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TRAJECTORY-BASED MULTIMODAL TRANSPORT MANAGEMENT FOR RESILIENT TRANSPORTATION

Summary. The transport of goods and persons with two or more transport carriers (road, rail, air, inland waterway, or sea) results in multipartite transport chains whose profitability depends on the cost-effectiveness of the transport carriers involved as well as on the capability of multimodal transport management. Currently, differences with regard to the technical equipment used and infrastructural facilities available as well as administrative and public organizational structures in place are the major obstacles to comprehensive multimodal transport management within and beyond European Union borders.

Though information and communication technologies (ICT) have entered into all traffic and transport systems, the levels of ICT penetration achieved in controlling, monitoring, and managing of system operation and processes are currently quite different [1-5]. One of the reasons for that is the lack of homogenous ICT standards and, as a result, the technological barriers for interconnectivity between different systems, processes, applications, and stakeholders [2]. The proposed trajectory-based concept is considered as suitable approach to perform the smart and adaptable planning, operation, and management of systems with dissimilar structures, a wide diversity of actors, and distributed responsibilities. It is therefore expected that it will be especially well suited to facilitate multimodal transport management for future Intelligent Transport Systems (ITS). Based on the “transport trajectory” formulation introduced here, it will be shown that a trajectory-based status description is generally possible for all transport-relevant components and processes. The expected benefit of the trajectory-based transport management is illustrated by means of selected transportation scenarios.

1. INTRODUCTION

1.1. Challenge

In recent decades, various national working programs have been initiated to force and coordinate the development of Intelligent Transport Systems (ITS): the ITS Strategic Plan 2015-2019 of the U.S. Department of Transportation [7], ITS Canada’s Strategic Plan 2015-2019 [8], or the Freight Transport and Logistics Action Plan of Germany [9]. The purpose of ITS is the integration of “telecommunications, electronics, and information technologies with transport engineering in order to plan, design, operate, maintain, and manage transport systems” in a more efficient manner [1]. The challenges of ICT implementation grow, if “a safer, more coordinated and ‘smarter’ use” of integrated multimodal traffic and transport networks” has to be achieved [1]. Consequently, the highest grade of ITS will correspond with well-functioning multimodal transport and traffic management, ensuring resilient transport processes also in times of traffic disruption.

1.2. Scope

Generally, a transport system is composed of a broad spectrum of systems, services, and components required for the relocation of persons and goods. These cover inter alia the transport infrastructure (e.g. marked-out routes, means of transportation, and transshipment points) and facilities for traffic guidance, control, and management. Persons and goods to be transported and all actors involved should be equally considered as part of the transport system. At the macroscopic level five different transport systems can be distinguished: road, rail, air, and water transport [10, 12]. The use of pipelines as the cheapest means to transport fluids and gases may be considered as the 5th transportation mode. At the microscopic level, each of these transport systems consists of a wide range of subsystems, which differ with regard to, for example, ownership, operating companies, types of transport means applied, regional allocation, or existing technical equipment and operational tools. Transport corresponds more or less with the process of relocating of goods/persons from site A to site B. The transport system that can be used in principle is determined by usable places of loading/boarding (site A), transshipping/changing, and unloading/disembarking (site B) as well as existing marked-out routes between them. The final decision regarding the transport supply chain as well as subsystems and actors involved depends on the extent to which specific key performance indicators (KPI) such as period and duration of transport, type and quantity of persons and goods to be transported, costs as well as social and ecological aspects can be met.

1.3. Transport Management

Transport management serves the coordination of interdependent activities within transport, traffic, and transshipment systems. Through dependence on time horizon of coordination, the transport management may be performed on strategic, tactical, and/or operational level [10]. The management process serves the coordinated decision making taking into account and optimizing the diversity of interests of actors and stakeholders. An essential basis for the management is the monitoring of systems and processes, either for an improved performance characterization or the detection and, if possible, compensation of any disturbances or both. The overarching goal is an efficient and sustainable realization of transportation. This requires a task-driven and goal-orientated communication between actors and stakeholders during phases of strategic, tactical, and/or operational management [10-12]. However, the time horizon of these management phases is highly dependent on transport domain and business [10].

The planning of a specific transport may be considered as strategic task of transport management and specifies the cornerstones and target values of the transport supply chain aimed. The planning is improved if knowledge of scheduled operating restrictions (e.g. due to maintenance and servicing) and still available transport resources (e.g. as result of already requested capacities) allows reliable forecasting of the real usability of individual transport components, systems, and routes taking into account their characteristics and capacities, which vary dependent on time.

The setting up of an action list to perform the planned transportation may be considered as tactical management task [10]. The operational management focuses rather on the procedural realization of individual transportation steps [10]. Strategic mistakes by the human factor or an insufficient system database may result into a planning task that cannot be implemented by setting-up a feasible action list. As a result, a re-adjustment of strategic planning (change of milestones, open up alternative transport options) becomes necessary. Delays in previous transport processes, the occurrence of malfunctions and failures, and extreme weather conditions are several reasons that may induce differences between target and achieved set point values. Early identification of such differences allows to ask for appropriate compensatory measures on tactical as well as strategical level taking into account the remaining transportation task.

A generalized flow chart of transport management processes on strategic, tactical, and operational level is illustrated in Fig. 1. In the ideal case, a new transport order triggers a strategic management plan followed by tactical management up to the operational realization. If the tactical management is

unable to set-up a coordinated list of actions for the proposed strategic solution (e.g. expected transport resources are not available at intended time of transportation), there must be the opportunity to readjust the strategic management solution. If a scheduled transportation step cannot be realized (e.g. quickly blocked road) or is significantly delayed (e.g. increased traffic density), the necessity arises to readjust the tactical and/or strategical management solution.

The demand to increase the effectiveness of management is not specific to transportation [13-15]. It is the subject of current research and the main reason for continuing need for suitable tools enabling adaptive assessment and management [3, 10, 12-16]. The requirements on these tools increase if they are used for the management of multimodal transport: on the one hand because of the combined coordination within and beyond dissimilar transport systems with distributed responsibilities, and on the other hand because of the necessity to ensure a seamless data exchange between strategic, tactical, and operational management of all systems taking into account the stakeholders involved. Generally, it can be assumed that each transport subsystem monitors its status, plans and predicts the use of its resources, and ensures as far as possible fault-free operation in compliance with the original planning. However, multimodal transport management requires more: a readiness for cross-system information exchange as well as a mutual willingness to influence and modify operational processes across systems at all management levels.

2. MODULARIZATION OF MULTIMODAL TRANSPORT SYSTEMS

The spatial movement of goods and passengers may be depicted graphically [17-19] by the following:

- nodes acting either as the start and end point of transportation or as the turnover point, where a change of applied transport vehicle or transport system is enabled;
- path elements as a transport-system-specific connection between two nodes; and
- assigned technological components and personal resources to facilitate cargo and passenger handling at nodes as well as transportation along the paths.

Fig. 2 illustrates some assumed transport options between Berlin and Gdańsk on the macroscopic level under consideration of connections supported by the current transport systems. The shortest route is the one via Szczecin and is supported by road, rail, and water transport. Due to unsupported non-stop flights between Berlin and Gdańsk, the flight connections via Munich and Frankfurt have the longest routes. Therefore, from the macroscopic point of view, cities such as Poznań, Szczecin, and Rostock are perfectly suited to serve as turnover points for the intermodal transportation of goods, passengers, or both.

Each macroscopic node and path element can be disassembled into a network of nodes and path elements and the disassembling can be repeated over and over until modelling at the microscopic level is achieved. At the microscopic level, it becomes possible to describe individual steps of transportation and transshipment, including the specific demand on personnel and facilities. Ports such as Rostock or Gdańsk have diverse terminals to facilitate the changing of ferry and cruise passengers, the ro-ro-traffic (roll-on roll-off of cars, buses, trucks, and trains) as well as the transshipment of a variety of cargo types (e.g. bulk, container, oil, or chemicals). This implies differences in terminal equipment, demands on intra-port transportation and transshipment as well as supported traffic connections (railway, motorway/highway, and public transportation network).

Fig. 3 provides an example of a small Baltic port consisting of 7 ferry terminals, 4 ro-ro-terminals, 12 cargo terminals, 8 bulk terminals, 3 grain terminals, 5 oil terminals, and 1 chemical terminal. The port is connected with the hinterland by rail and road for the transportation of goods. Additionally, city and intercity bus stops enable the departure/arrival of ferry passengers from/to the port by public transport.

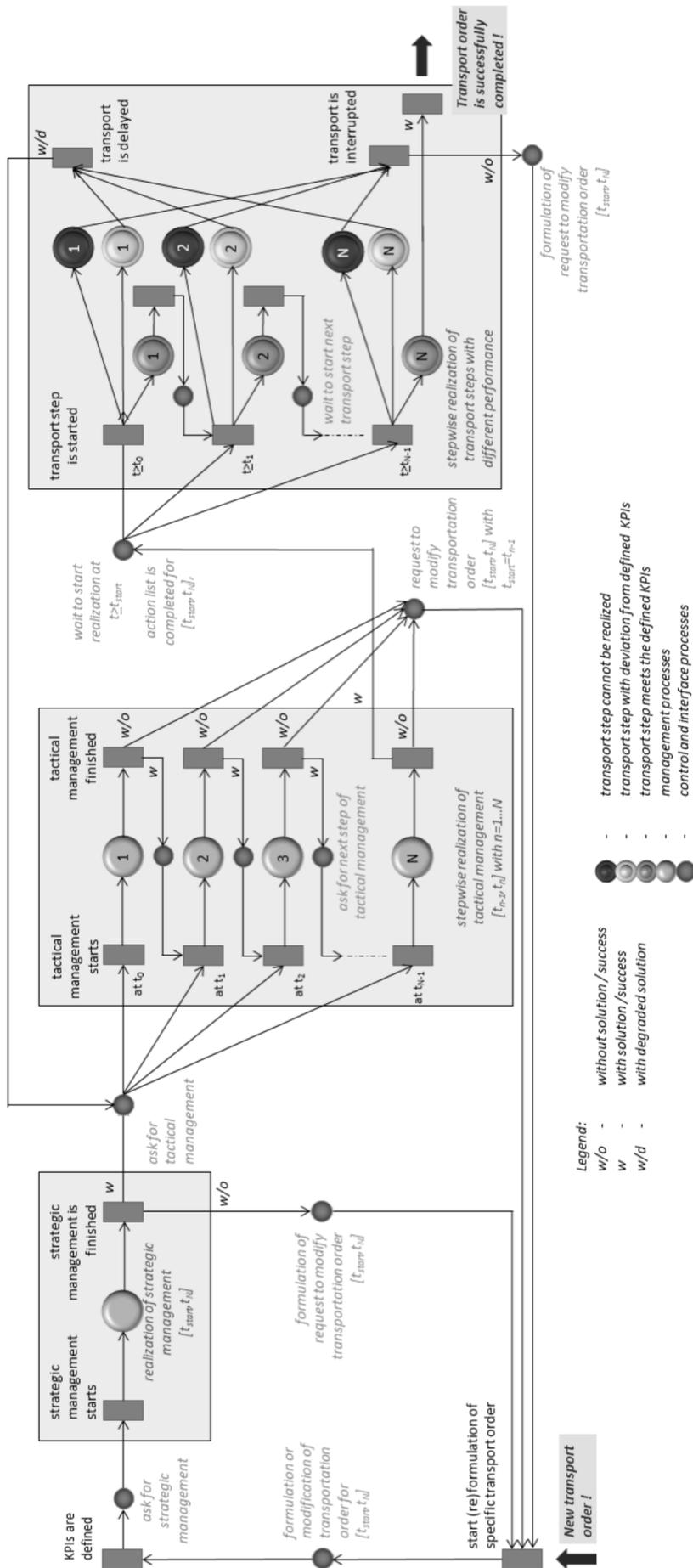


Fig. 1. A generalized flow chart illustrates transport management on strategic, tactical, and operational level and interactions between the management processes (assumption: a transport order, which may be realised by N transportation steps)

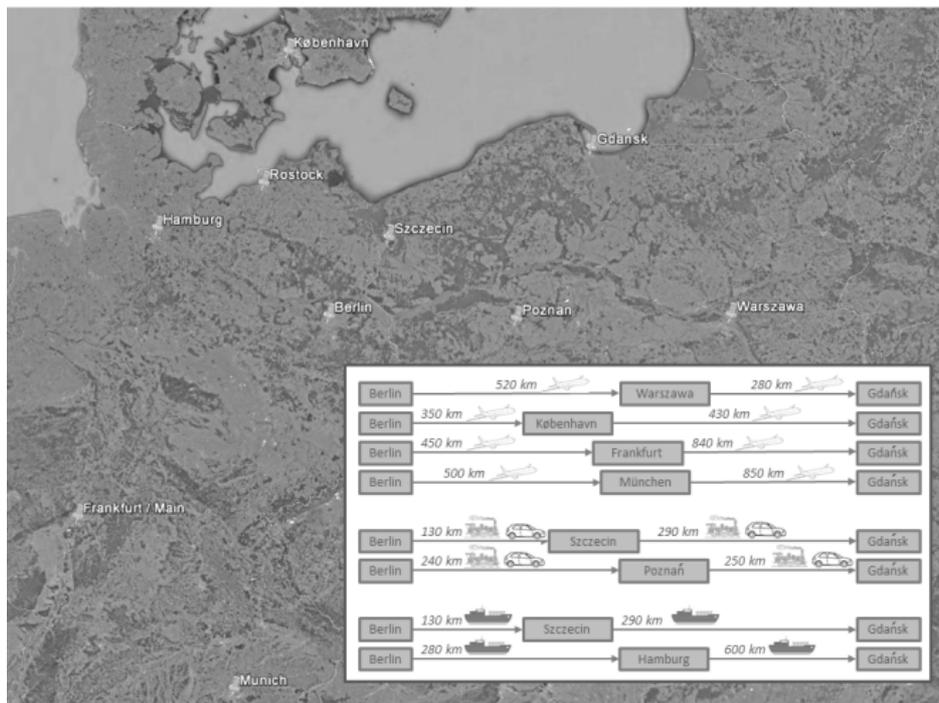


Fig. 2. Transport options between Berlin and Gdańsk (linear distances are rough estimates)

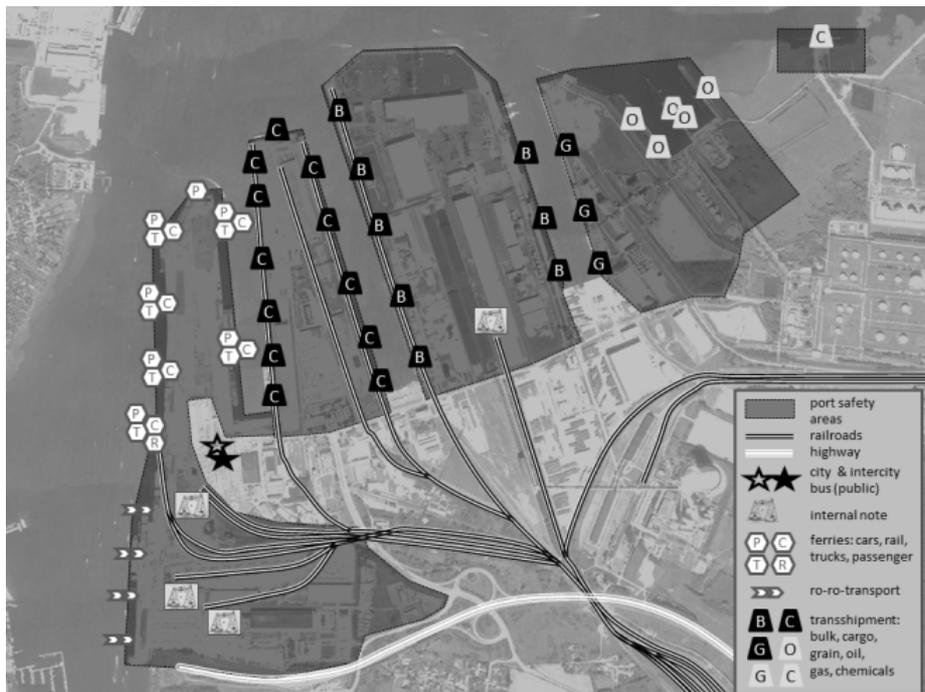


Fig. 3. Small Baltic port to illustrate diversity of transshipment and passenger changes

The associated model of port-internal transportation and transshipment processes is given in Fig. 4. As can be seen, the oil and chemical terminals are directly connected with tank depots via pipeline; therefore, the transshipment is performed without any additional demand on port-internal transport capacities. At grain terminals, the existing conveyor system performs direct transshipment from/to grain silos. The operation and maintenance of loading/unloading equipment and pipelines as

well as tanks and silos may be done with responsibilities divided between the port and companies trading in oil, chemicals, or grain. In the model presented, it is assumed that the operation and maintenance of terminal equipment, pipelines, and conveyor systems is the task of the port, as is the direct transshipment of grain from/to external trucks.

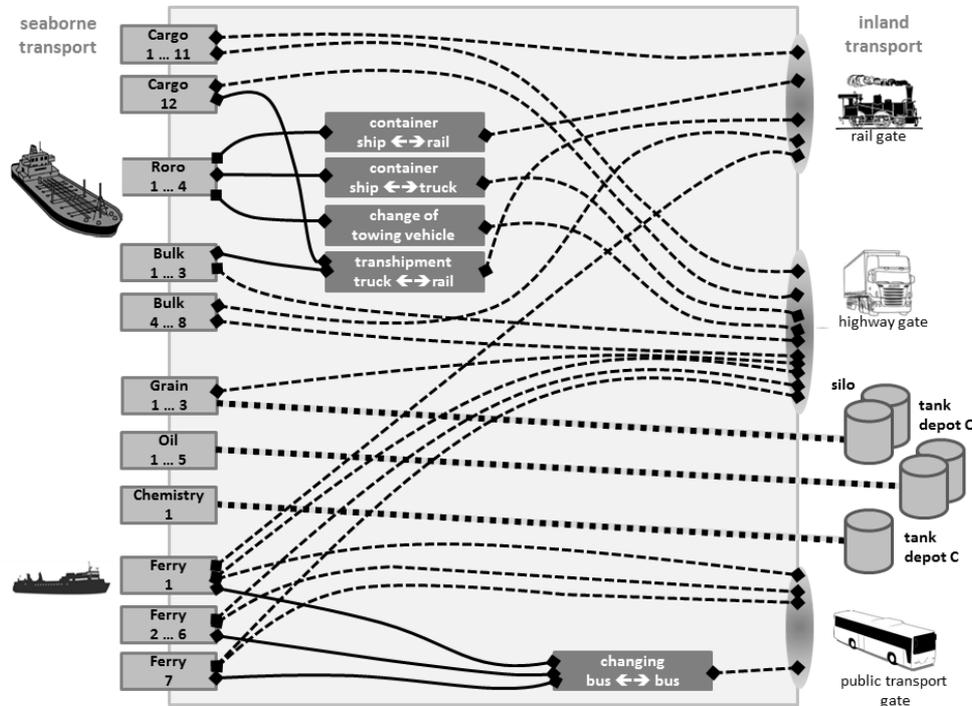


Fig. 4. Microscopic model of example port illustrated in Fig. 2 (solid line: transport facilitated by port; dashed line: transport facilitated by external actors; dotted line: transport by pipelines; squares: points of transshipment/ changing)

Generally, all bulk and cargo terminals are able to undertake direct transshipment between ship and road transportation. Only 5 of the 8 bulk terminals and 11 of the 12 cargo terminals also support direct transshipment from/to rail transport. The other 4 terminals would require port-internal transportation and additional transshipment processes to enable a connection to rail transport. Only one ferry terminal supports the ro-ro-transportation of goods by train. Most of the ferry terminals facilitate the sea transportation of passengers with/without their own cars, trucks, or buses. For passengers without their own cars, it is important that transport possibilities from/to public bus stops are provided. From the point of view of the port authority, port-internal passenger transportation also serves the safety and security of ports. Ro-ro-terminals enable the “roll-on roll-off” of movable goods either being realised autonomously by trucks themselves or by the port’s semi-trailer tractors and forklifts. The 3 internal nodes, which are located near the ro-ro-terminals, serve the transshipment of containers from/to trains or from/to trucks or the temporary storage of trailers.

The feasibility of a single-stage transshipment process requires the simultaneous availability of the delivering transport (ship, wagons, and trucks) as well as the usability of the transshipment equipment and resources required (cranes, crane driver, dockworkers,...) in a specified time period (see the example cargo 1 ...11). A multi-stage transshipment process becomes feasible if a sequence of single-stage transshipment processes and connecting transportation processes can be coordinated in time (see the example ferry 7 to public transport gate). Typically, the means of transport delivering passengers and goods from/to ports are not operated by the port authority. This implies that transshipment by a port requires comprehensive and efficient coordination between all actors involved. Trajectory-based management is an appropriate means for generalising, updating, and making real the description of transport processes throughout all the phases of strategic and tactical coordination and operation.

3. TRAJECTORY

3.1. Definitions

The existing variety of trajectory definitions comes from multiple applications in natural and social science as well as engineering. In mathematics, the trajectory is the solution of a partial equation. In physics, it is used to describe the movement of an object by a sequence of way points [20]. Social sciences apply trajectories to illustrate social, historical, economic, ecological, and technological courses of development as well as expected trends [21]. All these definitions have one thing in common: a trajectory is suited to describing spatial and temporal changes in individual components, processes realised, and characteristics. Preferably, for this purpose, a sequence of single or associated vectors is used, whereby the vector components contain static and dynamic parameters for georeferencing and time synchronization as well as for the description of changes in performance, status, or characteristics. This explains why trajectories are suitable for use in transport operation and management.

Generally, a transport trajectory may be defined as a development process of the transport systems or parts thereof, which are enabled and predefined by the specific transport conditions. However, the development process has an open outcome, whereby forecasting reliability decreases with increasing forecasting horizon.

3.2. Specification of transport trajectories

Transport trajectories may be classified into component-related trajectories and system-related trajectories in compliance with the given definition and under consideration of the intended application. Component-related trajectories are associated with specific individual components of the transport system (microscopic level) and will be used to describe either movement over time, operational status over time, or characteristics dependent on location and time. Application examples of component-related trajectories are summarized in Table 1. Principally, component-related trajectories are an adequate tool for realising planning and for describing the results of planning and the as-is situation within transport subsystems.

Examples of system-related trajectories are provided in Table 2 and serve either the abstracted description of transport and/or transshipment capacities or the modelling of temporal changes in performance characteristics and demand to improve in particular transportation planning by means of more realistic forecasting. An abstraction is achieved by the summarized presentation of transport and/or transshipment capacities in relation to certain areas, ownership, or time periods. These system-related trajectories serve the trade in transportation services on the macroscopic level and support decision-making in the choice of intermodal transport chains. The abstracted presentation of transport subsystems can prevent a disproportional increase in data exchange processes. Furthermore, it helps to protect property rights and sovereignty of the stakeholder. For example, system-related trajectories are used to describe the utilization of a specific port as a transshipment node in relation to specific goods and time periods – on a planning as well as on an operational level. However, the final decision as to which terminal will be used during transshipment is taken by the port.

Temporal changes in performance characteristics of transport systems, subsystems, or single components can be attributed to both internal and external causes. For example, a single transport or transshipment vehicle will be subject to the usual signs of wear. Therefore, the vehicle is either in operation, in maintenance, or out of operation. Its component-related trajectory can only consider the predictable vehicle states. A good maintenance strategy helps to minimize the periods when the vehicle is in an unscheduled out of operation state. However, the residual probability of such events can only be determined on the systemic level (representative sample) and is system-specific (maintenance strategy). The impact on transportation planning and realisation may also be compensated on the system level, e.g. by planning reserves or the provision of additional stand-by vehicles.

Table 1

Examples for component-related trajectories

Components of transport systems	Examples	Movement	Operational status	Characteristics	Explanation
transport vehicles	ships, train, plane, trucks	x	x	x	core elements of transportation process which should be managed in time and space to achieve efficiency and resilience
transport routes	railway tracks, roads, river, pipelines	(G)	x	x	
transport operator	driver, pilots, captains,	x	x	x	
transshipment vehicles	crane, tractors, dredger,	x	x	x	
transshipment points	terminals, gates,	(G)	x	x	
transshipment operator	operator of crane, dredgers, longshoremen	x	x	x	subjects/objects of transportation and demand on transport carriers should be harmonized with transportation process
transport carrier	container, wagons, trailer	x	x	x	
transport objects	container, bulk, cargo, oil, gas, vehicles	x		x	
transport subjects	passengers	x		(x)	should be considered as far as necessary in relation to influences on transport process e.g. as part or bottle neck of transport routes, or as decision maker to be taken into account, or ...
traffic infrastructure	locks, bridges, traffic lights, one-way roads, railroad switches	(G)	x	(x)	
traffic infrastructure operation	snowplough, gritting vehicle	x	x	x	
traffic infrastructure services	petrol stations, parking spaces, catering, waste disposal	(G)	x	(x)	
traffic management services	pilots, vessel traffic services, air traffic control		x	x	

(G) Georeference (x) Performance features

It is known that there are trends (e.g. increase in global trade) and temporal variations (e.g. rush-hour traffic, holiday time, and parcel transport volume at Christmas time) which underlie demand and load on transport capacities. Monitoring and modelling of such interdependencies is a necessary prerequisite to enable their effects to be considered in planning as well as for the modernisation and expansion of intermodal transportation. However, such information can only be included in planning if barrier-free access and application-friendly provision for planning is supported, e.g. by providing additional system-related trajectories that may be easily associated with other transport-relevant trajectories.

Table 2

Examples for system-related trajectories

Example for abstraction	Components of transport systems	Example for modelled characteristics
fleet of transport company e.g. taxi fleet	transport vehicles	average time of operation, mean time to service provision
motorway, highway, inland waterway	transport routes	mean time of operation; mean time to service provision
staff of transport companies e.g. taxi drivers	transport operator	seasonal staff availability
fleet of port, fleet of airport, dispatcher vehicles	transshipment vehicles	
port, airport	transshipment points	transshipment volume, transshipment punctuality
staff of transshipment company e.g. dock workers, ground staff	transshipment operator	seasonal staff availability
wagon fleet, pallets	transport carrier	availability, mean losses
amount of goods per day, month, ...	transport objects	mean transport time, probability of loss
passengers per day, month, ...	transport subjects	connecting times

3.3. Formulation of transport trajectories

The movement of single vehicles, operators, goods, or passengers may be described by a sequence of N vectors $\underline{X}_{ID,n}$ ($n=1\dots N$), whose components provide the coordinates of waypoints \underline{x}_n and the time of arrival t_n in a defined reference system. Each transport component or system is administrated with a personalized or anonymised identification number (ID) and may be enriched with associated static information such as loading capacity, manoeuvrability characteristics, or physical dimensions.

$$\underline{X}_{ID,n} = \begin{bmatrix} ID \\ t_n \\ \underline{x}_n \end{bmatrix} \quad \text{with} \quad \underline{x}_n = \begin{bmatrix} x_{1,n} \\ x_{2,n} \\ x_{3,n} \end{bmatrix} \quad \text{and} \quad n \in \{1, 2, \dots, N\} \quad (1)$$

A sequence of vectors $\underline{C}_{ID,n}$ ($n=1\dots N$), can also be used to illustrate the changing characteristics \underline{c}_n of single transport components. In this case, a single vector is an indicated milestone of changing characteristics. In order to avoid a strong association of trajectories with changing positions, a single vector is considered as a milestone in relation to any changing parameters, e.g., time, location, or characteristics. The vector formulated in equation (2) supports the description of K different properties. This enables, for example, recommended or expected line speeds to be provided separately for each traffic lane of a specific road section for a certain time point t_n .

$$\underline{C}_{ID,n} = \begin{bmatrix} ID \\ t_n \\ \underline{c}_n \end{bmatrix} \quad \text{with} \quad \underline{c}_n = \begin{bmatrix} c_{1,n} \\ c_{2,n} \\ \dots \\ c_{K,n} \end{bmatrix} \quad \text{and} \quad n \in \{1, 2, \dots, N\} \quad (2)$$

In general, it may be possible that single components of a transport system change location and characteristics simultaneously. Therefore, the milestone $\underline{M}_{ID,n}$ ($n=1\dots N$) of a generalized trajectory fuses equations (1) and (2) and is enriched with operational status information \underline{s}_n . A representative example is the change in load status of multi-stop ferries.

$$\underline{M}_{ID,n} = \begin{bmatrix} ID \\ t_n \\ \underline{X}_n \\ \underline{C}_n \\ \underline{S}_n \end{bmatrix} \quad \text{with} \quad \underline{s}_n = \begin{bmatrix} s_{1,n} \\ s_{2,n} \\ \dots \\ s_{L,n} \end{bmatrix} \quad \text{and} \quad n \in \{1, 2, \dots, N\} \quad (3)$$

Status information serves to indicate process progress in relation to process targets. Thus, progress in transportation can be described, e.g., by remaining transportation distance, performed part of goods handling, time of arrival, or pollutant emissions and fuel consumption per kilometre driven. Most of these can be expressed in the form of time information: delayed, punctual, or ahead. In principle, it may be sufficient that the progress of transportation is measured by the achievement of planned milestones. The transport process will be considered as running according to plan only if deviations between planned milestone $p[\underline{M}_{ID,n}]$ and achieved milestone $a[\underline{M}_{ID,n}]$ can be considered as negligible.

During planning, a status parameter may also be used to indicate whether an individual transport component is still usable for transportation, is bound by an order agreement, or is in maintenance. During operation, a status parameter describes whether or not the transport component is operable at the milestone. Inoperability at a certain time and location may be the result of delayed arrival, loss of personnel, or equipment failure. Additional status parameters may be helpful for self-controlling of transport components, re-scheduling, and the ad-hoc adaption of transportation means and paths.

4. APPLICATION EXAMPLES

The following examples (aviation and maritime shipping) have been chosen to demonstrate that transport as well as transshipment processes can be modelled and described by trajectories as specified by equation 3. Furthermore, the potential benefit of using trajectories for process management will be explained on the basis of a specific scenario from the example.

4.1. Airport passenger management

Multi-modal passenger transportation (e.g. flight in combination with train, bus, or car journeys) is the responsibility of the travellers. During strategic planning, they select the transportation services in the right order with adequate time buffers in schedule to minimize the risk of missed connections. Results of their strategic planning are milestones such as start and end point of journey with corresponding time specifications, latest check-in time, or the earliest possible connection after approach. These milestones are determined using timetables and information provided by the transport services. During tactical management, the multi-modal traveller buys the ticket and orders additional services (e.g., baggage transport or support for handicapped person). During the journey (operational management of trajectory), they try to achieve the milestones with currently available guidance and operational information. Significant delays in transportation may result into readjustment of the individual tactical as well as strategical management solution (e.g. later flight with rebooking or new purchase of flight ticket).

A number of providers along the passenger trajectory serve the provision of transportation and transshipment services required. The coordination between the passenger's trajectory and service providers' trajectories is often limited to strategic and tactical interactions (e.g. provision of transport timetable, ticket purchase). During the phase of operational management, passenger and service trajectories within the same operational share may be coupled loosely (passenger passes the security gate) or tightly (plane with passengers is on the way). However, the providers are not aware of the passenger's endeavours before or after servicing within their operational share. A flight passenger must reach the departure airport on time by any means of transportation. The airport feeder service is not controlled by the airline. Therefore, during their journey, the travellers bear the risk of failed connections, and it is their management task to find appropriate solutions for reaching intermediate as well as final destinations more or less on time.

The approach of milestone-based trajectories is a suitable mean to enhance the strategical, tactical, and operational transport management including a task-based and goal-driven communication management between all transport management levels as well as involved parties. Associating individual passenger trajectories with dedicated component trajectories proves the combinability of transport components (a task of strategic management). The trustworthiness of system-specific information used in this context determines if the transportation can be completed according to the plan. Consequently, it makes sense, not only at large airports, to plan with more realistic performance parameters derived from monitored system operation and taking into account spatial and temporal dependencies. Furthermore, in multi-user systems, the permanent allocation and release of resources may result into allocation conflicts, which become obvious at tactical management. The mass of observed transport subject and object trajectories (at airport, e.g., passengers and baggage) forms the counterpart of system trajectories, for example, to balance capacity and demand for transport vehicles and infrastructure (e.g., airport bus and check-in terminals). These examples explain the need of multilateral data exchange between all management levels (indicated already in Fig. 1), whereby a common syntax and semantics is a prerequisite to increase the effectiveness and responsiveness of management including communication.

Fig. 5 illustrates the connectivity to be maintained by the passenger during transfer to the airport and at the airport. A crowd-caused delay of bus services commuting to the airport is typical in cities with busy airports. A delayed bus may cause the delayed arrival of passengers who plan to board

different flights. The airline knows neither how the passenger comes to the airport nor the current delays of public transportation used by passengers. Successive transportation processes have the potential to absorb the delays occurred or may take actions to avoid further complications. However, for this purpose, it becomes necessary that the airport transport management will be informed as soon as possible about disturbances and threats occurred currently in the transport chains. This may be done by the passenger by permanent monitoring of the current deviation between planned and achieved milestones. If the deviation exceeds the time reserves at the next main milestones (times of association or disassociation of different trajectories), the passenger may ask the airport management for compensation measures. One possible solution might therefore include a bypass option for those with tight schedules at airport process stations (check-in, security, and border control), as available today for status groups granted to frequent flyers. It also makes sense to initiate a dedicated delay of the affected flight departures just to meet late passengers' arrivals at the gates, if a significant number of passengers is affected. With the possibility to process passenger trajectories at the management level of a transport network, special offers or dedicated instructions might be electronically transmitted to a smartphone or any handheld device preferred by the traveller. It may be noted, an intelligent transport management becomes only possible if a situation-controlled and need-driven management of data exchange processes is supported [22, 23]. A trajectory-based process description is a smart approach to associate transport and communication management tasks on functional level.

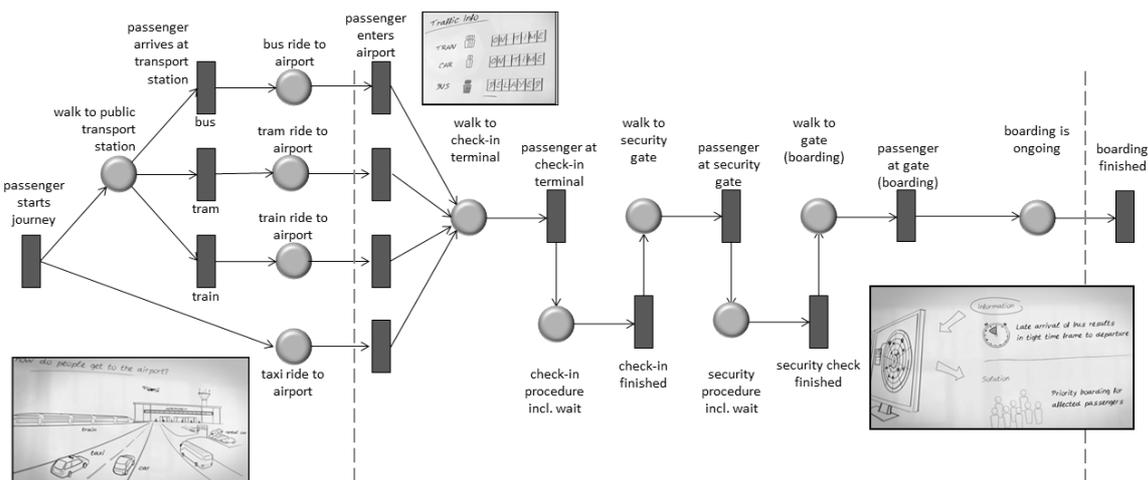


Fig. 5. Milestones of a passenger trajectory during journey to airport and at airport corresponding transport model given in [22]

4.2. Process management around a ferry terminal

A ferry serves the transportation of passengers as well as automobiles, trucks, and buses, including their drivers. Ferry-relevant processes around a terminal cover docking, unloading, loading, and undocking exactly in this sequence.

The trajectory of the ferry is shown as a solid line in Fig. 6 to illustrate the distance between the ferry and the intended landing stage over time. The planned start and end time of ferry-relevant processes around the terminal are specified by milestones (rhombs) $p[M_{F,f-2}] \dots p[M_{F,f+2}]$, whereby $p[M_{F,f-1}] \dots p[M_{F,f+1}]$ correspond with the planned arrival and departure time published in the timetable. During planning, the milestones are determined based on typical process parameters (e.g., mean duration of docking) and conditions (e.g., water flows). These process parameters are closer to realistic if they are derived from process monitoring taking into account influencing factors (e.g., ferry type and manoeuvrability, water flow per landing stage, and weather conditions). Such information covers static or dynamic characteristics of component-related trajectories (e.g., ferry) or system-related trajectories (e.g., port). Planning also requires coordination between involved components. Docking,

unloading, loading, and undocking are possible only if the landing stage $p[M_{LS,ls}] \dots p[M_{LS,ls+1}]$ is usable by the specific ferry for a sufficient time period. Equation (4) illustrates the time relationship between time points $p[t]$ of planned milestones which results from that:

$$p[t_{LS,ls}] + \tau_{LS} < p[t_{F,f-2}] \quad \text{and} \quad p[t_{F,f+2}] < p[t_{LS,ls+1}] - \tau_{LS} \quad (4)$$

The parameter τ_{LS} specifies the additional time before/after scheduled arrival/departure in which the landing stage is also considered as unusable for other vessels. The ferry milestones $p[M_{F,f-2}] \dots p[M_{F,f+2}]$ are main milestones indicating the beginning and end of the ferry's sub-processes with a certain association of transport components (here ferry and landing stage including usability of car and passenger terminals). Each trajectory may be enriched with additional individual milestones to improve the process description.

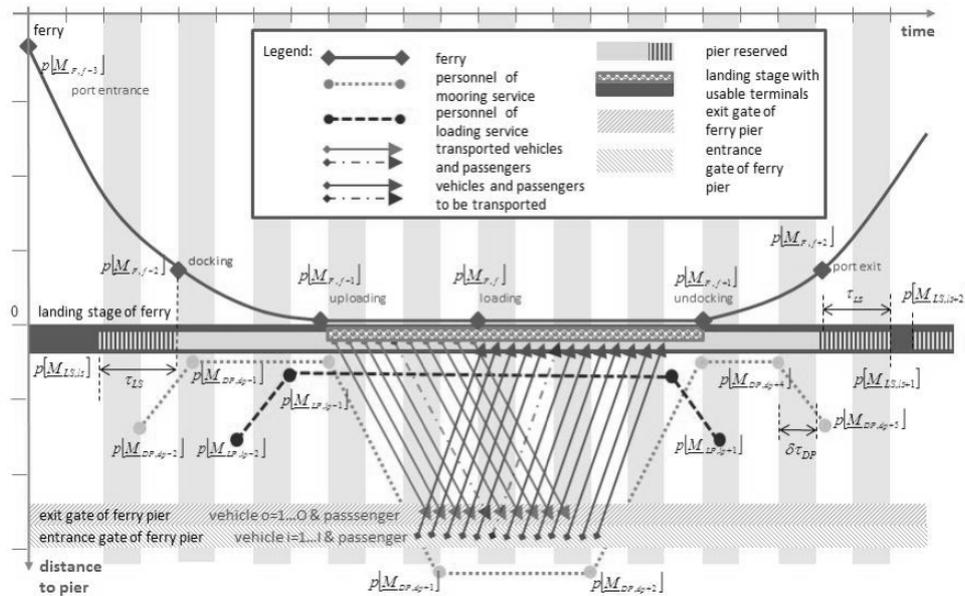


Fig. 6. Trajectory-based process modelling around a ferry terminal

Docking/undocking as well as unloading/loading of the ferry presupposes that during these time periods the ferry's staff and dock workers collaborate in a well-coordinated manner. This implies a need for the trajectories of required ferry and harbour personnel to be associated on a procedural level to perform the ferry-relevant processes. Trajectories of ferry personnel are spatially associated with the ferry's trajectory. Therefore, Fig. 6 may only illustrate the sum-trajectory of shore-side mooring service personnel $p[M_{DP,dp-2}] \dots p[M_{DP,dp+5}]$ and loading service personnel $p[M_{LP,lp-2}] \dots p[M_{LP,lp+1}]$. As has been seen, the main personnel milestones may be synchronized exactly with the ferry's main milestones or include small time shifts to handle the crossover between successive procedural steps (e.g., after loading is complete, the side trap doors of the ferry should be closed before starting undocking). However, an effective process realization requires that the trajectories of ship-side and shore-side transport components involved are coordinated in relation to each process and procedural step. During loading, the trajectories of passengers, automobiles, trucks, and buses are associated with the trajectory of the ferry; during unloading, their trajectories are dissociated. The planned time points of association must be between $p[M_{F,f}]$ and $p[M_{F,f+1}]$, and the time point of dissociation should occur within the time period $p[M_{F,f-1}]$ and $p[M_{F,f}]$. The uploading and loading periods should be sufficiently long to enable complete transshipment including in times of high transport volumes. Any disturbances of process flow result in the threat that planned milestones cannot be achieved.

During the summer period in particular, ferries between Central Europe and Scandinavia are operated at their capacity limits. Therefore, a time resource between the finishing of loading (e.g.

corresponds with $p[\underline{M}_{L,p,l_{p+1}}]$ and beginning of undocking $p[\underline{M}_{F,f+1}]$ is approaching zero. We assume that punctual undocking acts as one of the port's key performance parameters (e.g., to enable the repeated use of a landing stage or to optimise the personnel of port services). Punctual undocking becomes possible only if all previous processes have been completed up to the planned time point $p[t_{F,f+1}]$. A rough sea, bad weather conditions, or malfunctions in navigation equipment are some causes inducing delays during the journey to departure. For example, an observed delay $a[\]$ at the achieved milestone $a[\underline{M}_{F,f-7}]$

$$a[\Delta T_{F,f-7}] = a[t_{F,f-7}] - p[t_{F,f-7}]. \quad (5)$$

may be used directly as an estimate $e[\]$ of delay at subsequent ferry-specific processes and milestones.

$$a[\Delta T_{F,f-7}] \rightarrow e[\Delta T_{F,f-6}] \rightarrow \dots \rightarrow e[\Delta T_{F,f+1}]. \quad (6)$$

The expected delay at milestone $p[\underline{M}_{F,f-1}]$ (beginning of unloading) may be improved if the estimated travel time between successive milestones, e.g., $e[\delta\tau_{F,(i,i+1)}]$, is updated taking into account the current impact of weather conditions on travel time and the possibilities of time-saving navigation.

$$e[\Delta T_{F,f-1}] = a[\Delta T_{F,f-7}] + \sum_{i=-7}^{-2} e[\delta\tau_{F,(i,i+1)}]. \quad (7)$$

Effectively, the values $e[\delta\tau_{F,(i,i+1)}]$ are the expected gain or loss in travel time between 2 milestones which result from differences between the assumptions made for planning and the true situation. Therefore, the trustworthiness of $e[\Delta T_{F,N-1}]$ increases as the ferry approaches milestone $\underline{M}_{F,f-1}$ due to increasing agreement of the forecasted situation with reality (e.g. $e[\delta\tau_{F,(i,i+1)}] \rightarrow a[\delta\tau_{F,(i,i+1)}]$) and decreasing number of estimates needed. The true $a[\Delta T_{F,f-1}]$ is known only if $a[\underline{M}_{F,f-1}]$ is reached. As an example, the delay $a[\Delta T_{F,f-1}]$ may be smaller than $a[\Delta T_{F,f-2}]$ due to a seamlessly executed docking manoeuvre.

A trajectory-based process description is a suitable mean for supporting routine re-calculation of gains and losses in process progress. For this purpose, each milestone $p[\underline{M}_{F,f}]$ of the original planned trajectory contains a description of assumptions applied in the planning process (e.g. as characterising parameter $c_{k,f}$ with $k \in K$). For the crossover from $p[\underline{M}_{F,f-1}]$ to $p[\underline{M}_{F,f}]$ as well as from $p[\underline{M}_{F,f}]$ to $p[\underline{M}_{F,f+1}]$, such characterizing parameters may be the mean number of transported vehicles per season and the mean time per vehicle needed to load or unload. The operational trajectory is fully described by 3 milestones: (1) the last milestone passed as real achieved process state (e.g. $a[\underline{M}_{F,f-2}]$ as start of docking); (2) the next expected milestone $e[\underline{M}_{F,f-1}]$ to indicate the process development since $a[t_{F,f-2}]$ (e.g. as status parameter $\underline{S}_{F,f-1}$); and (3) the forecast for the next main milestone $e[\underline{M}_{F,f+1}]$ based on (2) and using the newest monitoring results (e.g., number of vehicles on board the ferry instead of mean number of transported vehicles per season). The progress of the process is routinely evaluated by comparing (2) with $p[\underline{M}_{F,f-1}]$. If $\underline{M}_{F,f-1}$ is reached, the last milestones passed (1) and the next expected milestone (2) are updated. The comparison of the forecast and planned values of the next main milestone ($e[\underline{M}_{F,f+1}]$ vs. $p[\underline{M}_{F,f+1}]$) serves the earliest possible indication of threats arising in relation to planned association/dissociation of different transport components. If the information contained in $e[\underline{M}_{F,f+1}]$ achieves a certain level of trustworthiness, the difference between $e[\underline{M}_{F,f+1}]$ and $p[\underline{M}_{F,f+1}]$ may be expressed as expected delay $e[\Delta T_{F,f+1}]$. This assumes that the target values (e.g. loading completed) can be met in principle. If $e[\Delta T_{F,f+1}]$ exceeds the tolerable limit, a re-coordination of transport components involved in relation to intended association/dissociation becomes necessary. For this purpose, the planned milestone $p[\underline{M}_{F,f+1}]$ should include parameters formulating the constraints identified during the planning stage in relation to the feasibility of association/dissociation of transport components involved. In the example (Fig. 6), the tolerable limit of $p[\underline{M}_{F,f+1}]$ is determined by the planned reuse of the landing stage

$$e[\Delta T_{F,f+1}] \leq p[t_{LS,ls+2}] - p[t_{LS,ls+1}] = \delta\tau_{LS,(ls+1,ls+2)} \quad (9)$$

as well as by the availability of docking personnel (τ_{DP} indicates the time reserve in relation to the next milestone)

$$e[\Delta T_{F,N+1}] \leq \tau_{DP}. \quad (10)$$

In cases in which $p[M_{F,f+1}]$ can never be achieved (e.g. malfunction of car terminal), a re-organization of process flow (e.g., implementation of additional repair activities and re-coordination of transport) is the logical consequence. As has been illustrated, the use of trajectories at all levels is an efficient approach to manage integrated systems under consideration of existing interdependencies and taking into account target and actual performance identifiers. This enables autonomous detection if re-coordination and re-organization becomes necessary and paves the way for fully automated intermodal transport management and realization.

5. RESEARCH OUTLOOK

In the Optimode.net project at the German Aerospace Center (DLR), the passenger trajectory concept is applied to manage passengers at a simulated airport. The basic assumption is that in the future the key milestones of a traveler's journey are available digitally and are shared with the intended providers of transportation services. In this project, the data exchange of passenger trajectories is realized using the Object Notation JavaScript, which has the fundamental structure described as follows:

```
{"PaxID":"P","stopID":"X","trainID":"A","stopID":"Y","trainID":"B","stopID":"Z","flightID":"C"}.
```

Here, passenger P (serving as the primary key) travels from train station X using train A to train station Y in order to get from there to station Z using train B. Station Z is located at an airport at which flight C has to be taken. Legs of the journey before and after were left out in order to be able to clearly illustrate the principle. The data string contains passenger-related information and the sequence of transport nodes and modes. Additional properties may be included, for instance, booking and ticket information, personal preferences etc. The following discussion of application focuses on the transport-related content.

If passenger P shares this data set with the service providers along the intended route, they can easily gain an overview of the passenger movements in terms of both times and locations. To achieve this, the schedules stored in the booking system are applied as a first step before the journey even begins. On the day of operations itself, continuous estimates are published by the operators for the various transport modes. Network nodes such as the airport provide estimates for key process durations, e.g., for check-in, security, or border control processes. If the real-time information from each process stakeholder is collated for passenger P's journey chain, e.g., de-centrally with the user on a mobile device application or centrally in some kind of control center, the likelihood of achieving each connection also becomes transparent. The passenger management system is complete when the passengers themselves are identified at key waypoints, thereby documenting the progress of the journey along the way.

One important milestone – particularly from today's perspective – is reaching the gate, as air transport is dependent today on the passenger reaching the gate on time (Table 3). In our application, the milestone is named as 'Outbound Passenger at Gate Time (OPGT)'. The target point in time specified by the flight plan of the airline is the 'Scheduled OPGT (SOPGT)'. By announcement of passenger's personal information, e.g., selected arrival connection and current arrival progress, a forecast of the arrival time at the gate can be repeatedly made (Estimated OPGT, EOPGT). The example in Table 3 illustrates that the EOPGT determined at 10:30 leads to the conclusion "tight connection". The actual achieved arrival (here 12:10) is registered by scanning the boarding pass and serves as documentation of the journey progress (Actual OPGT, AOPGT). The EOPGT enables an

early detection of peak times at check-in desk which may also induce that the connection becomes ineffective. This can be prevented if the demand for opened check-in desks is adapted to passenger EOPGT. Otherwise, the customer and the service providers can initiate an immediate and appropriate change of plan.

The opportunity provided by digitalization in this passenger trajectory example is that key journey decisions can be made wherever travel services provide a sound assessment. Reaching a connection is often not a part of a company's transport management, at least not when the customer leaves the company's sphere of influence. Furthermore, the transport mode connections which have been booked by travelers only become visible when information is linked together, and normally this information is separated.

It is, however, up to those involved as to whether they will assist a passenger who is likely to become stranded by finding alternatives which lead the passenger to a successful journey. Considering the current technology, by which the airline (depending on their policy) will wait a defined period of time for delayed passengers, a conscious decision can only be made to either wait or not wait when there is a clearer picture of the expected demand.

Table 3

Example evolution of OPGT status

Time of status	Outbound Passenger at Gate Time	Gate closure	Connection status
one day before	SOPGT = 11:50	12:15	good connection
10:30, passenger on route	EOPGT = 12:12	12:15	tight connection
12:10, passenger reaches the gate	AOPGT = 12:10	12:15	connection effective

6. CONCLUSION AND ACKNOWLEDGEMENTS

The trajectory concept outlined promotes the digitalization of all relevant information. It provides a standardized description required to enable the association of transport components as well as the management of systems operated independently. It has the capability to optimize traffic and transport flows on strategic, tactical, as well as operational level as well as the data exchange between management levels, managed systems, and involved stakeholders.

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