AIRPORT CAPACITY REPRESENTATION BASED ON AIRSIDE SIMULATIONS

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Abstract

Airport capacity as key indicator of airport system performance, measures a variable with an increasingly constraining effect on air traffic development, so that airport capacity optimization is becoming one of the main objectives for future developments of airport infrastructure and aircraft alike. Computer simulations are commonly used to perform "what-if-studies" to evaluate alternative future development options in this field, while there is still no established practice for the presentation of meaningful airport airside capacity values based on simulation output. In this paper an approach is presented to establish robust capacity values based on fast time simulation results. It is based on previous work by E. Gilbo [1], adapted to ensure robust results while taking the requirements in the context of the simulation-based approach into account and enhanced to produce not only ultimate capacity figures but to also evaluate the practical capacity of an airport system, which has direct practical relevance especially in the context of flight scheduling. The results of an exemplary application demonstrate that the capacity representation provides a good understanding of the capacity impact for different development alternatives while it is also possible to aggregate the results to a single relevant performance indicator value.

1 Airport Capacity – Key Indicator to Measure Airport Performance

Forecasts indicate continuing growth of today's air traffic while airports are approaching their capacity limits. Especially hub airports which are handling the majority of today's flights [2] are close to economic centres and have thus mostly limited possibilities for infrastructural expansion. Increasing environmental considerations (e.g. noise) [3][4], rising delay levels at congested airports and resulting considerable financial losses for airlines [5], call for the maximization of current airports' performance as one of the major challenges of air transport [3]. Hereby the airside of airports in general and the runways in particular, have long been known as most constraining elements impacting overall airport capacity [6].

When considering alternative future developments of airport systems, computer simulation tools are commonly used to assess the air traffic flow on runway systems [7] and to optimize airport infrastructure [8] by conducting "what-if-studies" and analyzing the observed effects. Capacity as the prime indicator of airport system performance depends on many factors and its determination is complex. E. Gilbo (1993) [1] presented an approach to properly represent an airport's operational limits, considering various operational conditions using specific arrival/departure capacity curve diagrams.

While the capacity curve's original application is the evaluation of historical airport performance data, the objective of this paper is to outline a comprehensive approach to generate capacity curve diagrams based on airside simulation of predefined operational cases. Additionally requirements regarding the robustness of the resulting curve [1] and monitoring functions addressing the aircraft mix are to be implemented to ensure that the predefined operational case is sufficiently represented in the final capacity values.

2 Technical Approach to Establish Robust Capacity Values Based on Fast-Time Simulation Results

Fig. 1 provides an overview of the technical approach: After implementing a simulation model of the airport system subject to the investigation, an operational case is to be defined specifying a typical operational condition including the definition of a characteristic aircraft mix – a central determinant of airport capacity. The basic principle of the subsequent data aggregation step is the execution of multiple simulation runs - similar to an approach presented by Theiss (2007) [10] - where demand volume and arrival to departure ratios are systematically varied. The output of each simulation run is analyzed in sliding time intervals to generate the data points for the capacity curve diagram [1]. Each data point contains information regarding the arrival rate, the departure rate, the average delay and the aircraft mix of all aircraft movements measured in the respective sliding time interval. In a following step the aggregated simulation data are then evaluated to reject those data points which do (a) not sufficiently represent the aircraft mix specified in the operational case and which are (b) identified as outliers and therefore would lead to a non-robust result when included in the capacity curve. Since the “frequency of occurrence” method to identify outliers proposed by E. Gilbo [1] lacks practicability in conjunction with the analysis of simulation generated data, the local outlier factor (LOF) algorithm by Breunig et al. (2000) [11] has been identified to overcome this limitation. It fulfils the requirements specified by E. Gilbo [1] to only include robust data points in the capacity curve and can handle simulation generated data with its distinctive characteristics.

3 Airport Capacity Representations

Airport capacity has many influencing variables and can be expressed in different indicator values. While most influencing variables can be assumed as constant within a given operational case that is studied, arrival to departure rations in the aircraft movements are most volatile even within one operational case and have thus to be treated as variables in the airport capacity representation.

3.1 Capacity Indicators

To measure airport capacity impacts quantitatively and thus objectively, two different established capacity values can be calculated: The main performance indicator of a runway system is the ultimate capacity. It describes the maximum number of aircraft movements within a defined time interval under certain preconditions: (a) constant, and regarding its composition continuous and stable air traffic demand, (b) compliance with all relevant separation and air traffic coordination regulations and (c) no limiting factors (e.g. adverse weather conditions). The ultimate capacity is alternatively also referred to as saturation, theoretical or maximum throughput capacity. [12][13][2][14][15][16]

The practical capacity is the second common

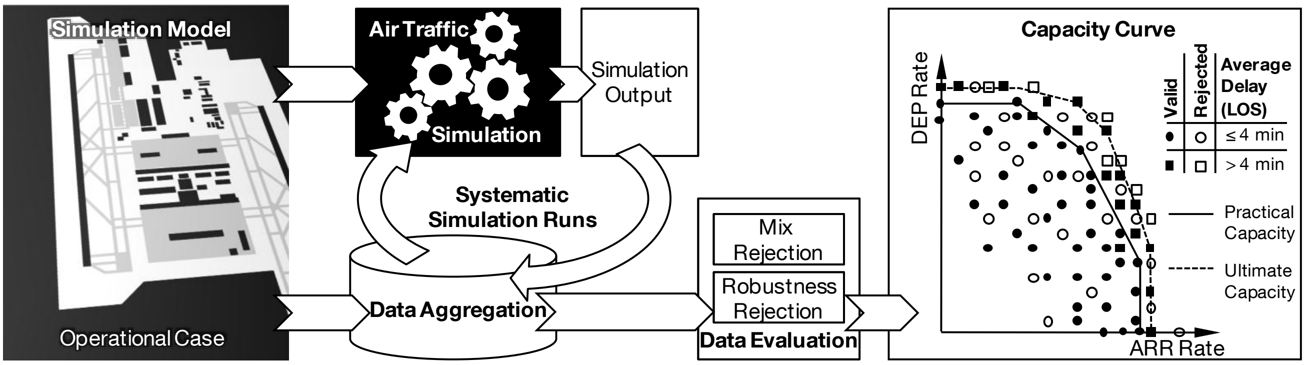

Fig. 1. Overview of the technical approach to generate capacity curve diagrams visualizing the operational limitations of an airport system for a predefined operational case based on air traffic data generated by fast-time simulations.

capacity measure additionally considering the average delay of all aircraft movements as quality criterion and therefore having a higher practical relevance especially in the context of flight scheduling. Due to the air traffic flow's behavior according to the queuing theory the ultimate capacity represents the upper capacity limit where delays increase infinitely. The practical capacity returns a capacity value below the ultimate capacity that can be achieved when a specified average delay of all movements (level of service) is maintained. Based on previous studies, four minutes of average delay represents an established level of service for aircraft movements on airports today. When studying the long-term behavior of an airport system and thus the practical capacity of a stable system in a time-independent stationary state, as it is common practice in capacity assessments, the aircraft movement demand per time unit equals the number of actually executed movements. [13][17][15][12][16]

Comparing ultimate and practical capacity regarding application related aspects, the ultimate capacity tends to return more robust evaluation results even with small sample sizes due to its pole characteristic, while practical capacity values rely on high amounts of data since they are highly affected by the stochastic nature of air traffic demand. [15][17]

3.2 Capacity Curve Representation

E. Gilbo [1] presented the capacity curve to visualize the performance of runway systems at various arrival to departure ratios. Originally its intended use was to visualize the capacity envelopes of airports based on real operational data by delimiting feasible and infeasible areas regarding maximum facilitated arrival and departure rates. Historical airport performance data measured as arrival and departure rates in finite time intervals are plotted into a two-dimensional diagram and subsequently enclosed by a convex, non-linear curve. E. Gilbo also emphasized that the results are only relevant for certain operational conditions and that robustness of the curve has to be ensured by systematically excluding outliers (see Fig. 2).

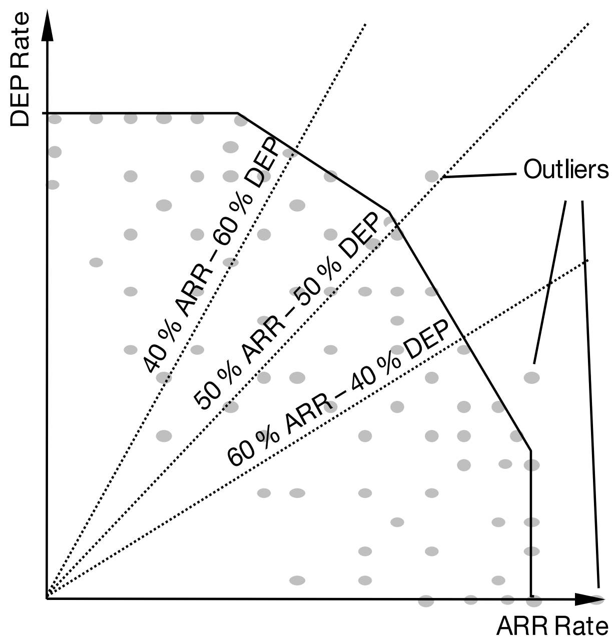

Fig. 2. Capacity curve representation based on E. Gilbo [1] to visualize the capacity of an airport system for various arrival to departure ratios.

4 Simulation Set-Up

To generate basic air traffic data for an implemented simulation model of a given airport system including a defined characteristic traffic demand structure (e.g. aircraft mix and route usage), multiple simulation runs with systematically varied demand volume and arrival to departure ratios are performed: Starting with 100 % arrivals, the arrival share is stepwise decreased to 0 % while the departure share increases complementary to 100 %. For every arrival to departure ratio, multiple simulation runs with identical operational conditions are performed while the traffic volume is incrementally increased until no further increase in either departure or arrival rates can be observed and thus the point of ultimate/saturation capacity is reached.

The actual aircraft arrival and departure sequence is random while the demand structure is predefined as aircraft type shares, route utilization shares, etc.

The basic data for the capacity evaluation are result of an aircraft movement count in sliding time intervals for every simulation run excluding a transient start-up phase to ensure

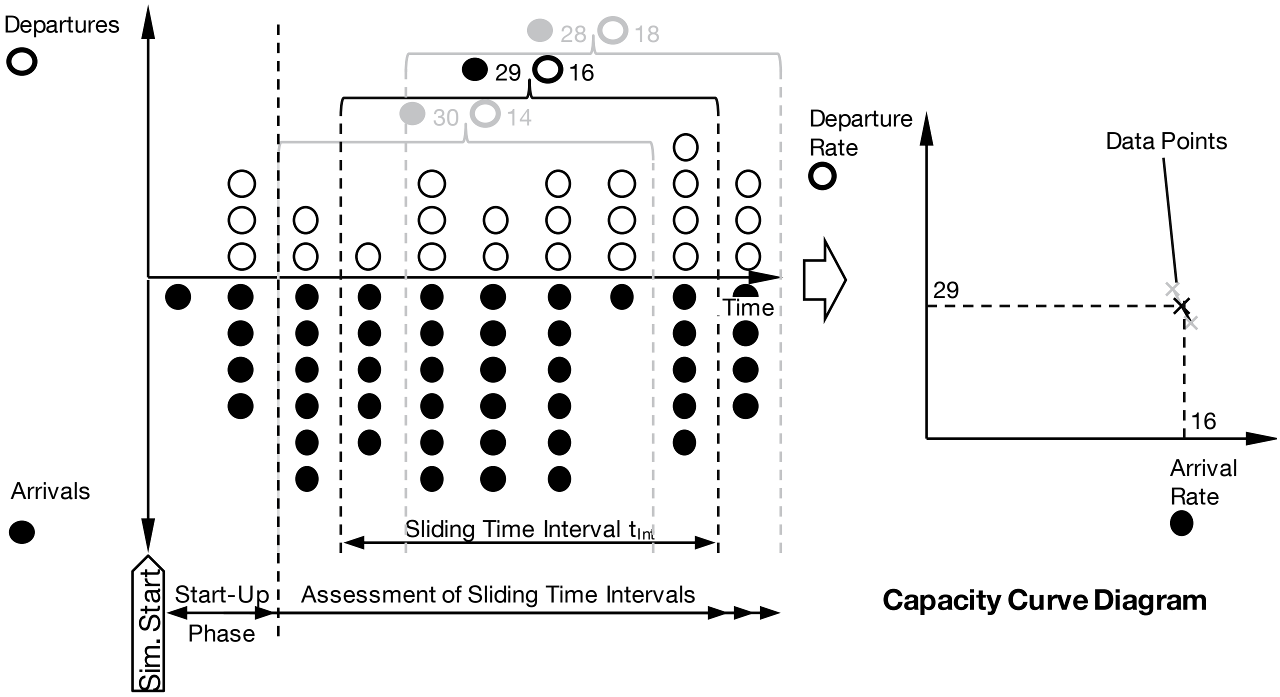

Fig. 3. Basic data generation using sliding time intervals.

that the measured data represent a quasi-stationary system state. Fig. 3 shows a schematic representation of this process (compare to ‘data aggregation’ in Fig. 1). To produce accurate results, the sliding time interval duration depends on the granularity of the predefined air traffic demand structure. The more detailed its definition the longer the sliding time interval should be chosen. With a typical demand structure definition based on only four to five representative aircraft groups, a time interval of 120 minutes sliding in 10 minute increments has proven to return good results.

5 Data Evaluation

To ensure validity of the final results as mentioned in (3), each data point has to be evaluated and potentially rejected from the final data set, if either (5.1) the operational conditions regarding the traffic demand structure of the aircraft movements counted within the data point does not sufficiently represent the predefined typical operational case or (5.2) the data point is identified as an outlier and could thus potentially lead to non-robust results if it is used to define the capacity envelope.

5.1 Mix Rejection

Due to the random aircraft movement sequence based on a probabilistic definition of the underlying traffic demand structure, the traffic sample within a sliding time interval resulting in a data point in the capacity curve diagram may differ to a certain degree from the defined operational case. To ensure that each included data point sufficiently represents the predefined case, a relative data evaluation and rejection process is proposed that allows to only include those data points with a traffic structure most similar to the defined operational case in the capacity curve generation. By defining relative instead of absolute rejection criteria, this process step can be applied regardless of the sample size and inherent accuracy how the actual operational case is represented by the results. The proposed rejection process has four steps:

1) Calculation of the aircraft mix share of every defined aircraft group for each data point.
2) Calculation of the aircraft mix share deviation from the respective target share

for each aircraft group within each data point.
3) Calculation of the average mix share deviation for each aircraft group across all data points.
4) Rejection of all data points in which the mix share deviation for one or more defined aircraft groups is above the average.

Following this process, only those operational conditions can be included in the final capacity curve generation that represent the defined operational case best, given the underlying simulation accuracy.
This rejection process incurs a relatively high reject rate. Due to the big amount of specifically simulation based generated data points, this is acceptable and even desirable with view on the quality of the results.

5.2 Robustness Rejection

E. Gilbo [1] used the frequency of occurrence of distinctive arrival-departure-rate combinations to identify points with relatively rare occurrence as outliers and thus to exclude them from further analysis in favor of robust capacity curve results. Due to the intention to express capacity

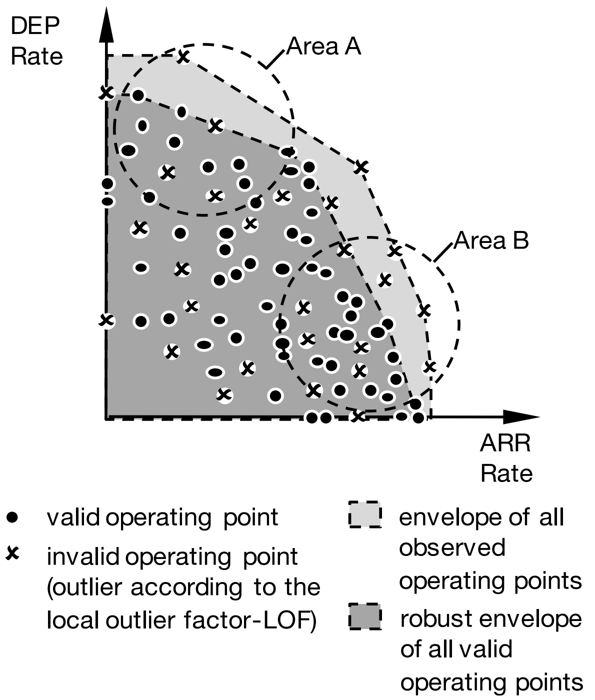

Fig. 4. Example application of the local outlier factor [9] as rejection criterion in the context of the generation of capacity curves.

values in movements per hour and the possibly low number of available data points, this approach proved not to be suitable for this evaluation of specifically simulation generated movement data.
Consequently the local outlier factor (LOF) (Breunig et al. 2000 [9]) is introduced to ensure robust operating points by providing an automatically measurable criterion to identify and reject outlying data points based on their outlier characteristic relative to their next neighboring data points.
Fig. 4 shows an example application of the local outlier factor as rejection criterion in the context of the generation of capacity curves: For each available data point the local outlier factor is determined according to Breunig et al. (2000) [9] to describe its relative outlier characteristic compared to its environment. Areas A and B in Fig. 4 with their different data point densities demonstrate the density related outlier identification.
The algorithm is based on an evaluation of a data point's distance (reach dist) to its N nearest neighbors as shown in Fig. 5 which is combined in a local reachability distance (LRD) value. The local outlier factor (LOF) is determined based on a comparison of a point's LRD compared to the LRD's of its N nearest neighbors. [9]
Experiments with different values of N for the outlier detection showed that higher values

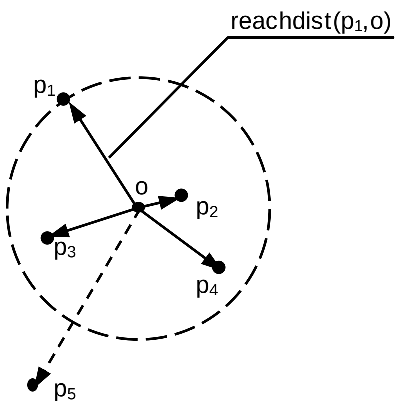

Fig. 5. Remoteness evaluation in the Local Outlier Factor (LOF) algorithm [9] to determine outliers for the capacity curve generation. Graphical illustration of the reach dist determination for an exemplary case of $N = 4$ nearest neighbors.

result in an increasingly poor coverage of the diagram axes and that optimal values are dependent of the overall sample size. *N* equalling 5 % of the sample size has shown to return good results while *N* should not be chosen lower than three and higher than 40.
After establishing a LOF for each data point, its value can directly be used as rejection criterion: If a local outlier factor of one is chosen as threshold value, all points with a more than average remoteness compared to all other points are rejected and only the most robust data points remain in the sample as basis for the capacity curve generation.

6 Result Visualization and Quantification

After generating aircraft movement data and rejecting those data points that do not sufficiently accurate represent the operational case studied or were identified as outliers according to the local outlier factor, the capacity curve diagram can be constructed for an aggregated result visualization. Fig. 6 shows an exemplary case where both established capacity indicators – ultimate and practical capacity – are expressed as capacity curves for different arrival to departure ratios. To construct the practical capacity curve, only those data points are evaluated that represent an average delay less than or equal to the target level of service of typically four minutes.
To analyze the effects of airport system element variations in “what-if-studies”, total movement rates (practical or ultimate capacity) at various arrival to departure ratios can be directly compared to a baseline case while deviations and thus their capacity impact can be expressed as positive or negative percentage changes (see Fig. 7).
If the capacity impact is to be compared based on a single representative indicator value, it is advisable to evaluate balanced arrival to departure ratios within a range of 50 % arrivals +/- 10 %. According to an evaluation of Öttl et al. (2011) [18] more than 67 % of all air traffic demand peaks at airports world-wide show arrival to departure ratios within this range confirming the significance of the resulting capacity value.

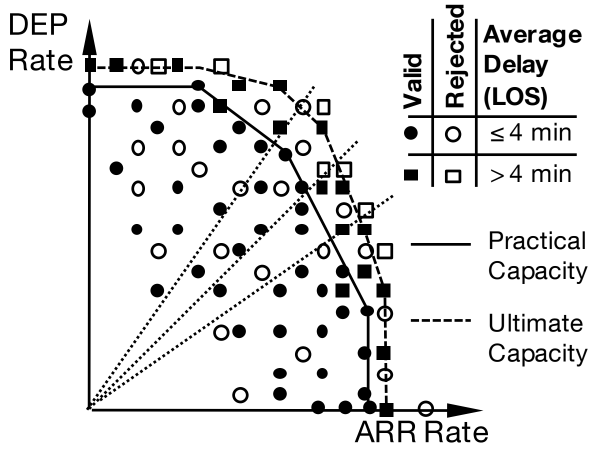

Fig. 6. Resulting capacity curve diagram for both, practical and ultimate capacity envelopes of a given simulated airport system.

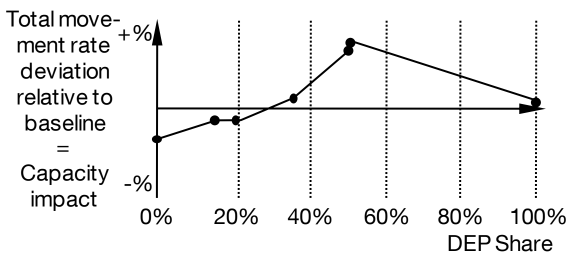

Fig. 7. Analyzing the effects of airport system element variations in “what-if-studies” by comparing total movement rates (practical or ultimate capacity) to a baseline case.

7 Example Application: Airport Capacity Impact Initial Climb Speed Variations

As part of a comprehensive aircraft parameter sensitivity study, the quantitative impact of the aircraft’s initial climb speed on the capacity profile of a single runway system was evaluated based on a simplified infrastructure model of Stuttgart airport (EDDS) and its distinctive origin and destination air traffic demand structure. In the presented case, the initial climb speed (v_{IC}) of all jet aircraft in the medium wake vortex category was varied. One simulation series (according to paragraph 4) generated the air traffic movement data for airport operations where v_{IC} of all affected aircraft was increased by 10 % and another simulation series was performed to generate data for the case that the initial climb speed is reduced by 10 %.

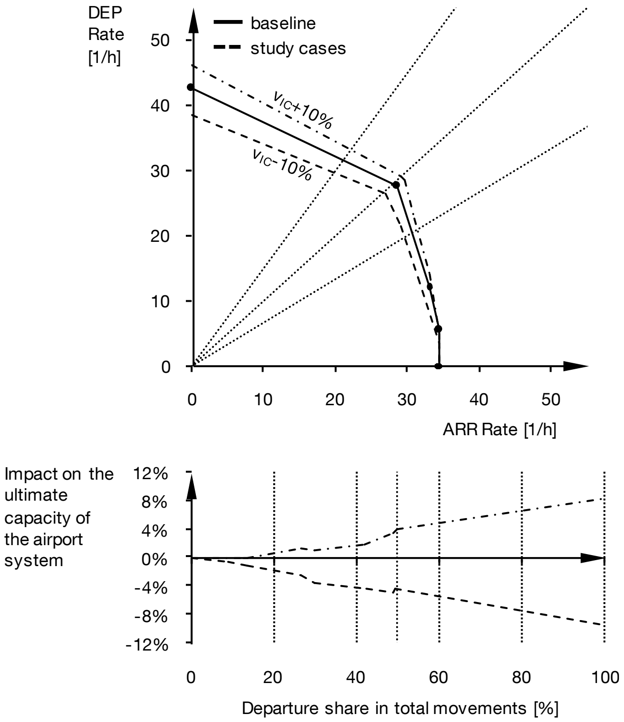

Fig. 8. Representation of the ultimate airport capacity impact of medium jet aircraft operations with increased/decreased initial climb speeds (v_{IC}) compared with a baseline case.

The resulting capacity curves for the ultimate capacity and the comparison of study cases and the baseline are presented in Fig. 8. As expected the impact measured is not uniform for all arrival to departure ratios, but can be observed to increase with the departure share. The average capacity impact for balanced arrival to departure ratios can be calculated as + 3.5 % for an increase of v_{IC} by 10 % and – 4.5 % for decreased initial climb speeds respectively.

7 Conclusions

As shown in the example case the presented airport capacity representation provides a good understanding of the capacity impact for different operating conditions when parameters of the studied airport system are varied while simultaneously allowing to aggregate the results to a single relevant performance indicator value. By the application of specific evaluation steps and potentially rejecting data points that either do not sufficiently represent the operational case or are identified as outliers prior to the capacity curve generation, fundamental requirements of result robustness and validity can be ensured.
By including the average delay of all aircraft movements represented by a data point, practical capacity values with direct relevance for flight scheduling purposes can be generated. Experience has shown, however, that the evaluation of robust practical capacity curves requires high amounts of simulation generated data so that in the case of time consuming simulation processes ultimate capacity values should be used for initial assessments followed by practical capacity evaluations for in-depth analyses.

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