternative (niche) logistics systems and their characteristics. The other agents are logistics companies who can choose to change the system that they use. There can be only one regime at any time, although the

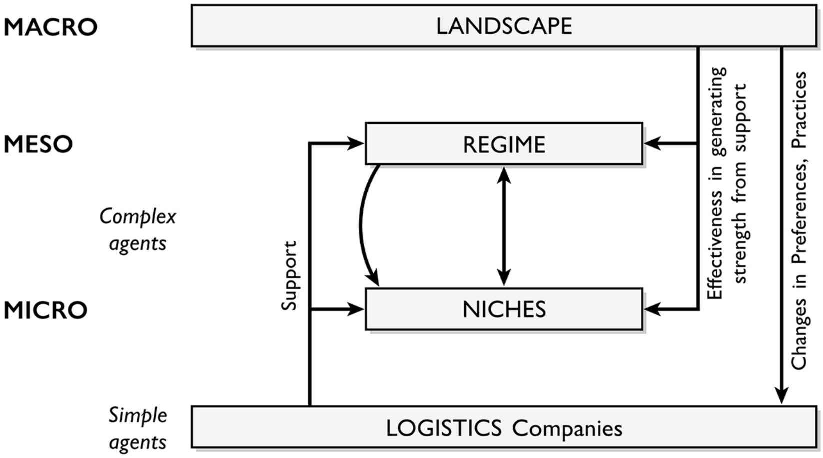

Fig. 12.1. Structure of the MATISSE Model. *Source*: Authors.

system might have periods in which there is no regime. There may be one or several niches at once. The regime is by definition the system which is adopted by the largest number of operators and dominates the system, while niches are much smaller. A logistics system agent's level of adoption determines its behaviour (or strategy), its interactions with other logistics systems, and (partly) its attractiveness to logistics companies deciding which system to adopt.

The model uses the concept of practices as the metric through which agents position themselves in society and over which behaviour is defined. Practices are characteristics of the logistics systems and are at the same time the dimensions over which logistics companies choose the logistics systems they will adopt. Practices are each represented as values along axes, constituting a multidimensional practice space. Agents are differentiated by their positions in the multidimensional practice space. Fig. 12.2 shows schematically a two-dimensional practice space, which might be CO_2 emissions in the x-axis (P_x) and cost of transport in the y-axis (P_y).

The logistics systems and the logistics companies are shown separately for clarity but actually occupy positions along the same P_x and P_y practice axes. Logistics companies are points in the space, while in the figure the size of the regime and niche system ovals are proportional to their relative support. The model is stochastic in that the logistics companies are initially randomly assigned over the practice space, with distributions of conventional logistics companies who use paper management systems and conventional trucks and railways and a smaller number of digitalised logistics companies operating alternative management systems and technologies. Companies are initially assigned in groups according to the system they already use (current logistics, physical internet, synchromodality, regionalised supply chain) over the practice space, with a stochastic distribution of the companies in a group around a central value for the group. In the model,

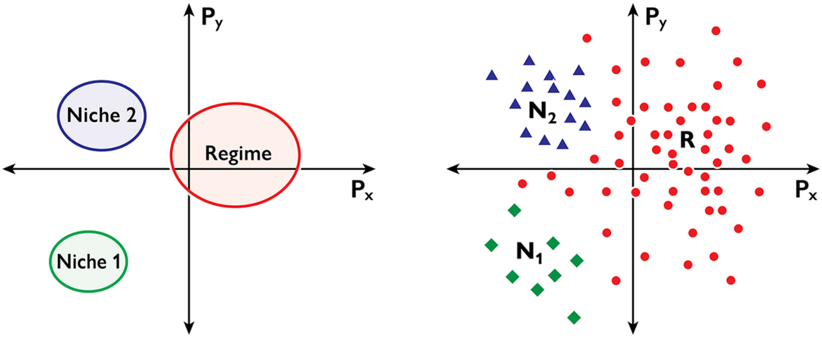

Fig. 12.2. Illustration of a Two-dimensional Practice Space. *Source*: Authors. *Note*: Practice axes P_x and P_y. Left: regime and niche logistics systems, which can move in the practice dimensions space and interact with each other. Right: the logistics companies scattered in the practice space, denoted by the type of logistics system they adopt, ○ = regime (R), ♦ = niche 1 (N_1), and ▲ = niche 2 (N_2).

the logistics agents choose to adopt the practices (logistics system characteristics) of the system that is closest to them; therefore, the positions of the regime and niches are based on clusters of support, i.e., like-minded logistics companies. The positions of the logistics companies in the practice space change depending on landscape signals (exogenous changes in the logistics companies desired system dimensions or practices), so the regime and niche systems develop, i.e., change their characteristics, not only to grow but often just to maintain their adoption by logistics companies.

The dynamics in the model, i.e., the development strategies of the regime and niche logistics systems, were modelled as follows. First, a review of developments in logistics (Köhler & Brauer, 2022) was used to identify the practices of driving factors in logistics companies' adoption of technologies and investment decisions, in a broader way than techno-economic models of freight transport. The dimensions describing the different logistics systems represented in this pilot model (practices in Fig. 12.2) are:

- CO_2 emissions over the supply chain;
- Transport costs along the supply chain;
- The capacity, i.e., the level of activity (tkm) growth or decline in the logistics sector (in the pilot version for the European Union (EU));
- The goal for time to deliver goods to customers;
- Level of digitalisation in data handling, contracts, and documentation for consignments;
- Level of automation of vehicles, loading and unloading equipment, terminals, and warehouses;
- The level of resilience of the supply chain;
- The level of centralisation or concentration of logistics markets and companies.

Each logistics system (regime, niche) has a different behavioural algorithm for its movement in these practice spaces. The algorithms we use are based on the policy-driven party dynamics of Laver (2005). The regime is an aggregator, adapting its practices to the centre of the logistics companies' 'cloud' in the practice space, in an attempt to maximise support. There is a restriction on the rate of change to reflect the tendency of the regime to display inertia. We add to Laver in that when the regime's support falls below a threshold, it attempts to aggregate all consumers to increase its support. This attempts to capture the regime's tendency to be entrenched in its practices and to seek optimisation rather than innovation. Niches are hunters, continuing movement in the same direction as long as their strength increases, otherwise moving randomly in another direction. This means that the niches are trying to grow their market, but this market is not well established. Niches are restricted to a certain range within the practice space. An example is that logistics control towers are required to reduce transport costs but do not necessarily have a high level of automation in vehicles or warehousing.

Validation of the behavioural parameters in an ABM presents a challenge because of the large number of behavioural parameters in such models. Therefore, the model is calibrated to represent the initial levels of activity and distribution of logistics companies using the different logistics systems, with the individual decisions as the variables to be calibrated. Each agent is individually parameterised (in the MATISSE model over 1,000 logistics company agents). The MATISSE-LOGISTICS model is implemented in a PYTHON agent-based modelling application. The theoretical structure of the model is described elsewhere (Bergman et al., 2008; Köhler et al., 2009).

External Factors and Logistics Policy

External factors, such as economic change or environmental policy, will cause logistics companies to change their position in the practice space, and logistics systems will try to develop to meet the requirements of the logistics companies while still remaining within their constraints (for example, reducing CO_2 emissions) but allowing for arising implications (e.g., increases in costs) if logistics operators are placing a higher importance on environmental performance. Social norms are not directly modelled but will have an indirect effect as the logistics agents' customer requirements change, for example, for better environmental performance.

The model does not include the details of transport policy implementation. However, these policies can be interpreted in terms of the 'practices' of the different logistics systems and also the practice requirements of the logistics operators deciding where to invest. Taxes (fuel taxes, emissions taxes, and so on) change the relative costs of the technologies and may also change the priorities of logistics operators. Measures such as standards for data exchange or regulations supporting digital technologies will change the priorities of logistics companies towards automation, as will investment subsidies. These are just a few examples of how policy measures can be reflected in the model parameterisation.

TRANSITION SCENARIOS

Discussion with stakeholders indicated that the adoption of digital technologies is already happening, especially in the development of automated warehousing and container terminal operations. Furthermore, it is considered that some of the aspects of synchronous mobility are being implemented by major logistics operators. These include real-time monitoring of traffic and updating of operational planning. However, the use of blockchain technologies to change market structures through more specialised web-based logistics markets and services is still being developed. One area where there are concrete applications is the 'logistics control tower concept'. Following the analysis from Köhler and Brauer (2022), a number of potential alternative logistics systems were identified and are represented in the MATISSE-LOGISTICS model. In the current logistics system, global 3PLs exist with a slow trend to concentration of services. This acts as a baseline for the simulations and largely determines the initial GHG emissions of the system. Alternative systems included logistics control towers, synchromodality, and the physical internet.

Logistics Control Towers

These are management centres or platforms where information about goods consignments over the whole length of a supply chain is collected and analysed. They enable, when fully developed, logistics operations to be managed over all links of the supply chain. This could also include performance monitoring of emissions for monitoring, reporting, and verification (MRV) of emissions to comply with emissions policies such as the incorporation of road freight vehicles or shipping in the EU emissions trading system.

Synchromodality

Synchromodal logistics systems (Tavasszy et al., 2017) utilise advanced federated information technologies (such as blockchain) for data sharing and smart assets – vehicles, warehouses and handling assets, and containers – to continuously update information about consignments. Big data analysis enables adaptive, decentralised supply chain networks to be developed. The routeing of consignments is re-optimised in real time to account for the current data on where a consignment is and the status of the transport systems (delays, accidents, and extreme weather). Consignments are switched between modes as a part of this continuous optimisation with automated intermodal cross-docking and data exchange.

Physical Internet

The physical internet (Montreuil, 2011) is the most radical vision of an optimised logistics system which fully deploys digitalised solutions. It extends the concept of synchromodality with multiple sizes of smart pallets/containers with vehicles and containers guided by system-level platforms to guarantee optimal utilisation of assets. This could enable a significant reduction in empty backhauls and could also enable the decentralisation of terminals if smaller consignment sizes – pallets or parcels – can be combined into the volume and weight envelope of the current standard container. Continuous data updating supports predictive production and distribution, in accordance with statistical or AI-based forecasts of demand in quantity and geographical distribution. This enables a large-scale reduction in warehousing, with the possibility of using the transport vehicle as a short-term warehouse that is mobile and can be rerouted to meet short-term adaptions to the predicted demand based on real-time sales data.

The above three logistics systems could also be configured to explicitly include reduction in emissions as a major feature of their operations. While significant emission reduction is always a possible positive effect of these systems, it is not guaranteed. Additions to secure this decarbonisation would be needed, such as alternative power trains, energy infrastructures, or supporting government policies. Therefore, the research also considered combined digitalised and decarbonised logistics systems: *sustainable logistics control towers, sustainable synchromodal logistics,* and *sustainable physical internet logistics*. These different systems were represented through different initial values of the dimensions (practices) listed above, describing the different logistics systems. In addition to these initial values, the logistics companies change their requirements for performance over time. Scenarios are developed by altering rates of change of the requirements for these dimensions or practices. These alterations may depict policies such as carbon taxes increasing the requirement to reduce emissions or a requirement of logistics companies for even shorter delivery times in response to consumer demand. These rates of change for the baseline and scenarios are shown in Table 12.1. The logistics systems change in response to the changes in the logistics companies' requirements and policies as explained above.

Table 12.1. Rates of Change of Practices.

Initial Rates of Change for Logistics Operators and Logistics Systems								
Name	GHG	Cost	Traffic	Time	Data	Auto	Resilience	Central
Baseline								
3PL	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Tower	0.0	−0.1	0.1	0.0	0.2	0.0	0.1	0.5
Synchro	0.0	−0.1	0.2	−0.1	0.2	0.5	0.1	0.5
Physical internet (PI)	0	−0.2	0.2	−0.1	0.3	0.5	0.1	0.5
Sustainable tower	−0.5	−0.1	0.1	0.1	0.2	0	0.1	0.5
Sustainable synchro	−0.7	−0.5	0.2	−0.1	0.2	0.5	0.1	−0.1
Sustainable PI	−0.7	−0.5	0.2	−0.2	0.2	0.5	0.1	−0.5
Scenario 1: Initial rates of change for logistics operators								
3PL	−0.5	0.1	0.1	0.0	0.5	0.5	0.0	0.0
Tower	0.0	−0.1	0.1	0.0	0.2	0.0	0.1	0.5
Synchro	0.0	−0.1	0.2	−0.1	0.2	0.5	0.1	0.5
PI	0	−0.2	0.2	−0.1	0.3	0.5	0.1	0.5
Sustainable tower	−0.5	−0.1	0.1	0.1	0.2	0	0.1	0.5
Sustainable synchro	−0.7	−0.5	0.2	−0.1	0.2	0.5	0.1	−0.1
Sustainable PI	−0.7	−0.5	0.2	−0.2	0.2	0.5	0.1	−0.5

Table 12.1. (*Continued*)

Initial Rates of Change for Logistics Operators and Logistics Systems								
Name	GHG	Cost	Traffic	Time	Data	Auto	Resilience	Central
Scenario 2: Initial rates of change for logistics operators								
3PL	−1.0	0.1	0.1	0.0	1.0	1.0	0.0	0.0
Tower	0.0	−0.1	0.1	0.0	0.2	0.0	0.1	0.5
Synchro	0.0	−0.1	0.2	−0.1	0.2	0.5	0.1	0.5
PI	0	−0.2	0.2	−0.1	0.3	0.5	0.1	0.5
Sustainable tower	−0.5	−0.1	0.1	0.1	0.2	0	0.1	0.5
Sustainable synchro	−0.7	−0.5	0.2	−0.1	0.2	0.5	0.1	−0.1
Sustainable PI	−0.7	−0.5	0.2	−0.2	0.2	0.5	0.1	−0.5

RESULTS

Scenario 1: Moderate Acceleration in GHG Policy and Digitalisation

In this scenario, there is a strengthening in climate mitigation policy and digitalisation which causes the 3PL logistics regime to change, but change in this regime is slow. The strengthening in climate mitigation policy is strong enough to create a tipping point where supporters move away from the conventional logistics systems to more sustainable systems. The results are shown in Fig. 12.3. There is competition between sustainable variants of the different digitalised structures, and while logistics towers are adopted for a few years, in the medium term, the advantages of synchromodality in terms of long-term cost savings as well as higher system efficiency enable a low emission, synchromodal logistics takes off. A sustainable form of synchromodality is a dominant solution in this system.

Scenario 2: Far-reaching Change to the Physical Internet

In this scenario, there is both strong policy support for decarbonisation and a more rapid development of digitalisation in a world which quickly realises the benefits of digitalisation in logistics through autonomous vehicles and systems, combined with rapid development of the necessary standards for data exchange and data security. Furthermore, technologies to reduce the large energy demands of blockchain computing technologies are developed. The results are shown in Fig. 12.4.

An interesting outcome is that the rapid development of digitalisation dominates the adoption choices, enabling the development of the physical internet *without* a concentration on GHG emissions reduction. In the longer run, the increasing requirement to reduce emissions enables sustainable synchromodality to take off, promoted by policy to increase the costs of emissions to operators. In the longer term, the physical internet partly replaces the role of synchromodality in decarbonisation with a next step in system-wide rationalisation. Other solutions are pushed to the background with only minor contributions. As in Scenario 1, the role of logistics control towers peaks between 2035 and 2040. Apparently, its importance for decarbonisation depends more on its intrinsic qualities than the presence of other innovations in its environment. Synchromodality peaks well before the final horizon year of 2050, and the physical internet takes the dominant role.

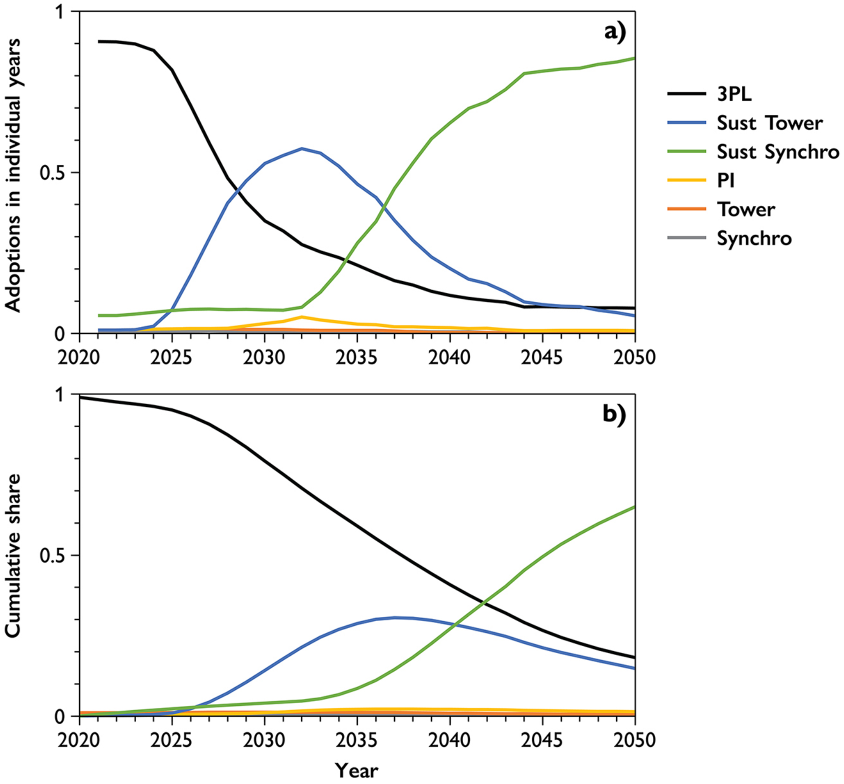

Fig. 12.3. Logistics Companies' Choice of System Types in (a) Individual Years and (b) Cumulatively Over Time, in Scenario 1: Moderate Acceleration in GHG Policy and Digitalisation. *Source*: Authors.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Our argument in this chapter is that logistics is in a period of fundamental change – a 'twin transition' of digitalisation and decarbonisation. There are important implications for transport policy in terms of climate mitigation policy and the development of the logistics sector as a vital part of the economy. However, the implications of digitalisation for achieving environmental policy goals for climate mitigation have not yet been addressed in policy analysis. Such analysis requires the support of policy modelling, but current transport models have so far not addressed the processes of digitalisation or the interaction between digitalisation and GHG emissions (Tavasszy, 2020).

We propose an approach for how such issues might be addressed in simulation modelling. It uses the concepts of sustainability transitions (Köhler et al., 2019) to derive a theoretical structure for an agent-based simulation model of transitions in logistics, following previous work on sustainability transitions in passenger transport (Köhler et al., 2009). Illustrative scenarios show that in

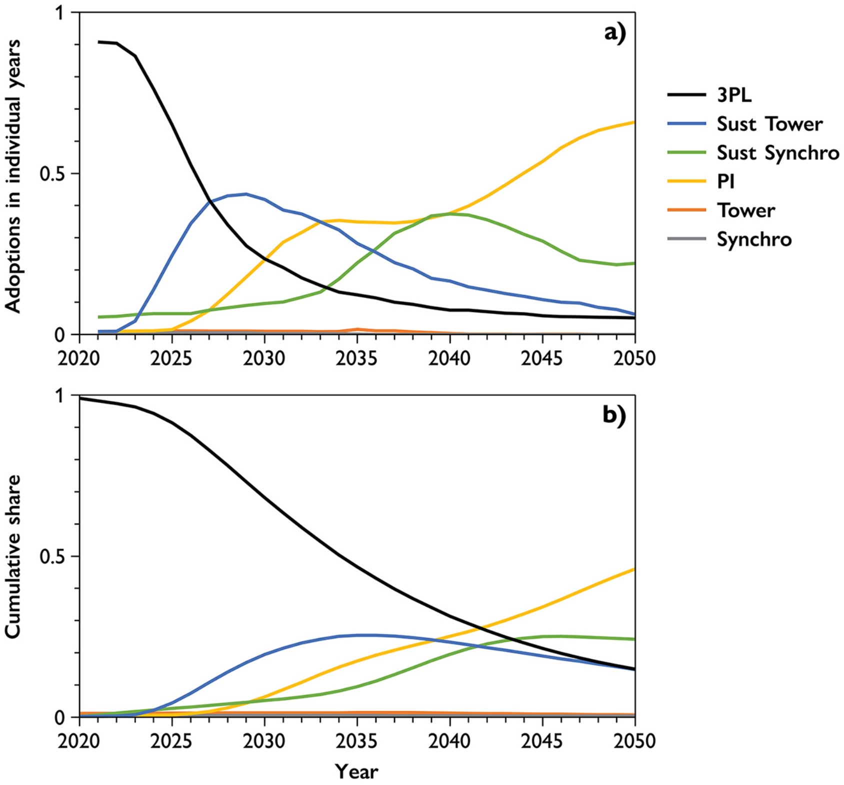

Fig. 12.4. Logistics Companies' Choice of System Types in (a) Individual Years and (b) Cumulatively Over Time, in Scenario 2: Far-reaching Change to the Physical Internet. *Source*: Authors.

comparison to a baseline where change is very slow, transitions to new logistics systems may occur. Current literature and assessments of logistics stakeholders suggest that a 'digitalisation transition' is already under way. The EU emissions trading scheme (ETS) includes transport fuels and therefore strengthens the GHG mitigation policy for the EU, which will require major changes in the EU freight transport system. Therefore, it can be argued that a 'no system change' baseline is not realistic. The transition scenarios illustrated here suggest possible pathways of change, given a current understanding of what future logistics systems could look like.

This analysis is a pilot to show how scenarios of system change in logistics and their results for freight transport can be assessed at an aggregated level. Here, the assessment of future scenarios is based on the literature review and discussions with stakeholders. However, the model could be used in a more comprehensive scenario analysis that combines structured qualitative scenario development with simulation modelling (Köhler et al., 2022).

The analysis leads us to the following findings which can be useful to guide large-scale decarbonisation policies. Concerning the effectiveness of decarbonisation strategies, the modelling results suggest that three solutions together can reduce the strength and impact of the current 3PL regime and reduce emissions to the degree required. A change in energy carriers and supporting policies appear to be crucial to achieve this impact, however. Second, solutions compete in terms of their influence and impact. Through the decades, different dominant regimes exist, with control towers peaking first, next synchromodality, and physical internet continuing from there. For the first time, this analysis shows a dynamic view on logistics decarbonisation, leveraging the digitalisation megatrends and demonstrating that targets can be met through different, complementary approaches. The implication is that policies going beyond single technologies and recognising the supporting regimes appear to be necessary, and research into how these play out together over the longer term is justified.

Further work is required to examine how logistics systems will be reconfigured through digitalisation. The development of digital paperwork and contracts is already happening, as is automation. However, there is still very little work on how digitalised logistics systems will reconfigure physical assets or market structures. While sufficient plausible narratives on innovation exist, including the scenarios discussed here, a scenario model of their autonomous development, interaction, and propagation is lacking. Overall, we argue that simulation models that have the objective of including individual innovation choices and new logistics structures can be a relevant direction for research into the understanding of transitions in logistics. Subsequent work also includes further operationalisation of the transition model with agent-specific logistics decision-making behaviour. This could include innovation adoption with respect to digitalisation, under influence of various regime and landscape forces. In particular, the behaviour of policymakers could be introduced as an endogenous force, making technology regulation, collective infrastructure, and fiscal policies part of the system that must achieve sustainability targets while digitalisation proceeds. The model does not explicitly calculate emission levels; therefore, further developments will include changes to GHG emissions, calculated from the adoption pathways.

In conclusion, social-technical simulation could help stakeholders to understand which are the feasible and effective pathways towards change, recognising which transitions are part of general developments in society, and how desired transitions can be realised through policy measures and industrial strategies.

NOTE

1. Kaya identity for factors determining GHG emissions: Emission level = human population * GDP per capita * energy used per unit of GDP * GHG emissions per unit of energy consumed.

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