Meta-CDM literature review

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1 Abstract

The present literature review aims at providing insight for the Meta-CDM project from a research perspective.

Air Transportation is intrinsically tied with other modes of transportation, such as rail, roads and water. The objective of making each passenger or cargo's door-to-door journey seamless cannot be achieved without a better understanding of the multi-modal transportation network. In its vision for Europe in 2050, the European Commission [1] sets the goal: "90% of travelers within Europe are able to complete their journey, door-to-door within 4 hours. Passengers and freight are able to transfer seamlessly between transport modes to reach the final destination smoothly, predictably and on-time." The regular occurrence of significant perturbations that propagate through the system and sometimes even paralyze it highlights the need for further research on its resilience and agility and for adequate coordination at the network level. At the airport level, this is beginning to be addressed by Collaborative Decision Making (CDM) initiatives, tools and procedures. The objectives of META-CDM are to study the conditions under which Collaborative Decision Making can help the transportation system deal with major disruptive events as they affect civil aviation and facilitate the passenger's journey.

2 Air Transportation Networks

The world transportation industry is a critical infrastructure with a significant impact on local, national and international economies. The worldwide air transportation network is a small-world network, for which the number of nonstop connections from a given city and the number of shortest paths going through a given city have distributions that are scale-free [2]. Guimera et al. find that the cities with the most connections are not always the most central in the network though. Most cities, or nodes, are peripheral, meaning that the majority of their connections are within their own community. The nodes that connect different communities are usually hubs, but not necessarily global hubs.

Many complex systems, such as networks, can display strong fluctuations at various time scales. To understand such complex networks, it is necessary to study the dynamics of the processes taking advantage of these networks. In [3], the authors take the example of the US airport network between 1990 and 2000. Even if the statistical distributions of most indicators are stationary, the microscopic level is dynamic, with the appearance and disappearance of several connections between airports. These connections have a very broad distribution of lifetimes. Moreover, the links that disappear have essentially the same properties as the ones that appear, and links which connect airports with very different traffic (explain) are very volatile.

In [4], the authors aim to determine which network between China, Europe and the US is the most beneficial to passengers in terms of travel time and accessibility, and analyze the associated network features. To account for travel times and scheduling coordination, they calculate departure time-dependent minimum paths between each airport pair in the network. They evaluate the quality of indirect connections in terms of circuitry times and routing factors. The European network has the highest percentage of destinations.

Waiting times for indirect connections account for between 30% and 50% of the overall travel times. The European network has the highest number of direct flights per airport, but connections requiring intermediate airports require larger waiting times than in the American and Chinese networks. There is evidence for a trade-off between the "openness" of the network and the average waiting time spent at intermediate airports. In Europe, there is a high percentage of airports accessible within a single day, probably because each country favors connectivity towards its own local airports. Such policies reduce the efficiency of coordination between countries, resulting in higher waiting times. On the contrary, the US network shows better coordination although its routes to secondary airports have gradually been marginalized.

Current air traffic forecast methods employed by the FAA assume that the structure of the network of routes operated by airlines does not change. Because of the dynamic nature of connections, this creates a gap between the fore casted and actual state of the US Air Transportation System in the long term, providing insufficient situational awareness to major stakeholders and decision-makers in their consideration of major technology and policy changes. In [5, 6], Kotegawa et al. develop algorithms to forecast the likelihood of unconnected city pairs to be connected in the future, primarily based on the nodal characteristics of airports in the US network. Similar forecast research is undertaken by Zhang et al. in [7]. Their forecast algorithm is based on different gravity models, which are used to predict the movement of people considering population and distance between any two places. Their work shows that airports in close vicinity tend to have collaborative rather than competing effect on air passenger demand. Controlling other effects, the closer the proximity of the airports, the higher the air passenger demand. Airports within a 550km radius have strong interactions in terms of attracting long distance international air passengers. Travel generation seems dissimilar for the studied hub airports and their connected spoke airports.

3 Delay Propagation and Performance in the Air Transportation System

In [8], experts from the FAA and Eurocontrol provide a comparison of ATM-related performance on both sides of the Atlantic ocean. They record similar arrival punctuality levels in Europe and the US, but higher variability in delays and related costs in the US. In the US, a schedule upwards creep and down-sizing is observed, departure punctuality is better but taxi out delays are longer and associated with higher unit fuel burn. Direct route extension, i.e. the difference between the actual trajectory and the direct path between origin and destination, is approximately 1% lower in the US than in Europe, providing the corresponding fuel burn benefits. There is no superior performance in terms of arrival transit time in the Terminal Maneuvering Airspace (TMA), except for London Heathrow.

Significant effort has gone into trying to better understand delay propagation in the air transportation network over the past few years. Indeed the cost of congestion in such a tightly interconnected network of airports and aircraft is huge, $41 billion in the US in 2008. Pyrgiotis et al. design an analytical queuing and network decomposition model that computes the delays due to local congestion at individual airports and captures the "ripple effect" causing the propagation of such delays [9], both in the US and in Europe. AhmadBeygi et al. study the relationship between the scheduling of aircraft and crew members, and the operational performance of such schedules [10], in order to develop more robust airline planning tools. Their work is based on propagation trees and the introduction of metrics (total propagated delay, magnitude, severity, depth, depth ratio, stay, crew-out, split and split ratio) to quantify the impact of delay propagation in the network. They make the following observations:

- Propagated delays create significantly more impact than the original root delays themselves,
- A single delay can "snowball" through the entire network,
- Keeping aircraft and crews together can help to mitigate the impact of disruptions,
- Delays that occur early in the day can cause greater propagation than delays later in the day,

- It is most important to prevent delay propagation early in the day.

From a more theoretic point of view, Kondo shows that the propagated delays are exponentially distributed by fitting the Weibull or Gamma probability density functions [11]. This work is based on the delay multiplier, i.e. the ratio of the propagated delay to the earlier delay.

Because flight cancellations are rare (less than 3% of domestic flights), they are difficult to predict. Research shows that flight cancellations are less likely on more competitive routes, flights into and out of hubs, and infrequently served routes. Full flights are inversely proportional to the likelihood of being canceled. Seelhorst et al. [12] investigate the relationship between flight cancellations and delays. They identify the factors inducing flight cancellations, using the characteristics of the routes, airports, aircrafts, passenger traffic and delay for domestic US flights. The cancellation prediction are used to estimate the reduction in flight delays caused by canceling some flights.

In [13], De Neufville points out that airport traffic used to be dependent on regional population and economic activity is becoming more dependent on airline and airport management. The development of "no-frills" airlines and low-cost carriers, and the expansion of secondary airports in metropolitan regions have led to the emergence of a parallel airport system. This parallel network can be distinguished from the traditional airlines network by the following characteristics: a distinct low-fare, no-frills product; an almost total lack of connectivity with the traditional full-service airlines; operations focused on uncongested, low-cost airports; distinct geographical networks with links that traditional full-service airlines do not duplicate. The growth of this parallel network could lead to the shift of passenger traffic from congested airports to low-cost secondary airports, the growth of suburban regions with low-cost airports and the decrease of traffic growth rates at major airports.

The multi-airport system is defined as a system with a set of airports that serve the air traffic of a metropolitan area. Many of these airports have coordinated operations in terms of sharing regional airspace, building metroplexes: some act as reliever airports in case of overshooting of capacity at other airports. The FAA has identified 14 airports in 10 major metropolitan regions in the US that will be capacity constrained by 2015. Nayak's disseration [14] provides valuable insight on quantifying the interdependencies between airports in a multi-airport system and it investigates the delay propagation from the system to the rest of the National Airspace System (NAS) and vice-versa. They show that queuing delay and adverse weather are major causal factors of delay in most of the studied regions. They stress the inter-dependability among different airports, the existing conflicts in airspace and the need for proper regional level airport and airspace planning. In particular, delays in the Washington-Baltimore, New York and South Florida regions have greater impacts on delays in the rest of the NAS.

In [15], the authors challenge traditional network theory and its applications to airline networks. Their analysis of the individual structures of the seven largest passenger carriers in the US show that networks with dense interconnectivity (with large k cores for high values of k, where the k-core of a graph G is a maximal connected subgraph of G in which all vertices have degree at least k) are very resilient to both targeted removal of airports and random removal of flight segments. They propose network rewiring schemes that increase resilience to different level of perturbations while maintaining the total number of flight and gate requirements. Although other studies have shown the optimality of the hub-and-spoke networks for nominal operating conditions, their findings suggest that point-to-point networks can be more resilient to perturbations. To support their point, they establish that Southwest Airlines is very resilient to both random and targeted failures of nodes and edges. Hubs located in the core of the network increase efficient connectivity but are critical targets. Hubs in the periphery offer smaller benefits with respect to efficiency but their failures do not destroy the connectivity of the rest of the network.

In Europe, reactionary delays, or "knock-on" effects, add up to nearly half of the delay minutes. Cook and al. [16] evaluate the costs of reactionary delays as a non-linear function of primary delay duration. They contrast flight-centric and passenger-centric delay propagation, and highlight the need for tactical delay models, taking into account marginal costs, reactionary cots and non-linearities.

4 Collaborative Decision Making

A number of European airports have, over the past decade, taken major steps that aim at coordinating surface operations with airborne traffic. These Airport CDM or, in short, A-CDM programs have resulted from many years of implementation efforts. Several European airports have by now completed their conversion to A-CDM. The objectives of A-CDM are to reduce delays and improve system predictability, while optimizing the utilization of resources and reducing environmental impact. Airport Collaborative Decision Making is one of the five priority measures in the Flight Efficiency Plan published by IATA, CANSO and Eurocontrol. An airport is considered a CDM airport when A-CDM Information Sharing (ACIS), Turn-Around Process (CTRP) and Variable Taxi Time Calculation (VTTC) concept elements are applied at the airport [17]. In the US, the CDM-based ground delay program planning and control appeared in 1998. Nowadays, more elaborate CDM-based tools are used for the control and planning of airspace flow programs. In Europe, airport CDM has been implemented successfullly at several airports and are expanding. Collaborative Air Traffic Management is now a key component in both SESAR and NextGen.

In [18], the authors develop and analyze two approaches to incorporate stochastic optimization models in a CDM-like setting. These models are able to create a traffic flow management plan for a set of flights whose flight plan intersect a volume of airspace undergoing a severe capacity reduction. In their scenarios, the ANSP allocates certain resources to the flight operators and the flight operators then optimize the use of resources they are given.

In the USA, the stakeholders for the CDM are the Joint Government Industry program, the Airlines (24 airlines), the FAA: ATC and Air Traffic Flow Management, the Airports.The mechanisms involve the provision of accurate data to stakeholders (estimates of arrival and departure times), the share of information, the airline decision to cancel or delay flights, and the rescheduling with priority constraints (to airlines that have canceled flights).

In [19], the authors seek to answer the following question: How should proposed enhancements to Traffic Flow Management be evaluated in a CDM environment? They build a sequential evaluation procedure including airline disruption responses and a quasi-compression operation, to mimic the three stages of the CDM process.

One of the first efforts to evaluate the potential of CDM at the network level is undertaken by Bertsimas and Gupta [20]. They propose an Air Traffic Flow Management model with a CDM framework from an airport setting to an airspace context incorporating fairness and airline collaboration. Their empirical results of the proposed model on national-scale, real world datasets, show promising computational times and a proof of the strength of the formulation.

5 Disruptions in Air Traffic and on the Ground

When a disruption occurs, airline schedule recovery tries to maintain operations and get back to schedule as quickly as possible while minimizing additional costs. The different mechanisms they rely on are aircraft swaps, flight cancellations, crew swaps, reserve crews and passenger rebooking. Usually airlines react by solving the problem in a sequential manner. First, infeasibility of the aircraft schedule is examined, then crewing problems, ground problems and finally the impact on passengers. In this process, the passengers' issues are the last accommodated.

In [21], Marla et al. introduce flight planning, to enable flight speed changes, to trade off flying time and fuel burn, in combination with the available mechanisms. Their computational model for integrated aircraft and passenger recovery with flight planning could bring up to an 83% reduction in passenger disruptions, as well as a 5% cost savings to airlines.

From a more theoretical standpoint, Lacasa et al. [22] study the diffusion of aircraft as dynamic agents in the European air transport network, comprised of 858 airports and 11,170 flight routes. They distinguish between a free phase, i.e. an efficient regime with no airport queues and high diffusivity, and a congested phase, where there exist bottlenecks and poor diffusivity, separated by a jamming transition. This behavior does not depend on the network topology. They suggest that this could be the basis for testing cooperative behaviors aiming at optimizing the dynamics of the system.

The initial implementation of CDM started with Ground Delay Programs. Balakrishnan [23] examine the design of slot reallocation mechanisms for the Ground Delay Programs adopted at airports during adverse weather disruptions. A range of airline strategies in the prioritization of flights is offered compared to the existing techniques in use. Yet transfers between airlines during slot reallocation needs further analysis to determine its acceptability from the policy and stakeholder standpoints.

In [24], a control theory approach is adopted to address disruptions due to weather in the NAS. Le Ny et al. present a modeling framework to the feedback control of traffic flows in eulerian models, to help prepare the NAS for fast recovery from a weather event. Their work covers the management of airport arrivals and departures constrained by runway capacity, which are sensitive to weather.

In his dissertation, Vikrant Vaze [25] evaluates the congestion impacts on the NAS stakeholders while explicitly accounting for their interactions and proposes congestion mitigation mechanisms that are beneficial to these different stakeholders. By measuring the NAS capacity inefficiently utilized, the author find that at the current level of passenger demand, delays are avoidable to a large extent by controlling the negative effects of competitive airline scheduling practices. The level of congestion in a system of competing airlines is shown to be an increasing function of the number of competing airlines, a measure of the gross profit margin and the frequency sensitivity of passenger demand.

Over the past few years, severe weather perturbations have paralyzed the air transportation system, such as Hurricane Sandy in the US recently. On the European side, the eruption of the islandic volcano in 2010 had the longest and biggest economic impact on aviation [26], with more than 100,000 flights canceled. Bolic et al. offer recommendations to better address such large disruptions, stressing the need for harmonization of volcanic ash risk thresholds and better information exchanges between all the stakeholders, with for instance a central repository of all information related to a given crisis.

6 Multi-modal Transportation

The Eyjafjallajokull volcanic eruption in 2010 had such an impact on aviation that it also had a series of knock-on effects on other modes of transportation. These can be explained by the rigidity and complex nature of transport networks, as well as by the lack of appropriate preparation. Steele et al. pose the problem of predicting the changes in passenger demand between different modes of transports during a disturbance of one or more of its systems [27]. Their research develops a simplified dual-mode UK transport model using system dynamics and recent data, to test responses to disturbances.

Similarly, in [**?**], Lewe et al. tackle the problem of forecasting multi-modal transportation demand.They combine a Systems Dynamics Approach with an agent-based model, and use historical data to calibrate predictions.

The partial substitution of some short-haul flights with High Speed Rail transport, either through modal competition or complementarity, is already in place in four European hubs (Frankfurt Main, Paris CDG, Madrid Barajas, Amsterdam Schipol). Janic [28] assesses the potential savings in the quantities and related costs of social and environmental impacts, such as airport air side delays, noise and emissions of greenhouse gases. The results show that the High Speed Rail substitutive capacity does not act as a barrier to developing air/rail substitutions at the airport. Even a a modest substitution may produce substantial savings in airline costs and passenger delays.

The recent growth of Low Cost Carriers and their use of secondary airports implies that air traffic is further scattered across several airports in the same metropolitan area. This has multimodal implications for airport access planning, and explains the cooperations between some LCCs and bus or coach companies (such as Terravision with Ryanair). In [29], Castillo-Manzano studies the transport mode to reach the airport of more than 20,000 passengers at seven Spanish airports, none of which with efficient rail-based public transportation at the time. He shows that LLC passengers are less likely to use a taxi to go to the airport and more likely to choose a rented car or a public mode of transportation.

In her dissertation Zhang [30] develops a framework to reduce passenger "disutility" due to delay and mis connection, to help airlines reduce operating cost and recover schedule more promptly, and to assist traffic flow managers to utilize and distribute scarce resources more efficiently and equitably. The study suggests that when there is a significant capacity shortfall, airlines with hub-and-spoke networks could incorporate ground transport modes into their operations. Real-time intermodalism includes the substitution of flights by surface vehicle trips and, when the hub is part of a regional airport system, the use of inter-airport ground transport to enable diversion of flights to alternate hubs. It recommends that the current CDM system be enhanced to realize a regional Ground Delay Program (GDP) by including regional transport agencies, regional airport authorities, airlines serving regional airports and others. These enhancements cannot be realized without collaboration between FAA, airlines, airports, passengers, and consensus on the importance of integrating underutilized regional airports into disruption recovery strategies.

For the passengers, traveling across several modes of transportation to complete their journey can be difficult, especially when it comes to planning travel times. To improve the passenger's experience, more and more advanced transport information systems (ATIS) provide services such as route planning, navigation, updates on disruptions, real time information alerts and replanning tools. Zhang et al. [31] build a supernetwork, where the networks for different modalities are integrated. They distinguish road, rail, air, water transportation as well as private (e.g. foot, bike, car) or public modes (e.g. bus, train, tram, metro). While routing in this supernetwork, the switch between modes occurs only when the transfer is possible. Some links are time independent, others time dependent or stochastic time dependent. The travel time and monetary cost may also be computed. The authors tested their tool for the Eindhoven region with success and are working on improving the computation time of their model.

Reliability of the schedule in a multi-modal trip is essential. Also, the traveling time in each mode and the waiting times in between should be balanced to improve passengers' experience. Hsu [32] develops a simple model to represent the transfer waiting time for a connecting service at multi-modal stations, where waiting time takes into account the characteristics of both the connecting service and its feeder service. The results show that transfer waiting times is mostly affected by the capacities and headways of the connecting and feeder services. They suggest that transfer waiting time cannot be improved without operational coordination with the feeder service.

The Strategic Research and Innovation Agenda (SRIA) is the new strategic roadmap for aviation research, development and innovation developed by ACARE. In the customer-centric mobility topic, "planning, payment and single ticketing support for intermodal journey selection" is expected to have started by 2020. By 2050, "door-to-door integrated journey planning, payment and single ticketing & accountability, and automatic journey monitoring and disruption management for over 90% of journeys" are to be in place.

7 Shifting the focus of transport operations towards the passenger

Flight delays do not accurately reflect the delays imposed upon passengers' full multi-modal itinerary. The growing interest to measure ATM performance calls for metrics, that reflect the passenger's experience. Cook and al. [33] design propagation-centric and passenger-centric performance metrics, and compare them with existing classical metrics, with regard to intelligibility, sensitivity and consistency. Their list of propagation oriented metrics comprises: departure and arrival delays, canceled flights, extra flight time, extra gate time, reactionary minutes, back-propagation, reactionary disruptions and their depth. The passenger oriented metrics cover: departure and arrival delays, the ratio of scheduled trip time to final arrival delay, canceled flights, missed connections, re-routes, extra flights, extra flight time, weighted load factor, aborted trips and extra wait time. The authors also identify the top ten critical airports in Europe according to three different network classifications.

In [34], Bratu et al. calculate passenger delay using monthly data from a major airline operating a hub-and-spoke network. They show that disrupted passengers, whose journey was interrupted by a capacity reduction, are only 3% of the total passengers, but suffer 39% of the total passenger delay.

The objectives of Wang's dissertation [35] are to estimate Air Transportation System-wide passenger trip delay using publicly accessible flight data, and investigate passenger trip dynamics out of the range of historical data by building a passenger flow simulation model to predict the impact on passenger trip time given anticipated changes in the future. The author did not have access to airline proprietary data. Airline data is also protected by anti-trust collusion concerns and civil liberty privacy restrictions. This is an obstacle to a straightforward way of evaluating passenger-centric metrics. The major findings from this research on 1,030 routes between the 35 busiest airports in the US in 2006 are as follows:

- High passenger trip delays are disproportionately generated by canceled flights and missed connections.
- Trend analysis for passenger trip delays from 2000 to 2006 shows the increase in flight operations slowed down and level off in 2006, while enplanements kept increasing, due to a continuous increase in load factor. Passenger performance is very sensitive to changes in flight operations, with an increase in annual total passenger trip delay in 2006, while flight operations barely grew.
- Route delay is shown to have an asymmetric performance on passenger trip delay in terms of routes and airports. 17% of routes generate 50% of total passenger trip delays. 9 of the busiest 35 airports generate 50 % of the total passenger trip delays.
- Congestion flight delay, load factor, flight cancellation time and airline cooperation policy are the most significant factors affecting total passenger trip delay.
- New system performance measurements from the passenger's view are developed, based on the Estimated Passenger Trip Delay.

Understanding the passengers' preferences is essential in a period of multi-airports regions' growth and intense competition between airlines, whether legacy airlines or low-cost. This is especially the case in regions where the increase in air traffic is most important. Four major competing airports are now located in the Hong Kong-Pearl River Delta region. Loo et al. [36] model the choices of air travelers for international and domestic flights, and describe scenarios of regional airport competition and airport coordination. Their continuum approach offers good results to understand the geography of air transportation, with possible simultaneous changes in variables. These variables comprise average propensity to travel, spatial distribution of air travelers, regional inflows and outflows of passengers, ground transportation infrastructure capacities, number and physical location of airports, ground transportation cost, congestion effect, cross-border cost, airport Level Of Service (LOS) and government's aviation policy. Later, Loo [37] identifies the determinants conditioning why passengers choose an airport over another within the same multi-airport region. Using stated preference data, the most important airport LOS attributes are air fare, access time, flight frequency and the number of airlines. In comparison, the number of airport access modes, access cost, airport shopping area and queue time at check-in counters were not significant. Slight differences are noted between long, medium and short haul, business or leisure passengers.

The needs and priorities of passengers once inside the terminal are hard to quantify. Correia et al. [38,39] study LOS measures for airport passenger terminals. They combine user perceptions and regression analysis to derive quantitative relationships and provide an illustration at Sao Paula Guarulhos International Airport. 119 passengers were interviewed. The following components are evaluated: emplaning curbside, ticket counter and baggage deposit, security screening, departure lounge, circulation areas and concessions. A similar effort regarding transfer passengers was carried at Banadaranaike International Airport in Sri Lanka, an international hub from Europe to South Asia and India. This research identified the factors that most mattered to improve the transfer passengers' experience.

Airports provide aeronautical and non-aeronautical services. Commercial activities are essential to the sustainability of many airports. Torres et al. [40] show that passengers' waiting times to board influence their possibilities for consumption. They also distinguish patterns specific to business and leisures travelers. Popovic et al. [41] examine how activities influence people's experiences in the airport, as part of a larger project to investigate passenger experiences and interactions with information, services, processes, equipment and technology at the airport. The macro-level encompasses the overall passenger flow at departure, including entering the terminal, check-in, security, customs and boarding. The micro-level focuses on passenger interactions at the domain level, such as the check-in counter, currency exchange, security check and discretionary activities.

Ma et al. [42] tackle the problem of simulating and understanding passenger flows to predict future capacity constraints and level of services. Their work uses agent-based models to simulate advanced passenger traits to enable detailed modeling behaviors in terminal buildings, particularly the check-in areas. Their scenarios demonstrate the progression of adding self-service check-in use, use of cafe, information and phone booth, based on passenger' comfort with technology, hunger, travel frequency. The simulations show a spread of passengers in the space and the peak check-in queuing times, which can be reduced by spreading passengers amongst the full range of facilities. Passengers also show more instantaneous utilization of the departure hall area than when only check-in is simulated.

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