Airport Apron Roundabout – Operational Concept and Capacity Evaluation

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***Abstract* - The paper presents one of the initial steps in the evaluation process towards possible implementation of an innovative taxiway design at Munich Airport apron. A roundabout is proposed as a potential solution for the 12-line intersection area expected at redesigned Apron 3. The paper presents preliminary design and operations concepts of the roundabout, followed by its capacity evaluation. The aim was to analyze whether a roundabout is suitable, in terms of capacity, to replace a conventional intersection under Munich Airport operating conditions.**

Key words - airport apron; taxiway intersection; capacity evaluation; simulation; analytical modelling

I. BACKGROUND

The role of a taxiway system is to enable safe and efficient aircraft movements from the runway to aircraft stands and vice versa. An apron taxiway system should be designed to provide safe aircraft-to-aircraft and aircraft-to-objects separations. At busy airports, parallel apron taxiways are introduced to provide higher throughput by enabling aircraft passing in opposite directions, and greater possibilities (fewer restrictions) for simultaneous push-back operations. Two parallel taxiways are typically used at apron areas, even at the busiest airports.

Munich Airport (MUC) is a rare case, in terms of apron taxiway system configuration. It operates with three parallel taxiways across all three aprons, see Fig. 1. At Apron 2 standard yellow marking is used for all three taxiways. They are designed to allow simultaneous taxiing of the two largest aircraft (ICAO code letter F), or three smaller aircraft (up to C). In other apron areas, side taxiways, orange and blue, may be used simultaneously only by smaller aircraft (A, B and C). The yellow central taxiway is used by larger aircraft (D, E or F). It cannot be used simultaneously with the blue and orange side lines.

In the current state, the most complex intersection is located on the southern side of Apron 2 (red rectangle in Fig. 1) next to the unidirectional bridges, S7 and S8 (links between Apron 2 and the taxiway system related to the southern runway). The intersection consists of nine intersecting taxiways (three sides with three lines per side).

Following MUC development (a third parallel runway on the northern side, reconstruction of Satellite building into Terminal 3 and redesigning of Apron 3) a 12-line intersection (four sides with three lines per side) was initially planned at the redesigned Apron 3.

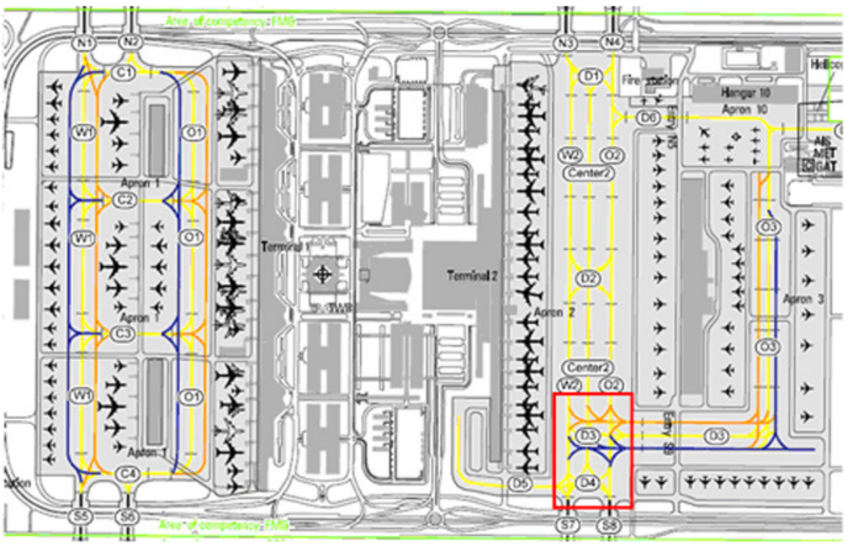

Figure 1. Apron layout at Munich Airport [1]

Such an intersection is seen as a potential problem (due to ambiguous traffic patterns, crossings, etc.) either for the apron controllers, or the pilots directly participating in the movement through the intersection. For this reason, a new potential design of the apron taxiway intersection area was sought out, aiming to provide a smoother flow than the conventional one, and at the same time, to allow capacity high enough to avoid the creation of local bottlenecks on the apron. The roundabout, a solution typically used for complex intersections in road transport, is proposed by MUC. An apron roundabout is not only an innovation for MUC, but an innovation in general, in terms of its purpose, design and location within the airport complex. MUC fully owns this roundabout solution for an apron intersection, both its technical and operational concepts.

The preliminary roundabout design is shown in Fig. 2. Dimensions, as given in Fig. 2, allow for three parallel yellow taxiways to be used simultaneously by three aircraft up to code letter C, or two larger aircraft (D, E, or F). The parallel orange and blue taxiways may be used simultaneously by two aircraft up to code letter C, while larger aircraft should use the central yellow taxiway and are not allowed to taxi simultaneously with any aircraft on the parallel blue or orange taxiways.

The circular taxiway centerline is designed to allow the safe movement of code letter F aircraft. It is unidirectional. A counter-clockwise direction is chosen, following the intention to place signs inside the circle so that they are visible from the captain's side of the aircraft.

Outer stop-bars are positioned at 60m from the circle tangent on each side, providing the required clearance between the apron taxiway and objects/aircraft for code letter F aircraft [2], [3]. Inner stop-bars divide the circle into equal quarters, as depicted in Fig. 2.

The apron taxiway directions, indicated by gray arrows, are adopted according to their expected usage in practice. The intersection under consideration is connected to the northern bridges, because the northern side is expected to have a greater load following construction of the third runway on the northern side.

The initially planned conventional intersection, located on the northern side of the apron area, is given in Fig. 3. Stop-bars W2' and O2' are placed at 60m from the closest yellow N-S taxiway. Stop-bars on the northern and southern side are as they are in the current intersection - at 40m from the D3' blue line and 50m from the D3' orange line. The same lateral separations between taxiways, and consequently the restrictions on simultaneous taxiway use are the same as for the roundabout intersection. Taxiway directions are indicated by gray arrows.

Fig. 4 and Fig. 5 show the locations of taxiing paths' merging and crossing points in the roundabout and conventional intersections, respectively. Only the lines in use, when line directions are as described earlier, are visible. Merging and crossing points are a certain indicator of intersection traffic pattern complexity.

The number of merging and, particularly, crossing points is significantly smaller in the roundabout case. Furthermore, in the conventional intersection the points are concentrated in the central intersection area, while in the roundabout aircraft taxi around the central area and that leads to the dislocation of potential conflict zones to four smaller peripheral areas.

Although by a rule of thumb the new design looks promising, a capacity evaluation was required before it could be taken into further consideration. The aim was to eliminate eventual capacity issues that could arise from a design that had not previously been used for the purpose of aircraft movements. The fact is that the roundabout covers a somewhat larger area, i.e. entry and exit points are further away than in the conventional intersection, implying a decrease in capacity.

Capacity evaluation was one of the initial steps in the overall evaluation process towards possible acceptance and implementation of the innovative taxiway intersection at MUC apron. The aim was to examine the performance of the roundabout operating in the MUC environment and to compare it to the conventional intersection under the same operating conditions.

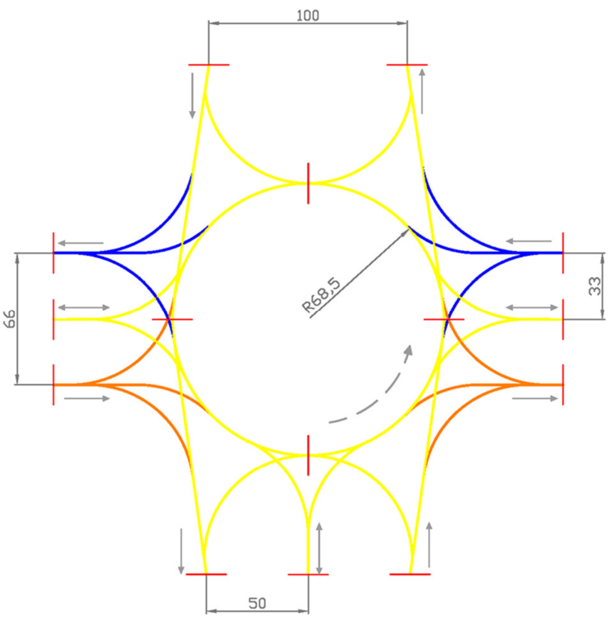

Figure 2. The roundabout geometry – preliminary design

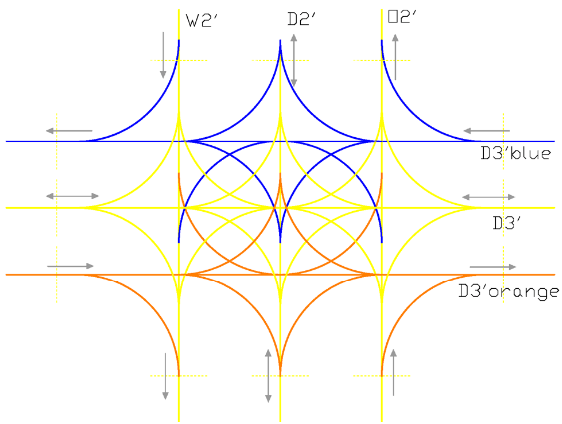

Figure 3. Geometry of the initially planned conventional intersection

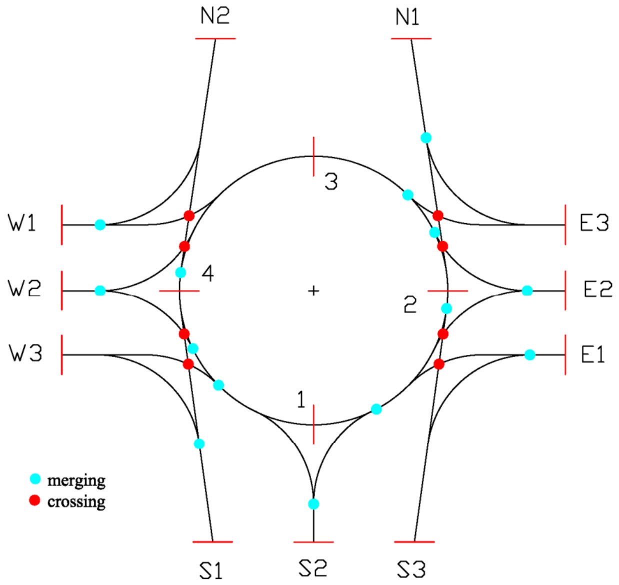

Figure 4. Merging and crossing points in the roundabout

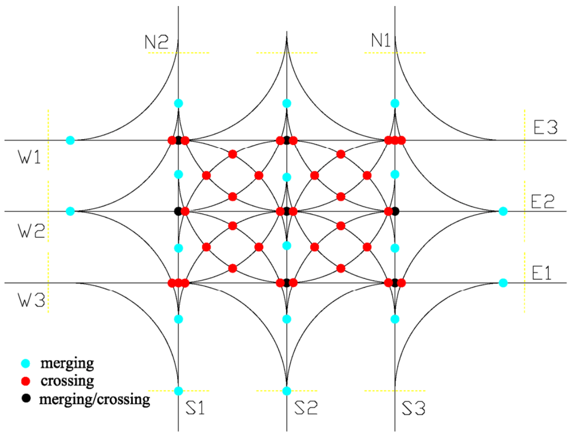

Figure 5. Merging and crossing points in the conventional intersection

The paper comprises the results from the project, [4] and [5], and findings from the thesis [6]. First of all, the operations model is described in Section II. The set of rules for the safe and smooth movement of aircraft through the intersection without violating separation requirements under MUC operating conditions is presented on the roundabout example. The same logic also applies to the conventional intersection. In order to obtain saturation capacity of the roundabout intersection under MUC operating conditions, a simulation model of the roundabout was developed. It is described in Section III, together with a conclusion based on the results from four traffic scenarios. Further on, for comparison of the two apron intersections, an analytical model for apron intersection capacity estimation was developed and it is described in Section IV. The roundabout and conventional intersection are compared based on the capacities obtained in all four traffic scenarios. Section V gives some concluding remarks on models for taxiway intersection capacity estimation and summarizes the results.

II. ROUNDABOUT OPERATIONS MODEL

Unlike the lateral ground separations recommendations, ICAO does not specify longitudinal separation minima for ground movements. In general, air traffic controllers, pilots and vehicle drivers use "visual observations to estimate the respective relative positions of aircraft and vehicles" [7]. Pilots and vehicle drivers rely on visual aids. During low visibility conditions, air traffic controllers rely on surface movement monitoring equipment and pilots' reports when monitoring spacing and identifying potential conflicts. [7]

Any exemptions from general practice in aviation, permanent or temporary, related to specific airport layout, or caused by equipment, obstacles, etc., require a specific set of rules for safe operations to be defined. Being an exception in ground movements, an apron roundabout is not expected to be operated on a "see and be seen" basis, but is rather a controlled area, regardless of visibility conditions. In this Section the set of rules for safe aircraft movements through the roundabout is defined, reflecting MUC operating conditions.

Longitudinal ground separation depends on the leading aircraft type and it aims to provide protection for the trailing aircraft from the jet blast. For the purposes of this study all aircraft were classified into two groups. Code letters A, B and C are grouped together as *small aircraft* and D, E and F as *large aircraft*. Safe longitudinal separation is assumed to be 60m behind small and 120m behind large aircraft, measured from aft end of the leading aircraft. That was confirmed as acceptable approximation by apron controllers.

In the model, *separation* refers to safe longitudinal spacing between the nose tips of two consecutive aircraft. It is determined as the sum of the aircraft length (adopted to be 40m for small and 70m for large aircraft) and required separation (60m behind small and 120m behind large aircraft), which makes the nose-to-nose separation 100m if the leading aircraft is small and 190m if the leading one is large.

The roundabout operations model is based on a general rule - when an aircraft reaches the entry stop-bar, the roundabout has to be checked with respect to restrictions imposed by longitudinal and lateral separations. Aircraft is allowed to enter the intersection if precisely defined *restricted sections* are unoccupied by other aircraft.

Restricted sections are the "mechanism" for ensuring a safe separation among all aircraft simultaneously moving through the roundabout. There are three types of restricted sections: in front, behind and other. The shape of the restricted sections depends on the entry point (from which side the aircraft is entering the intersection), on the aircraft trajectory (towards which side the aircraft is moving) and aircraft type (small or large). Restricted sections had to be defined for all 24 origin/destination/type cases.

Restricted sections *in front* and *behind* are defined based on the projected interaction between the reference aircraft (i.e. origin/destination/type case under consideration) and aircraft moving across dependent paths, when they meet on the common segment of their paths.

Restricted sections *in front* are defined from the entry stop-bar forward, in the direction of movement, for the distance that ensures safe separation with respect to the aircraft moving across dependent paths and that are physically in front of the reference aircraft.

Restricted sections *behind* are defined from the intersection point between the reference path and the circular taxiway, backwards (in a clockwise direction), for the distance that ensures safe separation with respect to the aircraft moving across dependent paths and that are physically behind the reference aircraft.

Other restricted sections are related to lateral separations and they are primarily important when aircraft use the East or West sides (orange-yellow-blue parallel taxiways).

For each reference aircraft *independent paths* are also identified. The independent path is the path that does not intersect with the path of the reference aircraft, or the path that intersects/overlaps with the reference aircraft's path, but it does not impose any specific restrictions to the reference aircraft.

When the100/190 separation is applied strictly, boundary points of the restricted sections for 24 reference aircraft are spread throughout the intersection. Too many boundary points are not user-friendly and they could affect situational awareness to a great extent. Due to that, boundary points are grouped into a smaller number of reference points that are already part of the intersection (stop-bars) or can be identified easily (additional markers). In Fig. 6 stop-bars are given in red and markers in green.

The closest reference point is accepted as the boundary point if it does not decrease separation to more than acceptable tolerance. Otherwise, the next (farther) reference point is used. Acceptable tolerance of 15m for small and 25m for large aircraft is assumed. The implementation of the tolerances is justified by the fact that paths in the roundabout and their relative relations are such that many direct interactions between aircraft are avoided. It is because aircraft do not taxi in trail (literally one behind the other) on the circular taxiway; they use different entry and exit lines on the same side, which causes divergence between some paths; they exit through different sides, which results in less overlapping; when they exit on the same side they can use different lines in some cases, so they avoid taxiing in trail on the straight portion, etc. Furthermore, assumed lengths for small and large aircraft are based on the length of the largest aircraft classified as small/large aircraft, which also allows for certain tolerance.

Restricted sections are illustrated in Fig. 7, in one example, "West-North-small". It stands for the reference aircraft being small-type, taxiing from west to north, i.e. entering the intersection at W3 and exiting through N1. Selected examples for restricted sections' boundaries, as given in the Fig. 7, are:

- *in front* – a small aircraft on the W-N path is safe to enter the intersection at W3 when the previous aircraft using the N-E, W-E or W-N path crosses at least marker 4' if it is a small, or marker 1' if it is a large aircraft;
- *behind* – a small aircraft on the W-N path is safe to enter the intersection at W3 if a large aircraft using the S-W or E-W path does not cross marker 2', and an aircraft (small or large) using the E-S path does not cross stop-bar 3;
- *other* – a small aircraft that requires entry at W3 to move towards N1 is not permitted to use the West side (between the circle and stop-bars W2 and W3) simultaneously with a large aircraft.

Examples for independent paths in this case: E-N-small aircraft (by-pass), E-N-large aircraft, E-W-small aircraft.

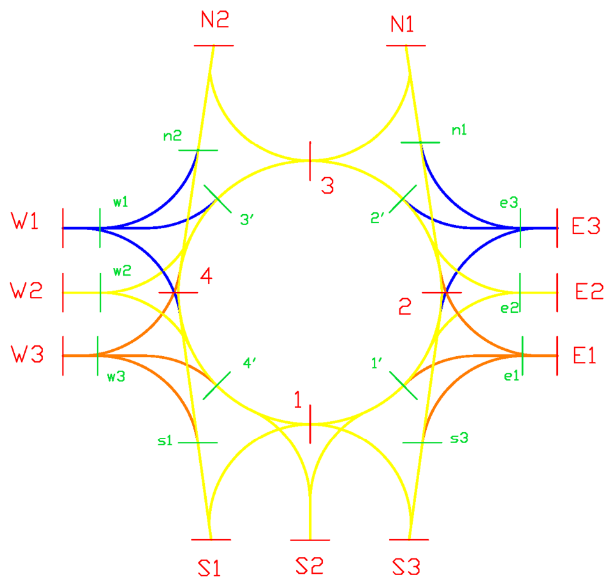

Figure 7. Stop-bars and markers in the roundabout

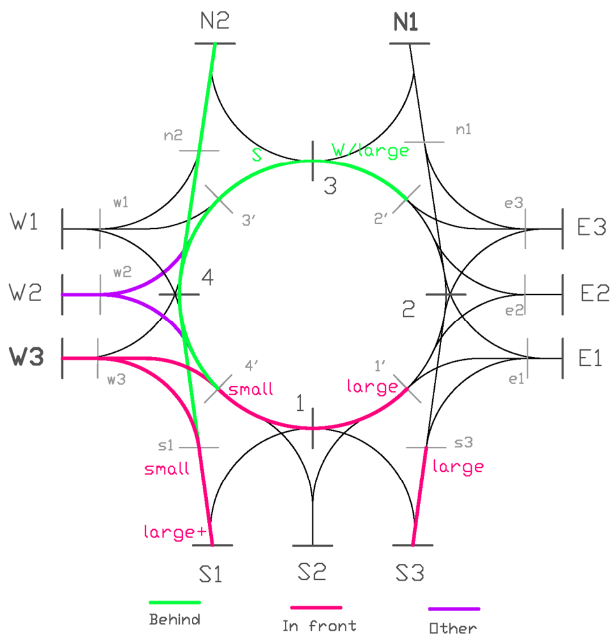

Figure 6. Restricted sections for West-North-small aircraft

Restricted sections and independent paths for all 24 reference aircraft make up the complete roundabout operations model. It covers the full set of rules for safe aircraft movement through the intersection that assures minimum separation between all aircraft, accounting for all possible interactions of aircraft moving through the intersection.

The set of rules for conventional intersections is simpler. There is no circular taxiway that causes additional overlapping between the paths. Aircraft are separated from each other relative to the crossing points of the dependent paths. It also accounts for independent paths for each reference aircraft.

In the model the *FCFS rule* is assumed, meaning that aircraft enter the intersection following the same order by which they have requested to enter the intersection. The FCFS rule applies at the intersection entry only. It does not necessarily mean that the sequence in which aircraft enter the intersection remains the same on exit.

III. ROUNDABOUT SIMULATION MODEL

In the paper *taxiway intersection capacity* refers to the maximum number of aircraft that can be served by the taxiway intersection, during 1h, in the presence of continuous demand, while adhering to all separation rules.

In order to obtain taxiway intersection capacity *conditions of saturation* are observed. This implies that there is at least one aircraft waiting to enter the intersection at all times. That way there is no idle period in system operation. Respecting the FCFS rule, the next aircraft enters the intersection as soon as conditions for minimum *safe separation* are achieved.

Traffic O-D matrix, aircraft type mixture and taxiing speed are the model *input data.* By varying them it is possible to create different traffic scenarios and compare them under the same operations rules (FCFS, separations, etc.)

The simulation of the roundabout intersection was developed using the simulation tool Flexsim (version 3.02). The platform of the simulation considers roundabout design and operations rules i.e. restricted sections for all origin-destination-type combinations.

The *Traffic O-D matrix* for the outbound peak is given in Table I. It contains a share of each origin-destination (O-D) pair in the total traffic. Origin stands for the side from which aircraft enter the intersection and destination is the exit point at which they leave the intersection. The traffic O-D matrix for inbound peak is transposed Table I.

TABLE I. TRAFFIC O-D MATRIX FOR OUTBOUND PEAK (%)

		Destination				Total
		S	***E***	***N***	***W***	
Origin	***S***	-	2.5	42	2.5	47
	E	2.5	-	8	1	11.5
	N	25	2.5	-	2.5	30
	W	2.5	1	8	-	11.5
Total		30	6	58	6	100

Two different *aircraft type mixtures* are decided, creating four scenarios:

1. Outbound peak, 90% small and 10% large aircraft,
2. Outbound peak, 80% small and 20% large aircraft,
3. Inbound peak, 90% small and 10% large aircraft, and
4. Inbound peak, 80% small and 20% large aircraft.

Taxiing speed is assumed to be 20 km/h. Acceleration and deceleration are not modeled, assuming taxiing speed to be as low as it is.

A. Simulation Results

For each scenario 100 iterations were run. Each iteration is a one-hour simulation, with the following input: 350 aircraft are generated; aircraft are created with inter-arrival times from a uniform distribution between 0.05s and 0.2s; aircraft origin-destination-type is generated according to the O-D matrix and aircraft type mixture for a particular scenario.

The generated aircraft are lined up in a queue waiting for their turn to enter the intersection. They request entrance into the intersection according to their order of generation, and are allowed to enter when all conditions for safe separations are achieved. This approach would not be suitable for examining queues or delays, but it is appropriate when the only required simulation result is saturation capacity.

Fig. 8 summarizes simulation results from 100 iterations, for Scenario1. It shows capacity distribution in steps of 5 aircraft. The capacity value is the highest value from the range it represents, e.g. 180 aircraft/h stands for the range (175,180] aircraft/h. Frequency is the number of iterations of the total 100.

Range, average values and standard deviation for all four scenarios are summarized in Table II.

TABLE II. ROUNDABOUT CAPACITY - MIN, MAX, AVG AND ST. DEV.

	Scen 1	Scen 2	Scen 3	Scen 4
Min	170	149	166	152
Max	204	189	199	190
Average	186	173	181	170
Stdev	7.45	7.67	6.71	6.75

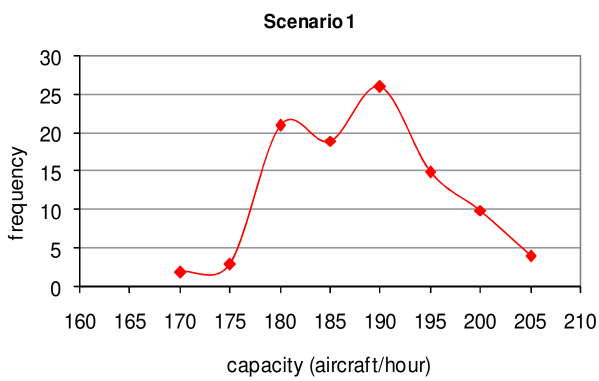

Figure 8. Simulation results for Scenario 1

In all four scenarios, capacity of the roundabout is about double the current runway system capacity (90 movements/h [8]) and about 50% higher than the future runway system capacity (120 movements/h [8]). Based on that, it is not expected that the roundabout will become a capacity issue at MUC apron area, under observed traffic scenarios.

IV. ROUNDABOUT VS. CONVENTIONAL CROSSING

For the purpose of comparing roundabout and conventional intersection capacities, an analytical model was developed. It is based on Blumstein's approach [9] for estimating runway capacity. Blumstein has defined runway capacity as the maximum number of aircraft movements that can be performed per unit of time (typically 1h) in the presence of continuous demand, without violating air traffic control separation requirements; and suggested a model for computing the single runway capacity. The essence of the model is to estimate the mean inter-arrival time, from which the capacity of the system is calculated as a reciprocal value. This means that it is the expected value of the capacity.

In the basic (single runway) capacity model, there is only one system entry point for all aircraft – the runway threshold. In this case, the inter-arrival time i.e. the minimum time period between two consecutive aircraft passes "through" the runway threshold, can be directly derived from minimum safe separations between aircraft in the air and aircraft speed on approach (assuming that runway occupancy time is less constraining). In the case of multi-runway systems, the whole system has to be observed, as well as interactions between aircraft within the system. The set of rules that assure maintenance of the minimum safe separations between all aircraft depends on the runway configuration and operations procedures.

The case of the apron taxiway intersection is specific as it has multiple-entrances, as well as multiple-exits from the system. In this case, it does not necessarily mean that the aircraft that enters the system first will be the first to leave the system. Also, the (physical) sequence of the aircraft moving through the intersection is not necessarily the same as the entry sequence, due to the position of entry/exit points. For these reasons the separations (by aircraft pairs) need to take into account the influence of other aircraft already using the intersection.

In order to avoid potential misleading with the term *inter-arrival time,* the term *inter-entry time* is adopted for the case of the taxiway intersection system. It is the time period between the moments two consecutive aircraft start entering (are allowed to enter) the intersection. This period begins at the moment the first aircraft enters the intersection and it lasts until the moment all conditions are achieved for the second aircraft to enter the intersection safely. All three characteristics of the reference aircraft (origin-destination-type) have an impact on inter-entry times.

A. Analytical Model Formulation

λ – intersection entry capacity,

$\bar{t}$ – mean inter-entry time, for all aircraft demanding service at the intersection,

i, j – the leading and the trailing aircraft, i and j, described with 3 characteristics: origin (entry point), destination (exit point) and type,

t_{ij} – the time interval between the moments two consecutive aircraft, i and j, start entering the intersection,

p_{ij} – probability of (i,j) pair appearance,

p_i – probability of leading aircraft i appearance,

p_j – probability of trailing aircraft j appearance.

Intersection entry capacity λ is determined as a reciprocal value of the mean inter-entry time:

$$\lambda = 1/\bar{t}\,. \tag{1}$$

$$\bar{t} = \sum_{i,j} t_{ij} \cdot p_{ij} \tag{2}$$

Appearance of any aircraft is considered to be an independent event, and the probability p_{ij} is determined as:

$$p_{ij} = p_i \cdot p_j \tag{3}$$

B. Determination of Inter-entry Times

First of all, inter-entry times are determined for each aircraft pair, based on the distance that the first aircraft has to taxi from its entry point to allow the second aircraft to enter the intersection safely. In addition, inter-entry times of aircraft pairs are modified with respect to the (possible) impact of their predecessors. This was achieved by observing aircraft triplets $1^{st}/2^{nd}/3^{rd}$ (1^{st} refers to predecessor and $2^{nd}/3^{rd}$ to observed pair). For each aircraft pair, all possible predecessor-aircraft pair cases are studied based on the rules defined in the roundabout operations model. In many cases there is no impact of the predecessor on aircraft pair inter-entry times, but some of them require correction.

Let us observe the triplet $1^{st}/2^{nd}/3^{rd}$. Translated into model language, this triplet is composed of two pairs $1^{st}/2^{nd}$ and $2^{nd}/3^{rd}$, which are merged by their common member (2^{nd} aircraft). Modification of inter-entry times between 2^{nd} and 3^{rd} aircraft mainly accounts for then additional time necessary to provide safe separation between 1^{st} and 3^{rd} aircraft. Modified inter-arrival times are included in the capacity calculation with the probability of the appearance of particular triplet $1^{st}/2^{nd}/3^{rd}$.

In the MUC case, due to distribution of aircraft across the traffic patterns and bigger share of small aircraft in the mix, the most important group (with the most significant impact on intersection capacity) that requires inter-entry times modification are *zero* pairs. *Zero* pairs are composed of two independent aircraft, that are allowed to enter the intersection at the same time, imposing inter-entry time equal zero, $t_{ij} = 0$.

Let us observe the triplet 1^{st}-2^{nd}-3^{rd}, composed of two *zero* pairs $1^{st}/2^{nd}$ and $2^{nd}/3^{rd}$. The following sequence is an example for this case: the 1^{st} aircraft enters from N and is moving towards S, the 2^{nd} aircraft enters from S and is moving towards N and the 3^{rd} aircraft enters from N and is moving towards S. (Aircraft type is disregarded, because the same applies regardless of aircraft type in this case. Each aircraft is described with two characteristics – origin and destination). This stands for S-N/N-S pair with N-S predecessor, or the triplet N-S/S-N/N-S. This triplet consists of two pairs: N-S/S-N and S-N/N-S. Having them both as *zero* pairs, it means that N-S and S-N aircraft can enter the intersection at the same time (inter-entry time t_{12} =0), as well as S-N and N-S aircraft (t_{23} =0). But, the independence between the 1st and 2nd and between the 2nd and 3rd aircraft does not necessarily imply independence between the 1st and 3rd aircraft. In this particular case, obviously N-S and N-S cannot be allowed to enter the intersection at the same time. New inter-entry time between S-N and N-S, with N-S predecessor is equal to inter-entry time for N-S to N-S separation. It is included in the calculation with the probability of the particular sequence N-S/S-N/N-S appearance. The same applies to all other cases that require additional separation.

There are a few exceptions when it is not sufficient to separate the 1st from the 3rd aircraft, but some extra time is necessary to separate the 3rd from the 2nd aircraft. It occurs when, while separating from the 1st, the 3rd aircraft becomes unsafely separated from the 2nd, because it has reached the restricted section behind in the meantime.

C. *Results from the Analytical Model*

Having 24 reference aircraft (12 entry points and two aircraft types), it makes for 576 aircraft pairs and a significant number of triplets to be examined.

The purpose of the analytical model is to show possible difference between the two intersection capacities. Since the roundabout has already shown significantly higher throughput than the runway system capacity, it was not necessary to carry out detailed analysis, but rough estimation is considered as acceptable in this case. Due to that, and in order to simplify analytical capacity calculation O-D pairs with 2.5% or fewer shares in the total traffic were excluded, by assuming that they will not have a great impact on the capacity estimation. Consequently, the probabilities of remaining O-D pairs are weighted (to bring the sum up to 1.0) before proceeding with the calculation.

In the case of the outbound peak four following O-D pairs remained: S-N, E-N, N-S and W-N; while "simplified" traffic for the inbound peak consists of: S-N, N-E, N-S and N-W. Having two aircraft types in addition, it makes for 64 pairs and 512 triplets to examine.

The triplets are nothing but a part of the full set of events. The pair S-N/N-S can be represented by four O-D triplets: S-N/S-N/N-S, N-S/S-N/N-S, W-N/S-N/N-S and E-N/S-N/N-S, which make 32 triplets when aircraft type is also observed. The sum of the probabilities of the triplets' appearance is equal to the probability of S-N/N-S pair's appearance.

In Table III the mean inter-entry times (in seconds) and the apron intersection capacity (in aircraft/h) are given for both intersections, in all four scenarios.

In this case, it was not feasible to follow the usual approach for model validation, since both "real" systems are non-existent. We have a conventional intersection expected to appear as a consequence of future airport development, and a roundabout as an innovative solution to replace the conventional intersection. Because of that, analytical capacity calculation is validated by means of the roundabout simulation.

TABLE III. ANALYTICAL MODEL RESULTS

	Roundabout Design		**Conventional Design**	
	Mean Inter-entry Time (s)	***Intersection Capacity (aircraft/h)***	***Mean Inter-entry Time (s)***	***Intersection Capacity (aircraft/h)***
Scen 1	18.5	194	16.6	217
Scen 2	19.8	182	17.9	201
Scen 3	19.6	184	17.4	207
Scen 4	20.7	174	18.5	195

Simulation results obtained with complete and simplified traffic data are compared in the first place, to show whether simplified traffic can be used as a representative traffic sample.

In Fig. 9, the distribution of capacities, in categories of 5 aircraft, is given for Scenario 1, for both simplified and complete traffic. In Table IV average capacity values for all scenarios are given, together with results obtained from the analytical model for the roundabout intersection.

TABLE IV. AVERAGE VALUES FROM SIMULATION WITH SIMPLIFIED AND COMPLETE TRAFFIC AND ANALYTICAL RESULTS

	Simulation – Complete Traffic (aircraft/h)	**Simulation – Simplified Traffic (aircraft/h)**	**Analytical model (aircraft/h)**
Scen 1	186	191	194
Scen 2	173	179	182
Scen 3	181	186	184
Scen 4	170	175	174

In Fig. 9, the capacity distribution curve for the case with complete traffic is moved slightly to the left (towards smaller values). It is similar in all four scenarios. In accordance with that, the average values (Table IV, columns 2 and 3) are somewhat lower than in the case of simplified traffic. But, still

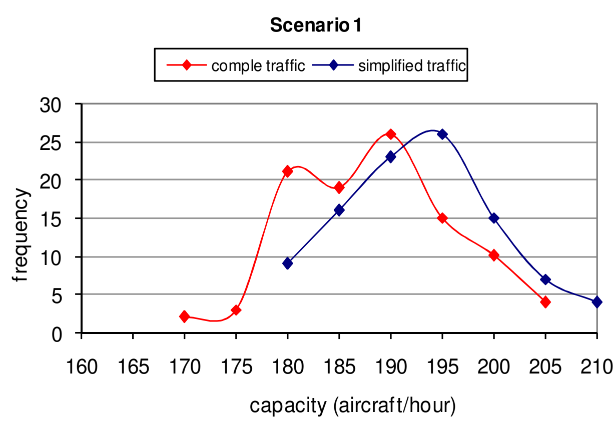

Figure 9. Simulation results with complete and simplified traffic data, Scenario 1

they are very close. The highest difference is 5 aircraft/h or less than a 3% difference, which confirms that the simplified O-D matrix can be used as a representative sample of the complete O-D matrix in the MUC case. Existing difference comes from the fact that O-D pairs excluded from the simplified traffic sample are the ones that are dependent on main flows (N-S, S-N), which imposes some additional separations when complete traffic is simulated.

Further on, for the purpose of analytical model validation, simulation results with simplified traffic are compared to the results from the analytical roundabout model. As given in Table IV (columns 3 and 4), average values from simulation (with simplified traffic) and roundabout capacities estimated analytically in all four scenarios match to a high degree. The difference in the worst case is 3 aircraft/h or 1.5%, which is considered as acceptable validation of the analytical model.

Based on the results summarized in Table III, the capacity of a conventional intersection is somewhat higher (approximately 10%) than the capacity of the roundabout intersection, in all scenarios. The nature of aircraft movements through the roundabout is such that it requires somewhat larger distances for aircraft to cross than in the conventional intersection on the same routes. Due to that, somewhat higher capacity for the conventional intersection is expected, but the issue is how significant it is in MUC environment.

If we observe intersections in the context of the airport as a whole, both designs provide capacity that is about double the current runway system capacity and about 50% higher than future runway system capacity. The existing difference is not significant enough to give an advantage to conventional design under the observed local conditions (separation rules, entry rules, traffic schemes, speed, etc.). Moreover, merging and crossing points (Fig. 4 and Fig. 5) speak in favor of the roundabout design.

In order to discern between these two solutions it would be advisable to take other performance measures into account, such as delays, queues, number of stop-and-goes, etc, observing apron intersections as a part of the complete airside system. Such an analysis would require the modeling of the complete airport airside operations, which was not in the scope of the first phase of intersection evaluation.

V. CONCLUSION

The essential part of the paper is the operations model which is the basis for both the analytical and simulation models. The roundabout operations model covers all possible interactions of aircraft within the intersection. The longitudinal separations between leading and trailing aircraft are built in the model through restricted sections (in front, behind and other). These sections assure that safe separation is always respected among all aircraft simultaneously moving through the intersection. The variables in the models (both analytical and simulation) are traffic data (traffic O-D matrix and aircraft mix) and taxiing speed. The same applies for the conventional intersection model.

The roundabout design, proposed by MUC, is currently a unique case, which justifies the development of the model that is not "easy to modify" when it comes to operational rules. Even if the roundabout would become commonly accepted, its design and operational rules may significantly differ from airport to airport, depending on the specific local conditions. Roundabout dimensions depend on apron layout and design aircraft, while traffic characteristics may require different classification with respect to aircraft types, or different traffic flows to be analyzed, etc. Consequently, specific set of restricted sections would have to be defined for each case.

The roundabout simulation model and analytical model for the taxiway intersection capacity estimation were developed for supporting roundabout capacity evaluation. Both models are based on the same operations model.

The results from the roundabout simulation model, for the four scenarios reflecting expected traffic at MUC, show that the roundabout is capable of providing 50% higher capacity than the future runway system capacity. It makes the roundabout a suitable candidate, in terms of capacity, to replace the conventional intersection at MUC apron.

The results from the analytical model for both intersection designs, for simplified MUC traffic scenarios, show the difference of up to 10% in favor of the conventional intersection. Bearing in mind that both intersections provide enough capacity from the perspective of the system as a whole, the difference is not considered as significant to give advantage to the conventional over the new design, i.e. to reject the roundabout, in this phase.

The evaluation process in its later stages involved real-time simulation, which resulted in very positive reactions from controllers, pilots, safety managers and other people directly or indirectly involved in roundabout operations. In the meantime the preliminary design has undergone some changes (e.g. outer stop-bars locations; signs are placed outside the intersection, consequently changing the direction of the circle to clockwise, etc). The MUC apron roundabout project is still in progress.

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REFERENCES

[1] DFS, Aeronautical Information Publication (AIP), 2004, Germany

[2] ICAO, "Annex 14 - Aerodrome, Volume 1 - Aerodrome Design and Operations", 2004a, Canada

[3] ICAO, "Doc 9157 - Aerodrome Design Manual, Part 2 - Taxiways, Aprons and Holding Bays", 2005, Canada

[4] Institute of Faculty of Transport and Traffic Engineering, "Capacity Evaluation of Apron Taxilane Circle vs. Standard Apron Crossing", 2006, Serbia

[5] B. Mirkovic, and V. Tosic, "Capacity Evaluation of Roundabout Intersection vs. Conventional Apron Crossing", European Modelling Symposium, University College London, 2006, U.K., pp. 144-148

[6] B. Mirkovic, "A Capacity Estimation Model for Apron Taxiway Intersection", Master's Thesis, University of Belgrade – Faculty of Transport and Traffic Engineering, 2008, Serbia

[7] ICAO, "Doc 9830 – Advanced Surface Movement Guidance and Control System (A-SMGCS) Manual", 2004b, Canada

[8] MUC, Facts and Figures 2012/2013, 2013, Germany

[9] A. Blumstein, "The Landing Capacity of a Runway", Operations Research 7, vol. 1, 1959, pp. 752–763