DEUTSCHE BÖRSE GROUP

White Paper

Continuous auction market model

A proposal for the future European intraday power market

Contents

1 Summary

Deutsche Börse AG proposes to introduce a so-called continuous auction market (CAM) model as future model for the European intraday power market.

The new model establishes an enhanced trading model intended to cover the full functionality required by the capacity allocation and congestion management (CACM) regulation, but currently missing in the cross-border intraday (XBID) market. Pricing of capacity, inclusion of grid losses and the option to operate with a flow based grid model in the intraday market.

The CAM model integrates important features of an auction within the context of continuous trading. It releases hidden liquidity and adds capacity trading functionality.

Key features are

- A flexible and simplified set-up of products based on market time units (MTUs).
- A broad range of order variants (limit orders, bid curves, profile mulipart orders) implemented as specialisations of a single versatile order type.
- The inclusion of congestion rent in case of scarce capacity as well as a new type of market priced capacity orders that could replace explicit allocations.
- Considerably improved market efficiency and liquidity increase by leveraging currently unused matching opportunities. By recalculating production days, an increase of 9 per cent (or 62 GWh per tading day) in the executed order volume compared to the XBID continuous model could be observed. Compared with day-ahead like auctions every performed every 15 minutes, the executed order volume was 38 per cent higher in the CAM model.
- Support for a broad variety of grid models (NTC-based, flow-based or hybrid) and the inclusion of extra physical constraints like losses or ramping conditions.
- High market transparency by dissemination of anonymised pre- and post-auction order book and grid data. Distribution of continuously updated top of the book volumes and prices, displaying inside-market information.
- A responsive, high-throughput, real-time market with low latencies for trading. In the prototype CAM implementation, and at 10 times higher production load, the measured latency was 15 ms (median) with a maximum observed end-to-end latency of 375 ms. The observed maximum sustainable load is 200,000 order events per second.
- An adaptive auction processing model that guarantees scalability in highly loaded market situations with low impact on latencies reducing the need of performance related investments.

2 Overview on existing market models

The continuous auction model (CAM) bridges the continuous and the day-ahead market models currently in place.

Day ahead coupling model. This is the market model used for coupling day-ahead cross border markets in a single auction. The European hybrid electricity market integration algorithm (Euphemia) implements this model.

Intraday continuous trading model. The cross-border intraday (XBID) market project implements a continuous model for intraday power trading.

The CAM model compares with these models as follows.

Maximisation of socio-economic welfare. Both, the Euphemia auction algorithm and XBID matching rules aim at maximising socio-economic welfare. The area or match prices associated with the outcome of the welfare maximisation or matching process are fair market prices.

The CAM model also bases on a welfare maximisation principle.

Explicit capacity allocation. The XBID model supports explicit capacity allocations. Explicit allocations are without a price, and essentially amount to grid capacity updates. However, this is not in line with fair capacity pricing stipulated in CACM. In case of congestion, capacity is scarce and therefore has economic value. Explicit allocations compete with implicit allocations for capacity, and should be priced at a marketable value.

The Euphemia model does not support explicit capacity allocations.

The CAM model provides capacity orders as a new type of orders allowing to buy or sell market priced capacity.

Congestion rent. The XBID model does not offer the possibility to generate congestion rent. If available, capacity can be used for free. Otherwise, no cross border matches can be executed.

In Euphemia, the welfare optimisation can generate congestion rent in case of scarce capacity. The congestion rent emerges from area price differences, indirectly determined by power demand and supply.

The CAM model also includes the possibility to generate congestion rent in case of scarce capacity based on area price differences too.

Market efficiency. A model is efficient if it facilitates clearing the maximum possible amount of volume subject to transport limitations by offering the entire liquidity available in the order book.

The XBID model is not maximally efficient in that sense, as it does not offer cross contract matching. Cross-contract liquidity is not automatically executed in the intraday market. Market participants can arbitrage between different contract durations (e.g. between hourly and quarterly contracts) and explicitly release liquidity that cannot be matched directly in the XBID market.

Euphemia is efficient as it includes executing different order types against each other in a single auction. In practice, however, a maximum in efficiency is not always achievable within the limited auction calculation time. In case of a time-out, the obtained result could be sub-optimal with respect to the theoretically achievable maximum in welfare.

Transparency. The key for a fair price fixing is public market information about supply, demand and available transport capacity.

The XBID model offers full order book transparency in the local views and public information about the capacity situation disseminated as hub-to-hub matrix.

Euphemia does not include public market information. Market participants need to blindly enter orders at operational costs (supported by bid curves) to be safe from execution below marginal costs.

The CAM model offers full market transparency via three types of public information:

- The anonymised order book contents and capacity situation right before and immediately after each auction
- Top of the book information, displaying volume and bests prices per MTU
- The hub-to-hub matrix

	Continuous auction model	XBID	Euphemia
Welfare maximisation	+++	+++	+++
Explicit capacity allocations	+++	+	–
Congestion rent	+++	–	+++
Market efficiency	+++	+	++
Pre-trade transparency	++	+++	–
Continuous access to market liquidity	+++	+++	+

Table 1: Comparison of market models

3 Continuous auction market model

3.1 Concept

What makes the key difference between continuous trading and auctions?

In continuous trading, incoming orders are executed one by one based on a “first come first serve” (FCFS) principle. Any partial execution of an incoming order concludes one commercial transaction resulting in one trade with a specific trade price. The competition between arriving orders is indirect and asymmetrical – earlier executed orders may influence later executions, but only indirectly, and not vice versa.

In auctions, on the contrary, orders are competing with each other directly, at the same time, and on an equal footing. There is a mutual influence on the execution price among orders, and a single common execution price per zone.

In practice, continuous matching often has short and auction processing large latencies. However, this is merely a technical necessity but a fundamental functional characteristic. The actual distinctive criterion is mutual, symmetric and synchronous competition between orders. The key question is therefore:

What qualifies orders as competing?

When softening a strict FCFS principle, one could argue that orders entered with small-time delay should be considered as (nearly) simultaneously entered. More precisely, all orders entered within a time frame shall be regarded as eligible for competition, and therefore must be traded in one auction.

The continuous auction model realises that concept using rather short time frames. A continuous auction is a continuous process defined as the sequential execution of surplus maximising short-duration auctions with high repetition rate and full market transparency.

The following chapters provide a high-level description of the model, and discuss its important features and implications on the market.

3.2 Process description

The process maintains orders and capacity data, generates order executions and issues (implicit) capacity allocations. Entered order events (order add, modify or deletions) are administrated in either of the following two pools.

- Incoming queue. The queue collects order events entered in the system, in the order of their arrival time. If an auction is currently in progress, incoming events have to wait in this queue for further processing.

- Order book. The order book contains all orders (power orders as well as capacity orders) that are about to take part in the upcoming auction. Depending on execution opportunities, orders may remain in the order book for more than one auction also, possibly subject to partial execution or modification.

The CAM process performs one auction after another, looping over the following steps.[1)]

- **Preparation**
  Dispatching of the events that are currently waiting in the incoming queue amounts to performing corresponding updates in the order book or on the grid data, one by one.
  Order add events create new orders in the book, deletions result in removal of the order from the book and modifications update the contents correspondingly.
  If the capacity has not been initialised so far, the available capacity is set to the initial capacity at the time of gate opening. Explicit modifications of the grid parameters requested by the TSOs (e.g. changes in the NTC) are also performed in the step.
- **Optimisation**
  The process performs a maximisation of socio-economic welfare, based on the current order book contents and the capacity situation. The optimisation result includes zonal prices and cross-zonal flows required to balance supply and demand while respecting the available capacity. The outcome possibly shows adjacent zones with deviating prices corresponding to a congested flow and thereby includes congestion income in the total generated economic surplus.
- **Update**
  Depending on the order limit prices, orders must or cannot be executed at the respective zonal prices. Fully executed orders drop out of the order book, partially and not executed orders persist in the book with their remaining quantity.
  Cross-zonal flows are netted with already allocated capacity, and the remaining per interconnector capacity is updated accordingly.
- **Publish**
  The system publishes public market data.

Note that the process could pause if no new orders enter the system.

Figure 1 illustrates the main loop.

[1)] We illustrate the CAM process for an NTC-based grid model.

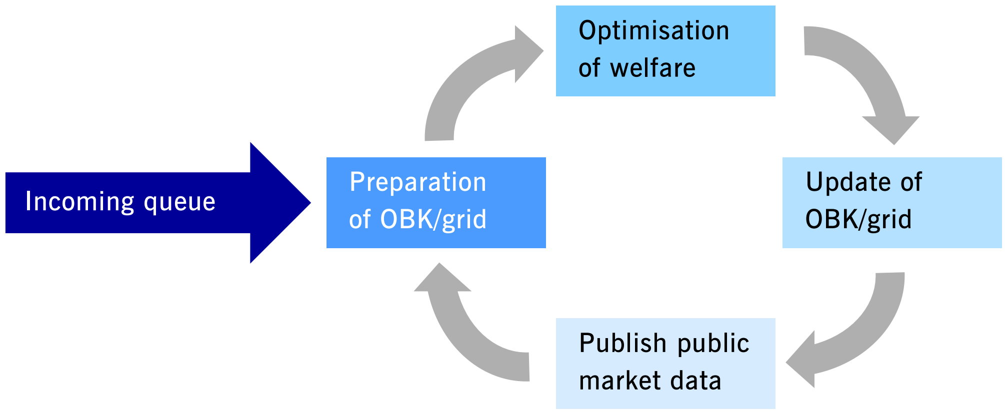

Figure 1: Main loop in the continuous auction process

Two variants of the CAM process are conceivable.

Consecutive

- The process loop executes without further delay. The execution frequency is determined by technical limitations and by system load as e.g. by the number of incoming events processed, the order book depth, the number of zones or the number of inter-connectors. Waiting queued events immediately trigger the next loop in the CAM process.

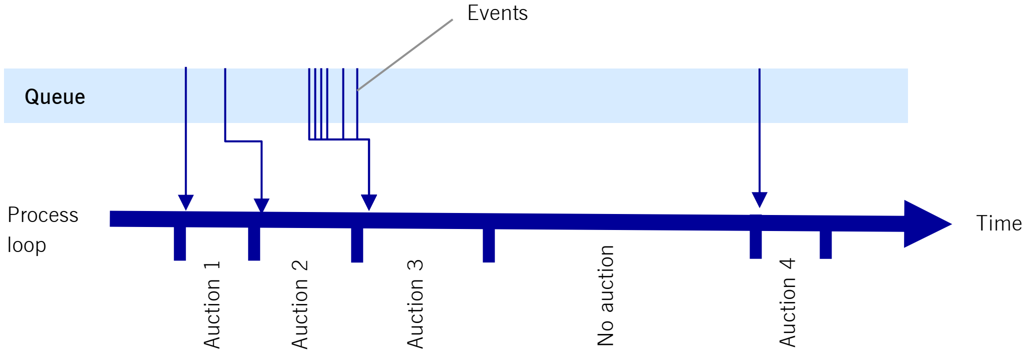

Figure 2: Consecutive auction processing mode. The arrival of an order or auction event triggers the auction. All events entered while an auction is in progress are queued. Queued orders are then submitted for execution in the next auction cycle.

Clocked

- The process loop is executed at a fixed rate (e.g. once per second). That means collecting arriving events in fixed time frames Δt, and processing them altogether in one loop pass. Higher rates lead to a market model which is closer to today's continuous trading market model.

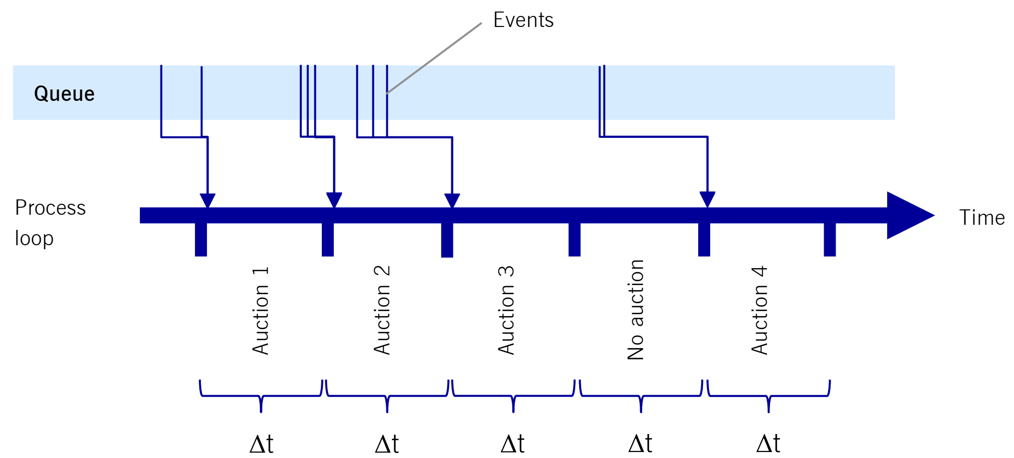

Figure 3: Clocked auction processing mode. A timer event triggers the auction. The auction is kept open for a certain period of time Δt and all events added during that time are collected and executed in the next cycle.

3.3 Features

The continuous auction model features the following properties.

Interpolating between FCFS and batch processing

Depending on the repetition rate, the CAM continuously interpolates between a more continuous and a more batched processing model.

For auction rates close to the event entry rate, only one new order would add to the order book in each iteration. The process resembles the case of a FCFS continuous trading model, with incoming orders processed one by one in sequence. There will be no congestion income; either there is remaining capacity, then an entered order potentially can be executed against one or more counterparts in the order book at a single execution price per zone, or no capacity is available, in which case the incoming order is written to the order book.

For order entry rates larger than the auction repetition rate, entered orders would queue up, and the optimisation step potentially identifies orders competing for scarce capacity. Congestion income will emerge in case of lack of capacity.

Self-adaptive

The continuous auction model is self-adapting to market pressure. For low order entry rates, it behaves like a FCFS market. This is the desired behaviour as the incoming orders are separated by large inter-arrival times qualifying them as not competing.

Conversely, high order entry rates could indicate a market situation with competition for remaining capacity in which case scarce capacity has an economic value. The CAM process starts to collect competing orders and performs auctions with capacity priced by congestion income. The anticipation is that this typically could be the case shortly after gate opening or shortly before gate closure. The self-adaptive behaviour automatically provides opening and closing auctions.

Transparent

As outlined above, current remaining capacity and order book situations is made public to the market before and after the auction.

Liquidity pooling

The auctions are performed in a continuous sequence such that the liquidity in the order book is available for the market at any time between gate opening and gate closure.

Market priced capacity orders

By introducing capacity orders, it is possible to process explicit capacity allocations in the auction. Capacity orders are equipped with a limit price, and are associated with welfare if executed. The processing of the capacity order inside the optimisation calculation guarantees non-discriminatory execution with respect to other power orders and capacity orders at a marketable price, and consistency with zonal price spreads in case of congestion. In this sense, capacity orders executed in the auction are priced allocations.

Simplified product set-up

The products traded in the auction model should avoid liquidity splitting and allow flexible definition of simple and multipart orders based on a single market time unit (MTU).[2)]

CACM conformity

The continuous auction model is fully in conformity with CACM.

3.4 Market model

3.4.1 Product set-up

The product set-up in XBID includes different products for different delivery periods. As cross product and cross contract matching is not part of XBID, hence liquidity is scattered across several order books leading to lower execution probability of orders.

Conversely, the CAM bases on a simplified product set-up offering only one product based on a so-called market time unit (MTU). The MTU is the smallest time period for trading. We suggest starting with an MTU duration of 15 minutes, but this could be adjusted to shorter periods in the future.

[2)] Referring to the current XBID setup, the market time unit corresponds to a delivery period of 15 minutes.

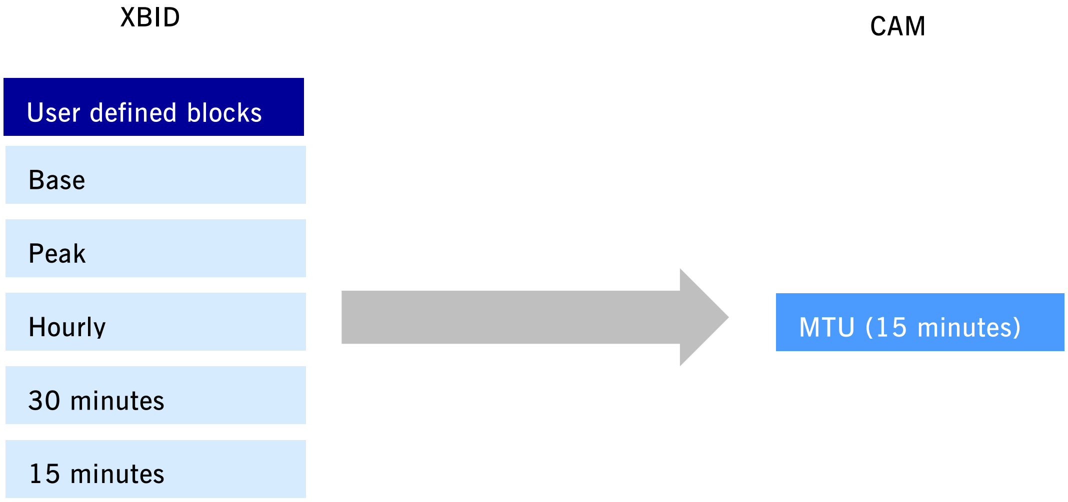

Figure 4: Changes in the product set-up

3.4.2 Power orders

The CAM supports a single but universal order type on the backend side, called multi-part order type. A multi-part order consists of a bid curve and a set of MTU periods. Multi-part orders allow market participants to link MTUs with delivery time intervals extending over more than one MTU. The following parameters characterise multi-part orders.

- Side. Defines if this order represents supply or demand (buy or sell order).
- Delivery MTU periods. A list of one or more consecutive or non-consecutive MTU period(s).
- Bid curve. A list of quantity/price pairs defines the price for the power traded at a given quantity. The bid curve is the linear interpolation between adjacent price/quantity pairs. The bid curve defined by the price/quantity pairs outlines a step-shaped curve. Adjacent quantity/price pairs have either equal quantity or equal price.
- Profile. The profile fixes an execution fraction per MTU period, in the range zero (inclusive) to one (inclusive). It defines the executed volume in individual MTU periods with respect to the nominal quantity on the bid curve. The ratio can differ per period.

Figure 5 illustrates the main components of a multipart order with execution conditions.

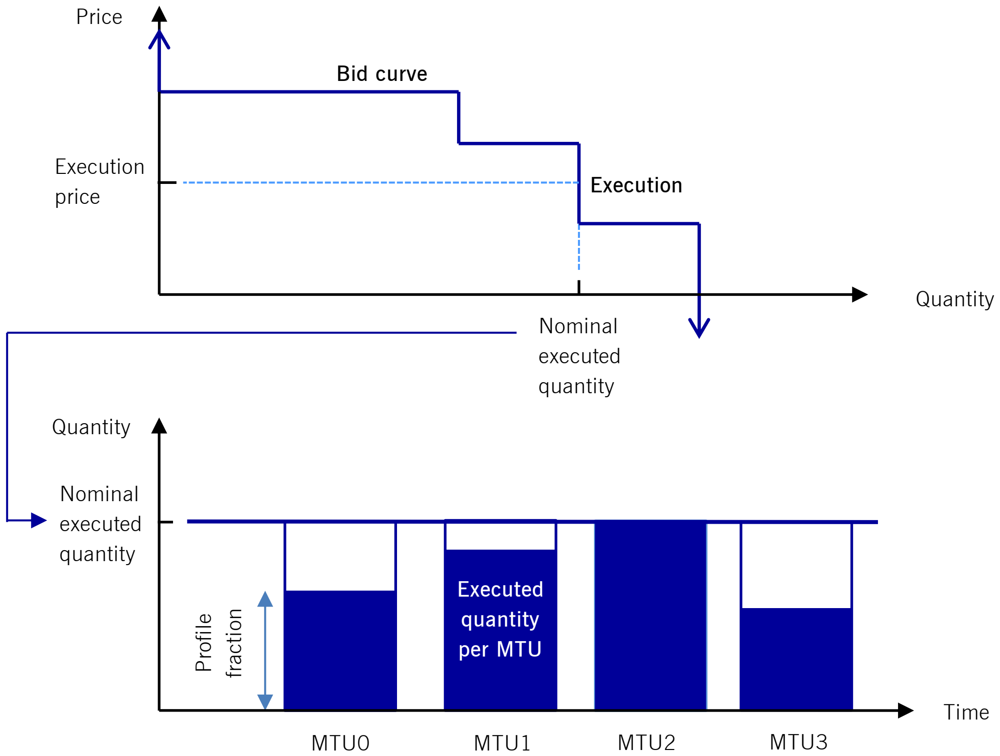

Figure 5: Bid curve and profile quantity ratios for a multipart order

The rules that apply for the execution of power orders are as follows:

- The nominal executed quantity and the execution price must lie on the bid curve.
- The executed quantity per individual MTU period is equal to the profile fraction of the nominal quantity in the respective period.
- The average zonal prices across the MTU periods, weighted with the per period executed quantities, must coincide with the execution price on the bid curve.

Multi-part orders allow market participants to link a range of MTU periods, e.g. an order in an XBID-one-hour contract would be entered into as a multipart order combining four consecutive MTU periods of 15 minutes duration each.

The following order variants are special cases of a multi-part order.

Single period step order

A single period step order covers only a single MTU delivery period with profile fraction of one. The order corresponds to stepwise aggregated hourly orders in Euphemia, but with a delivery interval of a single MTU period instead to one hour.

Limit order

A limit order is a special case of a multi-part order with a particularly simple bid curve. Only three quantity/price pairs define the bid curve: the corner points (0, limit price) and (maximum quantity, limit price) and the pair (maximum quantity, minimal market price) for buy, and (maximum quantity, maximum market price) for sell orders.

Referring to the XBID model, a limit order corresponds to a quarterly, half-hourly or hourly limit order, depending on the MTU periods included in the profile, with equal execution fraction of one in all periods.

If the MTU periods extend over a larger time interval, a multipart order corresponds to a block order without all-or-nothing (AON) restriction in the XBID and Euphemia models. Additionally, if the profile fractions differ between MTU periods, the order shape coincides with a profile block order in Euphemia (without AON restriction).

Limit orders are executed at quantities between zero (excluded) and the maximum quantity (excluded), and at the limit price, if the limit price is equal to the averaged zonal price over the MTU periods. Limit orders must be executed with maximum quantity if the average zonal price is below (buy order) resp. above (sell order) the limit price. Limit orders cannot be executed (zero executed quantity) if the average zonal price is above (buy order) resp. below (sell order) the limit price.

Minimum acceptance ratio

We anticipate extending the CAM market model in later release by including the so-called minimum acceptance ratio as an additional optional order parameter. The minimum acceptance ratio is a number ranging from zero (included) to one (included) that determines the minimum nominal quantity in case a limit order is executed. A minimum acceptance ratio of one corresponds to an AON restriction. A minimum execution ratio of zero defines a limit order that can also be executed partially.

3.4.3 Capacity orders

The CAM model allows to trade capacity at a marketable price. Capacity orders represent a new functionality intended to replace explicit capacity allocations.

The following parameters define a capacity order.

- Source and destination zone. Source and destination zones are not restricted to be linked directely by an interconnector.
- Quantity. The amount of capacity to be allocated between source and destination.
- Limit price. The maximum price for the capacity per unit of power.

An equivalent model for a capacity order is the simultaneous entry of a sell power order at the source, and a buy power order at the destination area. The hypothetical order pair needs to be executed at once with equal quantity, with an execution price difference of the buy-sell pair better than or equal to the limit price of the capacity order.

Capacity orders are executed in the auction together with other capacity and power orders. The execution of capacity orders depends on the price spread between destination and source area prices. Capacity orders are executable only if the order limit price is larger than or equal to the area price spread.

Like limit power orders, partial execution of capacity orders is also possible.

Example – execution of capacity orders

Figure 6 exemplifies capacity and prices on a congested interconnector. A pair of zones is linked by an interconnector A → B with limited capacity. For illustrative purposes, we consider the situation with only sell orders in A and only buy orders in B. The quantity/ price pairs defining bid and ask curves are enumerated by S_i and B_i, respectively.

In case of congestion, the cross border capacity is limiting the exchange between A and B. Consequently, the buy area price P_B is higher than the equilibrium price P_0, and the sell area price P_S is below the equilibrium price. The market value of the scarce capacity is the price difference $\Delta P = P_B - P_S$.

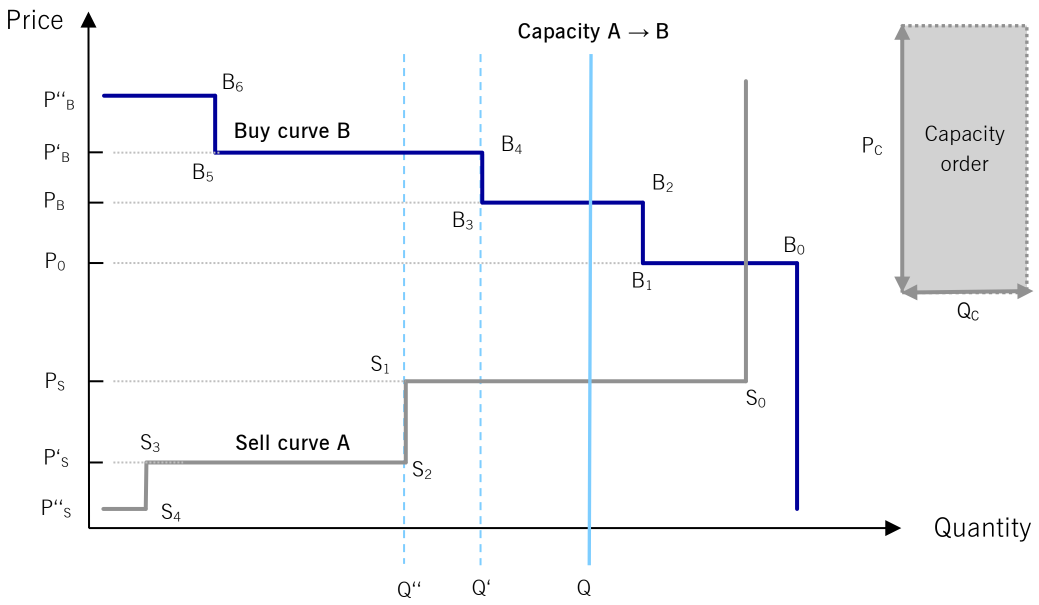

Figure 6: Initial situation of a congested interconnection. The indicated capacity order needs to be included in the cross border matching calculation.

In order to execute a capacity order with given limit price P_C and quantity Q_C, one needs to compare the limit price P_C with the price spread between bid and ask curves. In order to maximise welfare, the capacity order needs to be inserted in the bid curves at a position where the spread is as large as possible but not larger than the limit price of the capacity order. The bid and ask curves are cut at the insertion point, shifting the part with smaller spread to the right.

The initial price spread $P_B - P_S$ is smaller than the limit price P_C of the order. In turn, also the second largest spread $P'_B - P_S$ at executable quantity Q' is still smaller P_C. Only the next largest spread $P'_B - P'_S$ is larger than the price P_C of the order.

Figure 5 depicts the inserted capacity order for the example under consideration.

Inserting the capacity order into the bid curves amounts to cut the ask curve between S_1 and S_2 along S' – S'' and the bid curve between B_4 and B_5 along B'-B'' at the quantity Q''.

The quantity of the capacity order inserts into the curves and shifts the remaining parts by Q_C to the right. As a result, the price spread at the maximum cross border capacity Q increases to $P'_B - P_S$.

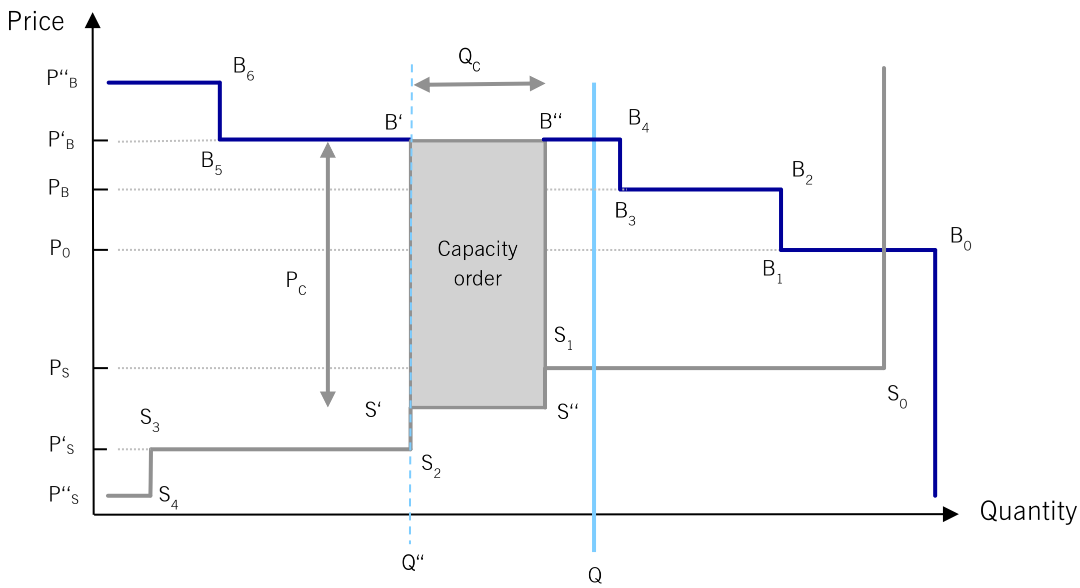

Figure 7: Welfare optimal insertion of the capacity order in between buy and sell bid curve

3.4.4 Public market data

Distribution of real-time market information in energy markets is a challenging task. Especially for XBID, the local view calculation turns out to be extremely expensive. A single trade can invalidate a large number of local views, as the number of dependent views depends on the product of the number of affected contracts and the number of zones. Consequently, in liquid markets, order processing is much faster than the local view calculation. Therefore, the local view calculation local lags behind the order matching calculation, and local views are potentially outdated at distribution time.

Instead of performing an expensive local view calculation for the CAM model, we propose to distribute raw public market data.[3)]

Auction results

The following auction results are distributed as public data stream.

- Zonal prices: the zonal prices per MTU period
- Traded volumes: the executed quantity per MTU and per zone is published.

Top-of-book information

The top-of-book information informs the market participants about the maximum quantity at the best available price, per MTU and zone. The information is based on the order book and capacity situation right after the auction.

The distributed top of book quantity/price pair corresponds to the maximum executable quantity and execution price achievable by entering a single MTU limit order in the corresponding zone. The displayed quantity accounts for the currently available capacity, but also considers potential matching opportunities against combinations of multipart orders.

With respect to XBID, the top of book information corresponds to the first level of the local view, but extended to include cross-contract matches.

The following information shall be distributed.

- Best bid price and quantity. The maximum quantity at the best execution price that could be achieved by executing a single MTU limit buy order in a zone.
- Best ask price and quantity. The maximum quantity and execution price that could be achieved by executing a single MTU limit sell order in a zone.

Public auction information

Anonymised public information could be disseminated at two points in time.

- Immediately before the auction, in step “preparation”, when the order book is updated with events from the incoming queue. All events (power and capacity order add, remove and modify events) are anonymised and distributed. This supplies market participants with the complete and consistent information on the order book and available capacity serving as auction input.

[3)] This does not exclude the local view calculation for CAM as a future extension. Referring to the CAM model, e.g. a calculation of the local view per MTU could be envisaged, scaling out the contract multiplicator in performance with respect to XBID.

- Immediately after the auction: after completion of the auction, (power and capacity) order executions and implicit capacity allocations are distributed. This allows to track the market state right after the auction.

Capacity information

The displayed capacity information depends on the chosen transport model.

In case of an NTC grid model, the capacity situation could be distributed as hub-to-hub capacity matrix.

3.5 Transport model

The transport model represents a coarse model of the physical grid. Transport constraints account for limitations of power transfer on the physical high-voltage network. In conjunction with trading, it determines the transfer of order quantity between different zones.

3.5.1 NTC grid model

The NTC grid model is characterised by zones linked by interconnectors representing a given topology. Power from one zone to its adjacent zone can only flow through interconnectors limited by transport restrictions. Flows in the NTC grid model commercial power exchange which does not necessarily coincide with physical power flows.

Capacity limits

The net transfer capacity (NTC) restricts the accumulated transport on interconnectors including all cross-zonal power flows from trades and capacity allocations. The residual capacity between the NTC and the already allocated flow is available for further cross-zonal trades.

Losses

Losses account for dissipation of electric power on physical lines modelled by interconnectors. A preconfigured fraction of the power flow injected at the sending end is lost at the receiving end. Losses are in general applied to DC lines only.

Ramping restrictions

Ramping restrictions account for the limited change in the power flow from one MTU period to the next and effectively act as a further restriction on the residual capacity. DC lines are typically subject to ramping restrictions.

3.5.2 Flow-based grid model

The model indirectly relates the power flow on critical network elements (CNE) with the net positions in the zones. The model presumes a linear dependency of the flows on the CNEs on the net positions.[4] Power transfer distribution factors (PTDFs) describe how the load on CNEs changes if power injection shifts from one zone to another.

Flow-based constraints

The remaining available margin (RAM) limits the capacity on CNEs. This indirectly also restricts zone-to-zone capacities for cross border trades.

3.5.3 Hybrid grid models

Realistic grids combine NTC and flow-based models. Typically, AC regions that combine a synchronised subset of zones could be modelled with the flow-based methodology. The regions are connected by DC lines subject to NTC, ramping and loss conditions.

3.5.4 Interoperatibility with the CAM model

NTC, flow-based and hybrid grid models are fully compatible with the continuous auction model. Mathematically, incorporating NTC or the flow-based conditions in the underlying Transport model of the CAM amounts to including linear constraints on decision variables. Therefore, calculating the optimal welfare in the auction still corresponds to solving a linear programme. The solution of linear optimisation problems has been studied extensively for over eight decades and powerful and performant techniques are at hand today. Most importantly, the inclusion of linear constraints does not increase the complexity class of the auction calculation.[5]

3.6 CACM conformity

The proposed CAM model is fully compliant to the capacity allocation and congestion management regulation (CACM) which is the legal frame for exploring implementations of possible continuous trading matching algorithms. With respect to capacity pricing, Deutsche Börse AG identified and considered the following relevant requirements in the regulation.

1. Capacity pricing must be based on congestion income.
   Article 55(1) states that "Once applied, the single methodology for pricing intraday cross-zonal capacity developed in accordance with Article 55(3) shall reflect market congestion and shall be based on actual orders."
2. Capacity prices must be available at the time of order matching.
   Article 55(2) states that "… This mechanism shall ensure that the price of intraday

[4] The presumption is valid as long as the flows resulting from trading do not deviate significantly from the base case pre-calculated by the TSOs.
[5] In practice, runtimes usually depend linearly or quadratically on the number of constraints and the number of decision variables. The implementation and choice of the calculation methodology (e.g. simplex or network optimisation) also affects performance to a large extend.

cross-zonal capacity is available to the market participants at the time of matching the orders."

3. Exclusion of charges.
   Article 55(4) defines that "No charges, such as imbalance fees or additional fees, shall be applied to intraday cross-zonal capacity except for the pricing in accordance with paragraphs 1, 2 and 3."
4. Continuous process.
   Preamble point (5) says that the MCO should "…use a continuous process throughout the day and not one single calculation …" in single intraday coupling.
5. Implicit allocation.
   Definition (27) states that " 'single intraday coupling' means the continuous process where collected orders are matched and cross-zonal capacity is allocated simultaneously for different bidding zones in the intraday market".

4 Proof of concept

To proof the feasibility of the CAM model, both with respect to performance and to sensible market design, Deutsche Börse AG implemented a prototype and exposed it to production like load. In order to cope with existing data, the following functionalities were included in the first phase of implementation.

- Power limit orders with bid curves extending over multiple MTU periods
- Immediate-or-cancel order restrictions for power limit orders
- Capacity orders
- NTC grid model
- Explicit capacity allocations
- Congestion rent for explicit and implicit allocations
- Top-of-book auction price information
- Dissemination of anonymised order, trade and capacity data

The implemented prototype is based on a MTU with a delivery period of 15 minutes.

The tests performed with the CAM show that it is possible to operate the European intraday power market based on a continuous auction based market model. Based on the test data:

- 99.9 per cent of the auctions are executed with an overal latency lower than 100 ms. The maximum in observed end-to-end latency was 375 ms.
- The auctions processed a total of 11,028,444 order events.
- By removing the current boundaries between the different delivery periods the market got substantially more efficient. The executed volume increases by 9 per cent (or 62 GWh per tading day) compared to the XBID continuous model. Welfare increased by 8 per cent, corresponding to cash amount of about €200,000 per trading day.
- The average congestion income per trading day was about €340 not including three exceptional days where neagative prices resulted in congestion loss of about €13,000.
- The measured maximum in sustainable throughput is 200,000 order events per second.
- Performing auctions in consecutive mode increases the executed order volume by 38 per cent compared to the clocked auction processing mode with auctions every 15 minutes.

4.1 Test data

Deutsche Börse AG evaluated the performance of the CAM model using an entry data set based on 30 high-volume production days between 1 January and 30 April 2018. The data consists of ten samples each covering three consecutive days in a row.

The order and capacity time distribution of the data set is identical to the events happening in production. However, to speed up evaluation and to challenge performance limitations, the data set was replayed at a speed-up rate of ten.

The order types used in the continuous market model are converted using the following rules.

- All orders are entered as limit orders with equal quantities across all MTU. Partial executions are possible, with equal execution ratio across MTUs.
- Orders for delivery periods longer than one MTU are converted correspondingly: an order submitted for a 30 minutes contract extends over two MTUs, an hourly order extends over four MTUs, and block orders extend over the MTUs of the delivery interval.
- Block orders are treated as limit orders ignoring an AON restriction.
- Iceberg orders are entered with full quantity.
- Immediate-or-cancel and fill-or-kill orders are entered as limit orders, but deleted after taking part in the next upcoming auction.
- Order modifications are implemented as remove/add, similar to the XBID market model.

Additionally,

- initial capacity allocations at gate opening are included.
- explicit capacity allocations are included alongtime with trading events.

The grid comprises of the zones FR, BE, NL, CH, AT, DK and four German zones.

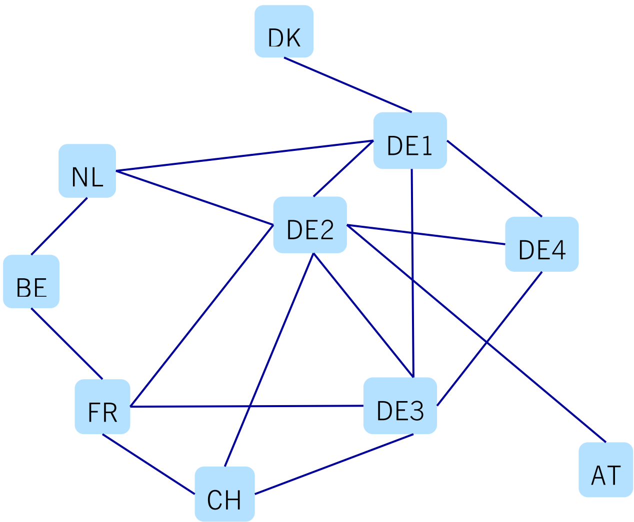

Figure 8: Grid used during proof of concept phase

4.2 Metrics

4.2.1 Match type

Trades involving more than two orders can be classified according to the match type based on the order delivery intervals involved in matching buy and sell sides. Important match types are

- 1:1
  This type summarises matches of two orders with identical delivery intervals at buy and sell sides. Most frequent matches of this type are quarterly : quarterly, half-hourly : half-hourly and hourly : hourly matches. Also included here are matches of one buy block order against one sell block order with identical delivery interval.

- 1:2
  This type includes matches of one order against two orders on the opposite side. Examples are matching of one houly oder against two half-hourlies, or one half-hourly against two quartely orders.

- 1:3
  One interval matches against three intervals. This includes e.g. the execution of one hourly buy order matching against one half-hourly and two quartely sell orders.

- 1:4
  One intervall matches against four intervals. The most frequent occurrence of this type is the execution of an houly order against four quarterlies.

- …

Matches outside the 1:1 combination cannot be executed in today's continuous markets like XBID.

4.2.2 Latencies and sizes

The measured latencies and sizes are defined as follows.

- Single event latency. The event latency is the duration between the entry of the event into the inbound queue and the arrival of the auction result that processed the event in output. The event latency includes the waiting time in the inbound queue and the auction calculation time.
- Batch event latency. The batch event latency is the maximum of the single event latencies of the events processed in a single auction. It accounts for the worst case waiting time of the events processed in a particular auction.
- auction duration. The auction duration accounts for the net processing time of the auction. It does not include waiting time in the inbound queue.
- Batch size. The batch size is the number of incoming events processed in the auction.
- Order book size. The number of orders in the order book immediately after the auction.

4.2.3 Events

Events considered in the statistics are:

- Grid set-up events like creation of zones and interconnectors
- The creation of MTU periods for zones
- Power order add, remove and modify events
- NTC changes and changes in the already allocated capacity

All auction statistics also include the initial grid creation and NTC/capacity set-up.

4.3 Results

4.3.1 Number of orders processed by type

The table below splits the number of orders by type accumulated over the 30 production days tested. The column "total events" is the total number of order events (add, modify and delete) per type. The column "active" indicates the number of orders (possibly after partial execution) that remained in the order book after the run.

Order type	Total events	Active	Fully executed	Deleted
Buy limit	5,574,776	34,556	763,173	4,777,047
Sell limit	5,040,237	30,264	755,525	4,254,448
Buy AON	5,676	63	324	5,289
Sell AON	5,726	59	323	5,344
Buy IOC limit	129,450	0	57,053	72,397
Sell IOC limit	129,009	0	60,221	68,788
Buy IOC AON	73,942	0	23,702	50,240
Sell IOC AON	69,628	0	22,349	47,279

Table 2: Total order event count processed split by order type

4.3.2 Generated welfare and order volume

The volume listed in the first row with match type 1:1 in Table 3 corresponds to the volume executed based on the continuous trading model (as used by XBID and the local trading solutions in the intraday power trading market).

Match type	Welfare buy and sell [€]	Relative welfare	Order volume [MWh]	Order welfare buy [€]	Order welfare sell [€]
1:1	68,096,891	92.11%	20,300,243	41,578,110	26,518,781
1:4	4,321,269	5.85%	1,189,798	2,726,037	1,595,232
1:5	555,110	0.75%	125,522	284,639	270,471
1:3	243,918	0.33%	93,541	154,835	89,083
1:2	186,246	0.25%	53,485	111,727	74,519
1:6	160,128	0.22%	50,440	64,864	95,263
…	…	…	…	…	…
Total	**73,927,185**	**100%**	**22,157,125**	**45,085,091**	**28,842,095**

Table 3: Executed order volume split by match type. Match type 1:1 summarises potential matches possible also in the XBID market. The CAM allows additional match combinations increasing the executed volume by roughly 8 per cent (all match types other than 1:1).

The CAM removes the boundaries between the different contracts used in XBID. As a result, it is possible to execute orders entered for different delivery periods against each other, as listed under match types other than 1:1. By removing the contract boundaries, the execution efficiency increases by approximately 8 per cent.

4.3.3 Number of events processed in auctions

The following diagram gives an indication on the number of events entering an auction. In roughly 50 per cent of the cases, the CAM algorithm works in single event mode, i.e. new events are processed immediately one after another.

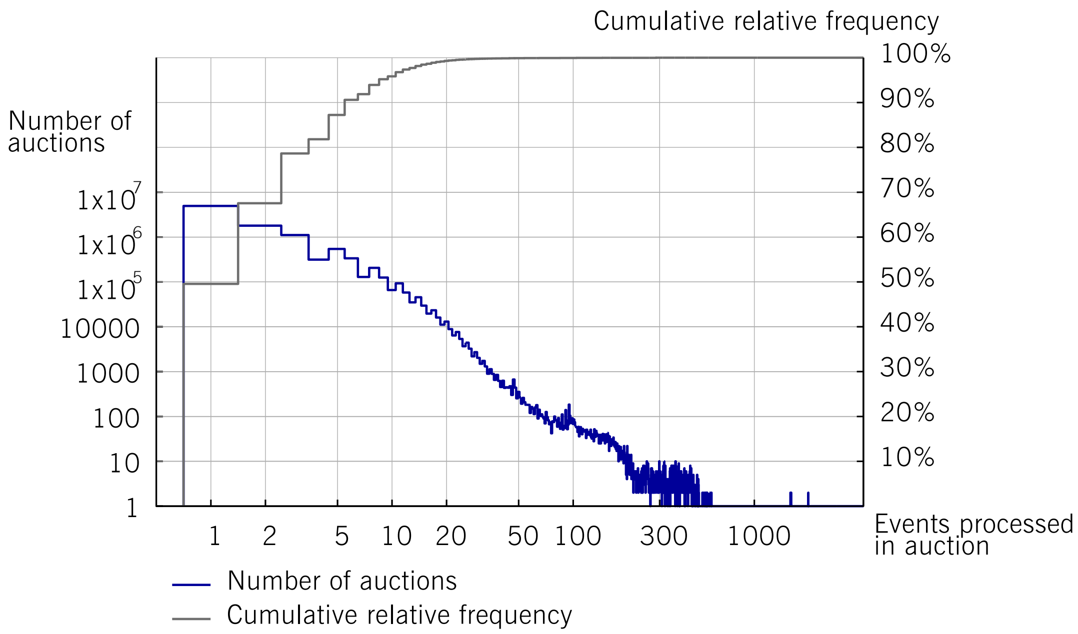

Figure 9: Distribution of the number of events processed in an auction.

4.3.4 Auction duration and event latency

The proof of concept demonstrates that the CAM is able to offer the performance required by the intraday power market. To evaluate the performance we measured both the time required to execute the auction ("auction duration", e.g. time between start of auction and finalisation of the calculation) and the time required to process events, which includes the waiting time of the events before entering the auction ("end-to-end event processing"). 99.999 per cent of all auctions have been executed with a latency below 100 ms and 99.9 per cent of all events have been processed in less than 100 ms.

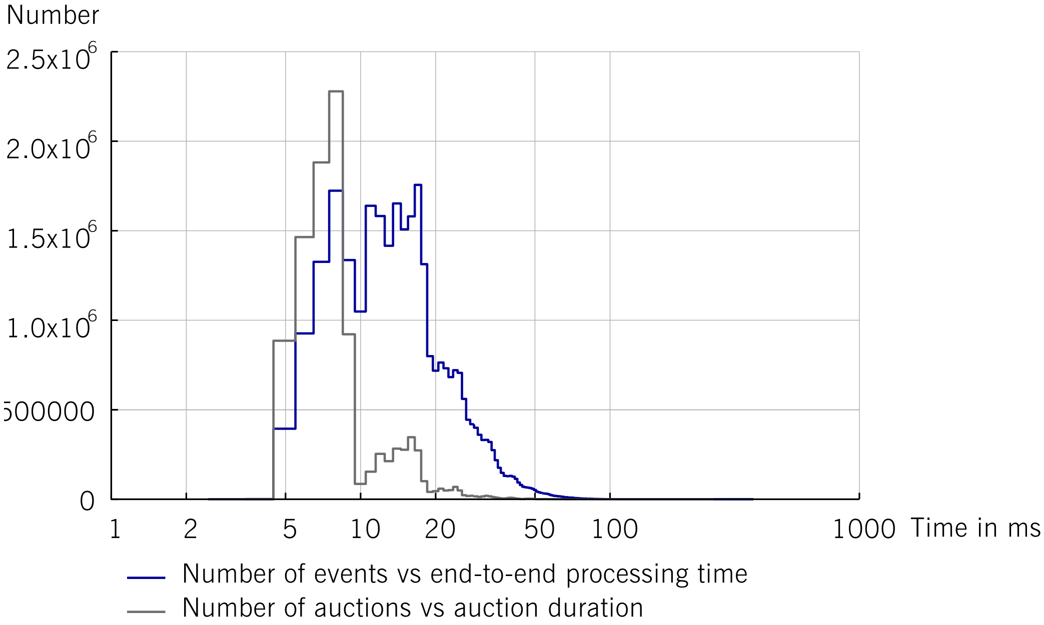

Figure 10: Distribution of the auction duration and the end-to-end event processing time. The event processing time includes the waiting time in the queue.

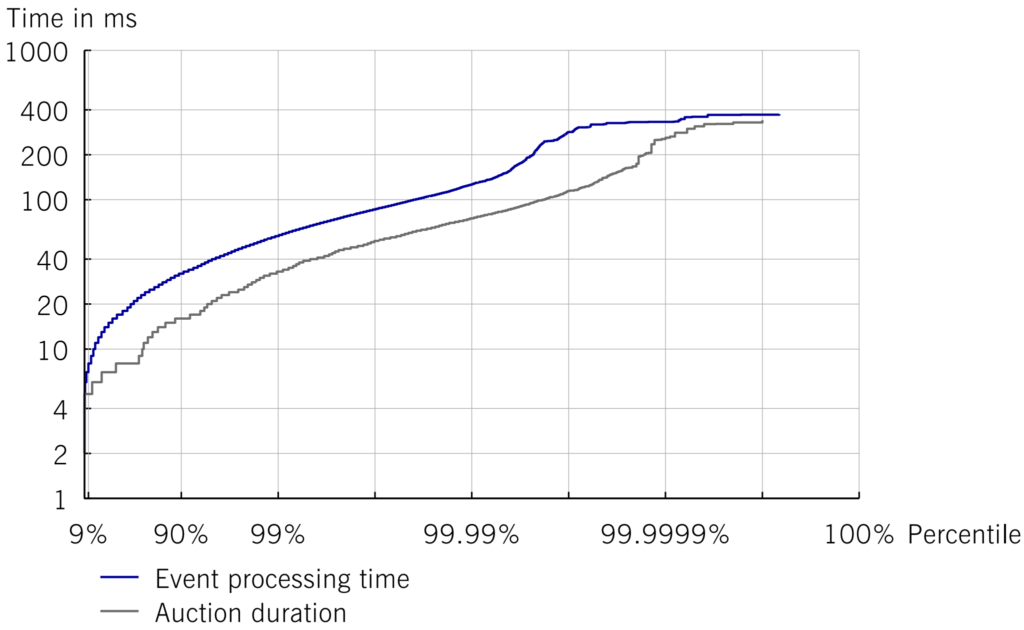

Figure 11: Latency percentiles for the auction duration and the end-to-end event processing time.

4.3.5 Impact of the auction batch size and the order book size on the latency

The number of newly added events and the order book size have little impact on latency. This is due to the fact, that the CAM algorithm re-uses the results of the previous auction in the process of optimising the current auction. With the used load we have not been able to touch the limits of the CAM algorithm.

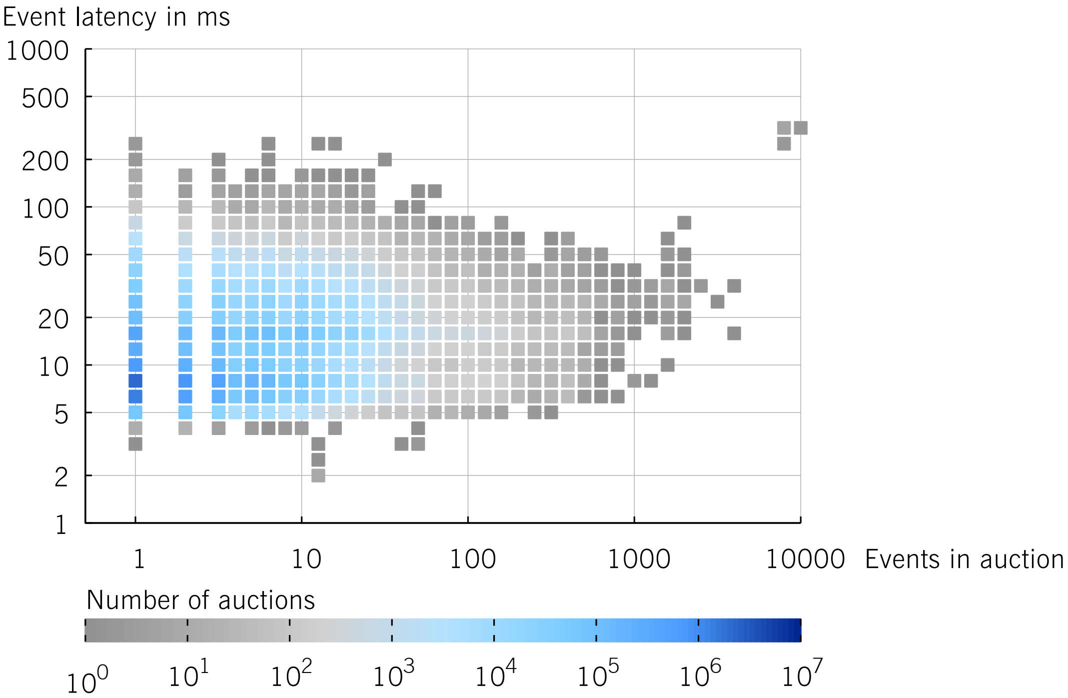

Figure 12: Impact of the number of events processed in an auction on the end-to-end event latency. The colour of a tile indicates the count of auctions with comparable latency and event count.

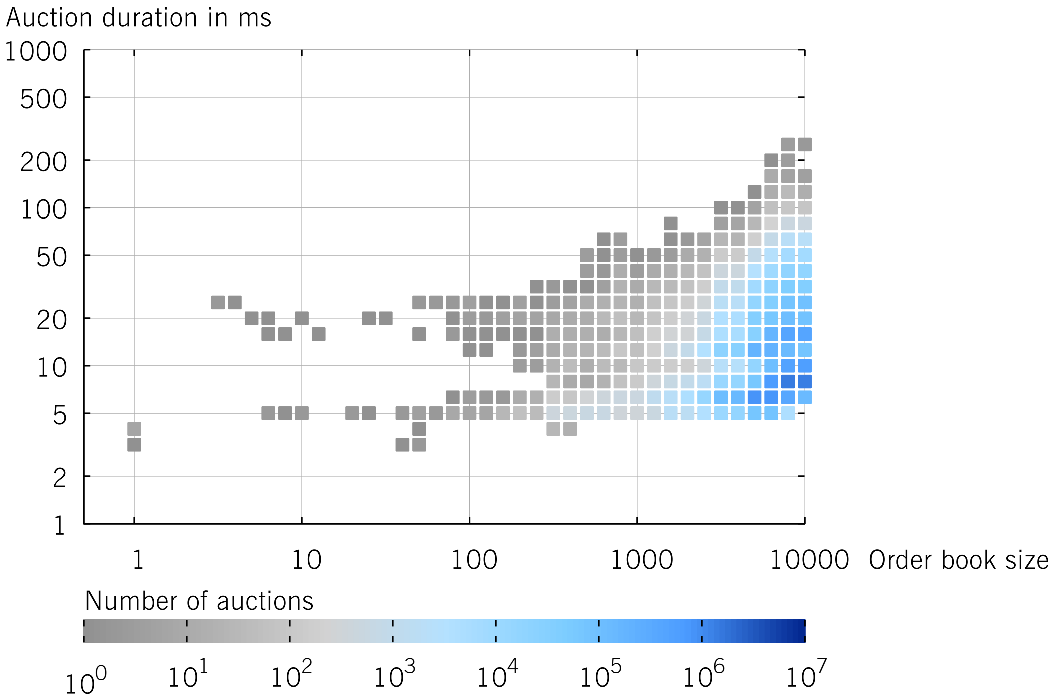

Figure 13: Dependency of auction duration on the order book size. The colours indicate the count of auctions with comparable duration and order book size.

4.3.6 Auction frequency

The configurability of the CAM algorithm in terms of consecutive and clocked execution frequency allowed us to analyze the impact of the duration of the auction timeframes on the executed volume and thus the liquidity of the market. The analysis investigated different auction frequencies using the three highest volume trading days starting 3 April 2018. Higher repetition rates have a significant positive impact on liquidity. Performing the auction in consecutive mode leads to the execution of 5.4 TWh order volume, 38 per cent more than in the case of performing the auction every 15 minutes (3.9 TWh executed volume).

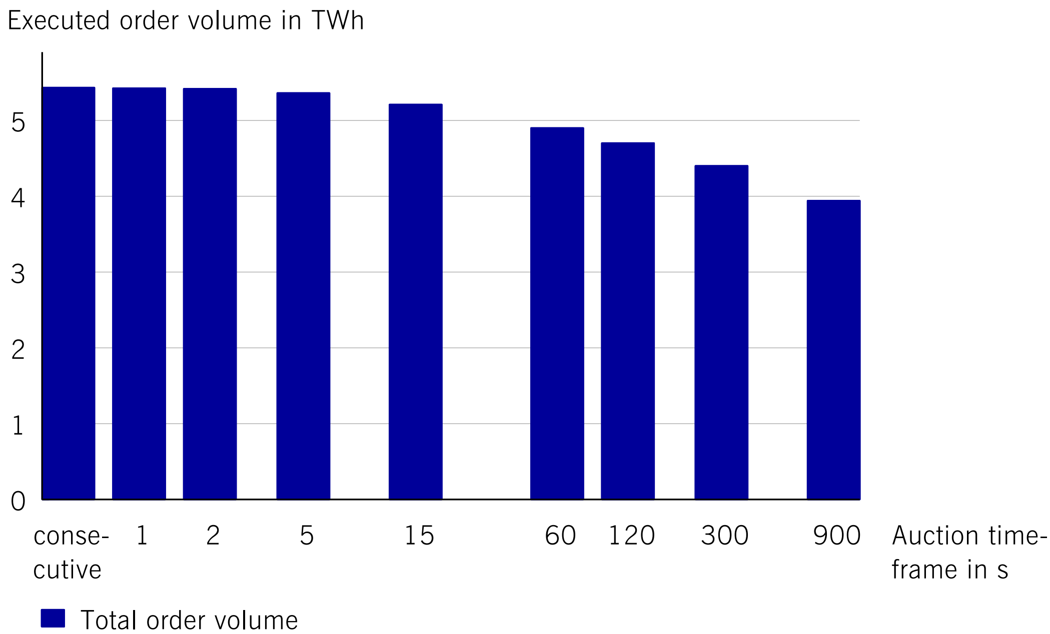

Figure 14: Total executed order volume for different auction timeframes.

4.4 Conclusion

The test results measured during the proof of concept phase indicate that the continuous auction model is well suited to operate the European intraday cross border market:

- It is able to handle high load situations (large event queues) with limited impact on performance.
- The CAM algorithm is able to handle large order books with limited impact on the end-to-end latency.
- The algorithm is automatically adapting to the event load.
- The CAM model considerably improves market efficiency and significantly increases available liquidity.

Published by
Deutsche Börse AG
60485 Frankfurt/Main
Germany

October 2018
Order number 9515-4818

Disclaimer