OPTIMAL CONFIGURATION OF COMPLEXES OF LARGE AIRPORT PASSENGER BUILDINGS AND THEIR INTERNAL TRANSPORT SYSTEMS

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ABSTRACT

This paper identifies optimal configurations for complexes of large airport passenger buildings, including their internal transport systems for passengers and bags. Spreadsheet models supported by queuing theory and decision analysis defined the performance, over multiple criteria and a range of situations, of combinations of configurations and technologies.

The analyses considered four configurations:
    Midfield Linear, as at Denver,
    Midfield "+", as for the new Kuala Lumpur,
    Centralized Linear with Midfield Linear, as at Atlanta,
    Centralized Pier with Midfield "X", as at Pittsburgh;
together with four passenger transport technologies:
    self-propelled automated people movers (APM);
    cable-driven APM;
    shuttle buses; and
    moving sidewalks;
and three baggage systems:
    single-bag destination-coded vehicles (DCV);
    multi-bag carts (Telecar); and
    tugs and carts.

Linear designs with Midfield Concourses appear preferable for complexes of airport passenger buildings designed to handle from around 10 to 40 million annual passengers. Cable-driven APM and tug and cart systems perform well for complexes designed for up to 20 million annual passengers, but self-propelled APM and DCV appear better for larger complexes and those with the possibility of expansion. Centralized Pier with Midfield "X" configurations appear preferable when parallel runways are closely spaced.

INTRODUCTION

The selection of a design for airport passenger buildings and their technology for moving passengers or bags is a significant issue. Errors can be extremely costly. Thus Kansas City lost about a third of its traffic when TWA moved its base of operations to St. Louis because the then new design of the terminal buildings was inadequate for transfer traffic. Designs that appear sound at the start may be inappropriate for future environments -- for example when the percentage of transfer passengers increases significantly, as it has been doing at many major hubs internationally. The question is: what is the best design?

This paper describes recent work that contributes to this discussion in three ways. First, it extends the analysis to include the most important recent innovation in airport planning, the use of long-distance internal transport systems such as people movers and destination coded baggage systems. Previous studies have focused on the buildings.

Second, the new work applies multiple criteria, including passenger waiting times and aircraft taxi times, over a broad range of loads. The idea is to identify designs that both meet the various needs of different users, and ensure good performance as traffic levels increase. This approach contrasts with the traditional focus on minimizing walking distances for travelers.

Third, the work incorporates realistic descriptions of the complex ways airlines and airport managers operate the passenger buildings, for example by assigning aircraft with significant transfer traffic to nearby gates. This contrasts with studies that either simply calculate maximum and average distances implicit in various layouts (R.M.Parsons, 1973; Anglo Japanese Airport Consortium, 1992) or use formulas to describe the distribution of aircraft at the gates and optimize the number and shape of finger piers and midfield concourses (Wirasinghe et al, 1987,1992; Bandara et al, 1990, 1992).

Efficient computer models have been the key to carrying out this work, which is far more comprehensive -- in terms of the design elements, the measures of performance, and the expansion possibilities -- than previous studies. The computer models are suites of "spread-sheets" that, through their cell structure, permit the analyst to consider many different, interactive elements, in many different situations, "at the touch of a button". Svrcek (1994) pioneered the application of this approach to preliminary planning.

The presentation first discusses the range of elements examined: the configurations of the airport passenger buildings; their size; and the corresponding transport technologies, both for passengers and bags. It next describes the methodology, presents results of the analyses for each of the criteria of evaluation, and concludes with an overall assessment.

CONFIGURATIONS OF LARGE AIRPORT BUILDINGS

Virtually all configurations of airport passenger buildings can be organized into a few primary categories based on their location on the airport, their geometry and their functional philosophy. Locationally, the key issue is whether the building elements are on the landside or in the midfield (and then connected to the landside by some transport system, as at Atlanta or Denver). Midfield concourses are the modern extension of the concept of satellites. For large airports, designed to serve 10 to 50 million annual passengers, midfield concourses now constitute a regular, and often preferred design alternative. (de Neufville, 1995)

Geometrically, the major distinction is between buildings that are linear and those that involve several piers projecting into the airfield. Midfield pier configurations are crosses, described according to their orientation to parallel runways: "X" if they are rotated as at Pittsburgh or Hong Kong/Chek Lap Kok, or "+" if they are at right angles as at the new Kuala Lumpur/Sepang. This distinction is important because it has significant implications for the efficient use of land and the cost of aircraft movements.

Functionally, it is possible to distinguish on the landside between centralized and decentralized facilities. Centralized facilities process the passengers in one major facility and thus provide a convenient way to access the mass transport systems that are becoming integral to the design of large airports. Decentralized facilities consist of separate access points strung along the landside, as at Dallas/Fort Worth, New York/Newark or Miami/International. Decentralized facilities reduce the walk distances for originating and terminating passengers, but increase the walk distances for transfer passengers (de Neufville and Rusconi-Clerici, 1978) and require costly duplication of manpower and equipment. These disadvantages mean that decentralized landside facilities are now rarely seen as an option for new large airports.

Table 1 summarizes the major pure concepts of airport passenger buildings for large airports. Each of these can be combined to form “hybrid” designs that borrow the most desirable features from the “pure” designs to create a configuration that provides a higher level of service to different passenger types, and may be more flexible to changes in future demand patterns. Examples of hybrid configurations of passenger buildings are at Atlanta (centralized linear with midfield linear design) and at Pittsburgh (centralized pier with a midfield “X”).

Table 1 : Elements of Large Airport Passenger Buildings

		Location of Buildings	
		Landside	Midfield
Geometry of Building	Linear	Centralized Linear	Linear
	Pier	Centralized Pier	"X" or "+"

TRANSPORT TECHNOLOGIES FOR AIRPORT PASSENGER BUILDINGS

The technologies for transporting passengers and bags within airports have evolved remarkably recently, along with the rapid deployment of people movers and automated baggage systems worldwide. These are summarized below, based on an extensive database on the location, layout, capacity, cost, and performance of these systems (assembled by Phua (1995) and available on request).

People Mover Systems: Two types of Automated People Movers (APM) are in use at airports: self-propelled and cable-driven. Self-propelled systems have the advantage of good performance over a wide range of distances, and easy expansion both of capacity and over the airport. Self-propelled systems are thus more common, constituting 19 out the 21 of installations on airports (Phua, 1995).

Self-propelled APM usually run on dual lanes as this arrangement enables frequent service, high capacity, and redundant reliability. They operate either as shuttles or on "pinched" loops that permit more than two APM to operate on two guideways. Shuttles operate well over shorter distances, up to 1250m. at Birmingham, England. Pinched loops are preferable over longer distances, up to 4400m. at Chicago/O'Hare, but more expensive because they require sophisticated controls to avoid collisions, operate switches and schedule trains.

Self-propelled APM can be easily be expanded. The system at Hong Kong/Chek Lap Kok, for example, has provisions to modify the initial dual-lane shuttle to a pinched-loop to serve the future midfield "X" shaped concourse. Similarly, the guideways at the new Denver airport can be extended to serve additional midfield concourses. Capacity can simply be increased by adding more cars to trains or more trains.

Cable-driven systems are usually cheaper and easier to operate. Their propulsion is a simple ropeway technology, and their controls are stationary and located within the passenger building. Their average capital cost is about 10% lower than that of self-propelled systems.

Cable systems operate as shuttles over short distances, as at Tokyo/Narita and Cincinnati. They are limited to shuttle operations, because each vehicle is attached to a cable and cannot cross over to a parallel guideway. Being also slower than self-propelled systems, their capacity is limited. Cable systems are thus generally unsuitable for situations requiring multiple stops, high capacities or travel beyond about 1.2km.

Buses are the major alternative to APM They operate over the aprons to remote aircraft stands, and along the circulation roadways in front of passenger buildings. Larger buses seating 100 passengers cost around US $330,000 each. In general, buses provide a low level of service as passengers can be uncomfortable exposed to the weather. Their great advantage is that they can be deployed to provide capacity when and where needed. They are often used to deal with seasonal peaks, as at New York/Kennedy, Zurich and many other airports.

Moving sidewalks, finally, provide the conventional passenger transport in airports. They are relatively inexpensive, costing around US $10,000 per meter. Their disadvantages are that they are slow, form barriers to transversal movements, and travel only in straight lines.

Baggage Transport Systems: Delivery time and reliability are the important criteria of performance for baggage operations. Distance is not the key factor it is for passengers, since baggage is not inconvenienced by long distances. The main baggage transport systems for long distances are Destination Coded Vehicles (DCV), Telecars and tugs and carts.

DCV systems potentially provide the best service: both high speed transport and sortation of the bags. Their disadvantage at present is that they are expensive, costing around US $10,000 per meter of track plus another US $10,000 per vehicle, and still under development, as the experience at Denver shows (de Neufville, 1994)

The DCV at the new Denver airport feature a tilt-tray on top of each vehicle, allowing bags to be automatically loaded and off loaded in the same manner as a tilt-tray sorter. This arrangement enables a continuous flow of bags, potentially minimizing delivery times. This design of course requires sophisticated and expensive controls.

Table 2 : Existing Telecar and DCV Systems (BNP 1990)

System	Telecar		DCV	
Airports	Atlanta	Singapore	San Francisco	Denver
Terminal	Delta Airlines	T1/T2	United Airlines	
Vehicles	80	20	184	3800
Length (km)	~1	2.5	2	32
Open in	1981	1990	1975	1995

Telecars provide high-speed, high capacity transport with no capability for sortation. The carts are propelled by linear induction motors along tracks at a top speed of about 32 km/h.

They are each capable of carrying around 10 bags and are loaded and, in practice, off loaded manually This system thus entails extra cost and delays compared to DCVs, due to the time and labor required to handle and sort bags. Telecars cost about US $8,000 to $10,000 per meter of track, including vehicles. Table 2 gives some data on the two systems.

Tugs and carts constitute the most basic system, used virtually everywhere. Their advantages include minimal capital costs of equipment (about US $29,000/tug and $3,500/cart), high capacity and reliability. Disadvantages are associated with labor intensity, leading to the high operating and maintenance costs, and low speed, leading to unacceptable delivery times over distances greater than around 800m.

Tugs and carts should be an integral part of the design of automated systems of baggage transport. They are most useful for routine emergencies, for example in transferring "hot" bags "tail-to-tail" between aircraft making connections with little time to spare. They are also used when time is not essential, for example at the new Denver airport, to deliver of bags to pick-up stations but not to departing aircraft. Of course, they also back-up automated systems against failure.

METHODOLOGY

The analyses to the determine the optimal configurations of large airport passenger buildings considered a broad range of traffic levels, building configurations, transport technologies, and sophisticated modes of managing the expected non-linear queuing conditions. No analytic formulas could describe these combinations. The analyses were made possible by suites of spread-sheet models, described by Svrcek(1994) and applied by Phua(1995). The results give reasonable first-order accuracy, sufficiently useful for defining preferable configurations.

This study looked at three levels of traffic: an airport capable of handling up to 20 million annual passengers, a larger airport handling up to 40 million, and an expansion from the smaller to the larger airport.

Four concepts were examined: Midfield Linear, Midfield “+”, Hybrid Centralized Linear with Midfield Linear, Hybrid Centralized Pier with Midfield “X”. Their geometric representations provided a consistent platform for comparing the concepts objectively using standard assumptions for fleet mix, building and aircraft characteristics; and defined the distances between points within a configuration. Together with matrices of probabilities that each distance is traversed by passengers or baggage, the model estimates the performance of a given configuration using criteria such as the distances passengers walk or aircraft taxi between exit taxiways and gates.

The passenger transportation technologies considered include self-propelled and cable-driven APM; shuttle buses; and parallel moving sidewalks -- each in appropriate numbers .

The baggage transport technologies compared are the DCV, Telecar and tugs and carts, which are also assumed to supplement the automated systems. Unlike passengers where the terminating traffic defines the critical surges of traffic, originating traffic is critical for baggage since flight close-out times depend largely upon the delivery times of the last departing bag.

The queues and delays associated with different technologies were analyzed with a computerized spreadsheet model developed to determine the multiple criteria performance of possible combinations of transport technologies and building configurations over a broad range of situations. The congestion that occurs in airports is always undergoing dynamic change so that the queuing processes rarely attain steady-state (Odoni and de Neufville 1992). The appropriate method for dealing with these transients is the approximate fluid dynamics approach (Newell, 1971). It has been used to size departure lounges (Horonjeff and Paullin, 1969) and ticket counters (de Neufville and Grillot, 1982).

RESULTS

The analyses led to three notable results concerning the elements of the system:

Linear concourses are broadly preferable to "X" or "+" midfield concourses;
Self-propelled are generally preferable to cable-driven APM; and
DCV or tug and cart systems are best, depending on the size of the complex.

These findings are discussed individually and then integrated into the conclusions.

Linear Concourses are broadly preferable: Linear midfield concourses minimize walking distances for most people, as compared to cross-shaped, "X" or "+" concourses. This result is contrary to the simple intuition, that the cross-shaped concourses are better because they minimize the maximum theoretical distances, but is easily explained.

Cross-shaped concourses are inefficient at providing aircraft gates. All the space around the intersection of the piers is unavailable to aircraft. In rearranging the concourse from a straight line to a cross, considerable length must be added in order to provide the same number of aircraft gates. The total length of piers in a cross-shaped configuration is about 40% greater than for linear concourses! This inefficiency is expensive. It also increases the length of the building the passengers must traverse.

Cross-shaped concourses further increase walking distances because they impose a perverse pattern of gate assignments. As only the smaller aircraft can fit into the angles at the center, the larger aircraft, with the most passengers, must park furthest away, toward the ends of the piers. Linear concourses however enable airlines to minimize average walking distances by

Table 3 : Linear Concourses Minimize Average Walk Distances (Phua, 1995)

Configuration of Airport Passenger Buildings	Relative Distance	
	Average	Maximum
Centralized Linear with Midfield Linear	1.00	1.85
Midfield Linear	1.03	1.77
Midfield “+”	1.08	1.28
Centralized Pier with Midfield "X"	1.13	1.39

placing the biggest aircraft with the most passengers right at the center, next to the people-movers, relegating the smallest, commuter aircraft to the far ends. United Airlines does this at Denver. Table 3 shows the result: linear concourses provide the lowest average walking distances.

Linear concourses have the further advantages of using the airfield space efficiently. Within a space defined by the distance between parallel runways and a given width, linear concourses can provide many more airbridge positions that cross-shaped concourses. This is because the cross-shaped concourses define dead spaces between their piers that can, at best, be used for remote parking of aircraft. Svrcek (1994) demonstrated this in detail.

Linear concourses also minimize taxiing time, compared to the cross-shaped designs. Aircraft can proceed directly to a linear concourse with just two turns off of parallel taxiways, compared to the greater distances and three or four turns they must take to get to a gate on a cross-shaped concourse. (Svrcek, 1994)

The advantage of cross-shaped configurations is that they can provide many aircraft gates within a single building, especially when the available distances between runways is tight. This is important when extensive transfers have to occur between these gates, as they do for a major airline at a hub airport. This is the case at Pittsburgh, and for this reason the "X" shaped design is best for that location for the current industry structure.

Cross-shaped concourses are however usually difficult to expand, since they are constrained on all four corners by taxiways. Extending linear concourses, on the other hand, is typically easy as land is normally safeguarded for this possibility, as at the new Denver airport.

Self-propelled APM generally preferable: Self-propelled APM provide equal or better service than cable-driven systems. Where distances are smaller, both systems perform about the same. Self-propelled systems, configured with pinched loops and using multiple trains, offer dramatically better service when distances are great and traffic is high. APM of either sort offer better service than busses, and far better service than moving sidewalks, which are unacceptably slow for long distances.

Considering cost per passenger, including both capital and operating expenses, cable-driven APM or buses are more cost-effective for a smaller airport given the good performance of such systems over relatively short distances. But self-propelled APM are virtually necessary to ensure adequate service for the largest complexes of airport passenger buildings, and are more cost-effective for these situations.

The conclusion is that self-propelled APM are generally preferable whenever there is a reasonable possibility that the system will eventually be extended. Conversely, cable-driven APM are better for shorter distances when there is little chance of expansion, for example as installed at the Japan Airline building at Tokyo/Narita or connecting Terminals 1 and 2 at Singapore (where a self-propelled system is in place, however).

DCV or Tug and Cart systems are best: DCV provide rapid service over long distances, and reduce the costs and delays of manual handling -- at great expense. If the advantages of DCV are neither worthwhile nor needed, tug and carts provide the best system for handling bags. Telecars appear inferior overall because they involve additional manual handling, as compared to using tugs and carts, which costs time and money. At Singapore, for example, operators routinely prefer to bypass the Telecar system between Terminals 1 and 2.

The DCV system has the merit of being able to deliver bags from check-in to the aircraft over great distances within about 15 minutes. No other system can do as well. Airlines using DCV in the largest complexes of passenger buildings can thus allow passengers to board at virtually the last minute, and thereby reduce the perceived travel time to a minimum. For this reason United Airlines considers that DCV are essential to its operations at the new Denver airport, where its gates can be almost 2 kilometers from the check-in points.

DCV can also deliver bags upon arrival. In this case, however, neither their speed nor capability to sort is particularly valuable to customers. Tugs and carts provide adequate service, relatively inexpensively, for arrivals. For this reason United Airlines was satisfied to use tugs and carts for arrivals during the start-up of the DCV operations at Denver.

Cost is the big disadvantage of DCV. Comparing costs per bag, including both capital and operating expenses, the DCV system is the most expensive, about 40% more than the Telecar which in turn is about five times the cost of using tugs and carts. (Phua, 1995)

Since DCV may be a practical necessity for the largest complexes of passenger buildings, it may be wise to imbed the flexibility to install them in initially smaller airports designed for large-scale expansion, such as the New Seoul or Kuala Lumpur airports. For airports expected to serve only up to 20 million annual passengers, over relatively shorter distances, tugs and carts appear to be most cost-effective.

CONCLUSIONS

Linear midfield concourses are better than cross-shaped “X" or "+” concourses. Given the advantage of being able to practice flexible, intelligent gate assignments without any geometrical constraints nor “wastage” of land, linear concourses provide a higher level of service to most passengers by way of reduced average walk distances. The “X" or "+” shapes benefit only a minority of passengers. Linear concourses also permit lower aircraft taxi times and more efficient aircraft movement.

“Hybrid” centralized linear configurations with midfield linear concourses (as at Atlanta) perform better than the “pure” midfield linear design (as at Denver) because they give a higher level of service to different passenger types. Their more balanced load distribution reduces overall walk distances and travel times. If constraints limit runway separations, then a hybrid centralized pier with midfield “X” configuration seems best. Table 4 summarily compares building configurations.

As regards technology, it is prudent to invest in self-propelled systems. These perform best for airports serving up to 40 million annual passengers, and provide the flexibility to expand the capacity of smaller complexes of airport passenger buildings. Cable-driven APM for passengers and tug and carts for baggage perform reasonably well for complexes of airport passenger buildings serving up to 20 million passengers per year. If expansion beyond this level is improbable, then a cheaper cable-driven system may be best. A more economical tug and cart system could also be adopted for smaller airports, with the provision to expand to a DCV system, thus providing the insurance against poor performance in the longer term.

Table 4 : Rankings of Four Airport Passenger Building Configurations (Phua, 1995)

Rank	Configuration	Advantages	Disadvantages
1	Centralized Linear with Midfield Linear	Lower Average Walk Efficient use of land High Level of Service for different passengers Flexibility for Expansion	Higher Maximum Walk
2	Midfield Linear	Same as above	Same as above plus High Level of Service only for transfer passengers
3	Centralized Pier with Midfield "X"	Good for close runways Lower Maximum Walk High Level of Service for many passenger types	Wasted space Higher Walk Distance Longer Taxi Time Less Maneuverability for Aircraft High congestion potential Less Flexibility for Expansion
4	Midfield "+"	Lower Maximum Walk	Same as above plus Extravagant use of Land High Level of Service only for transfer passengers Most costly

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